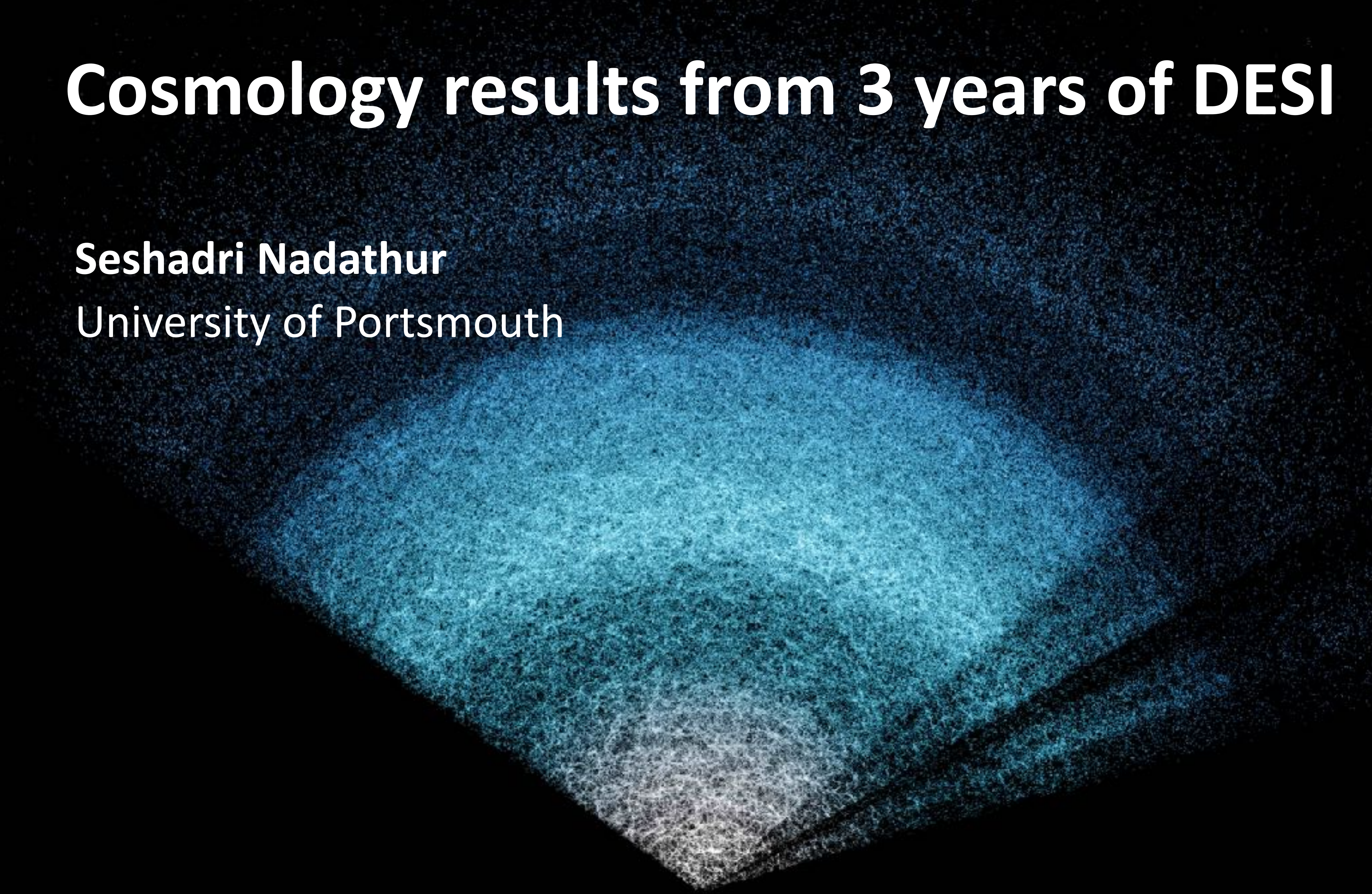
Cosmology results from 3 years of DESI

Seshadri Nadathur
University of Portsmouth



Mainz, November 2025

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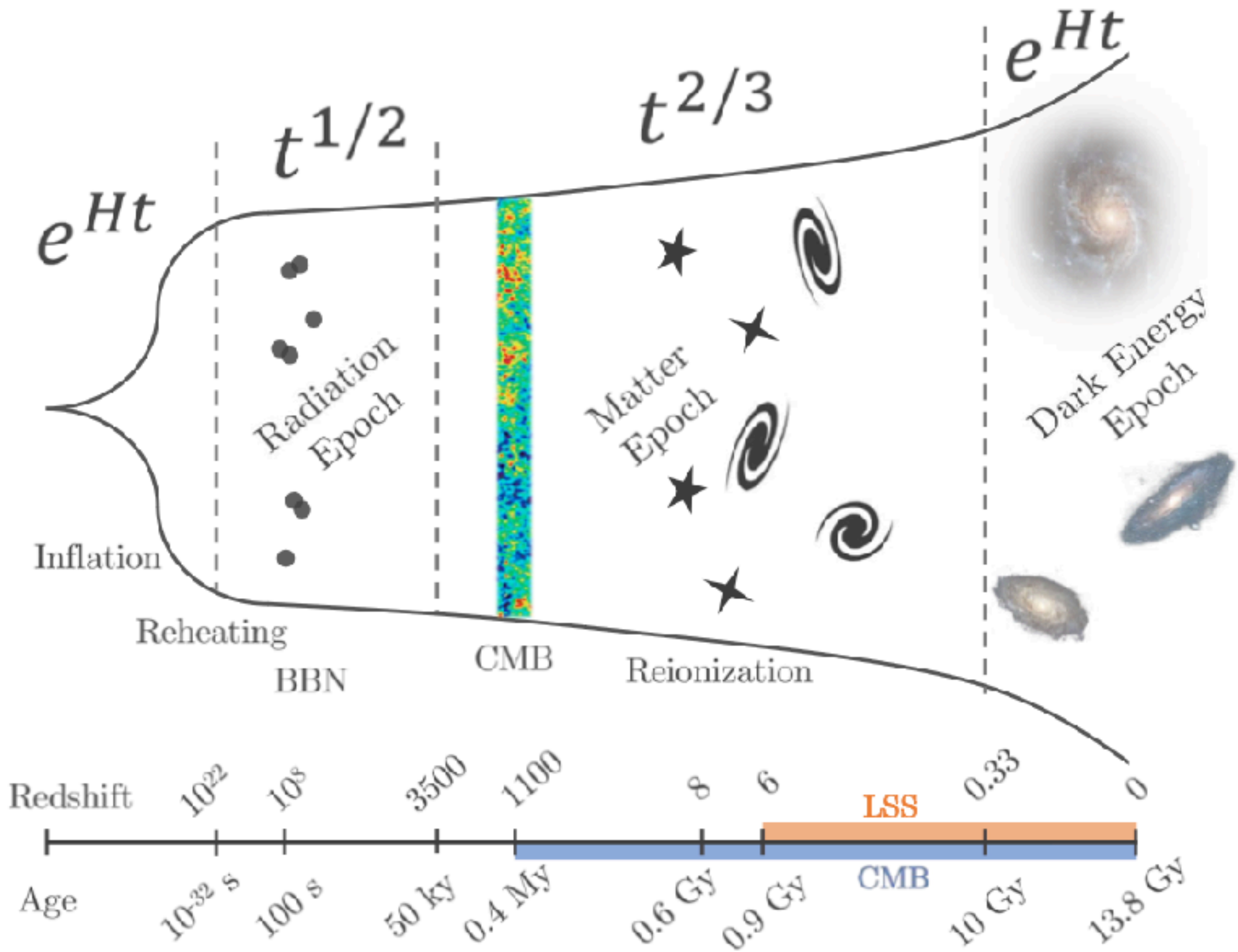
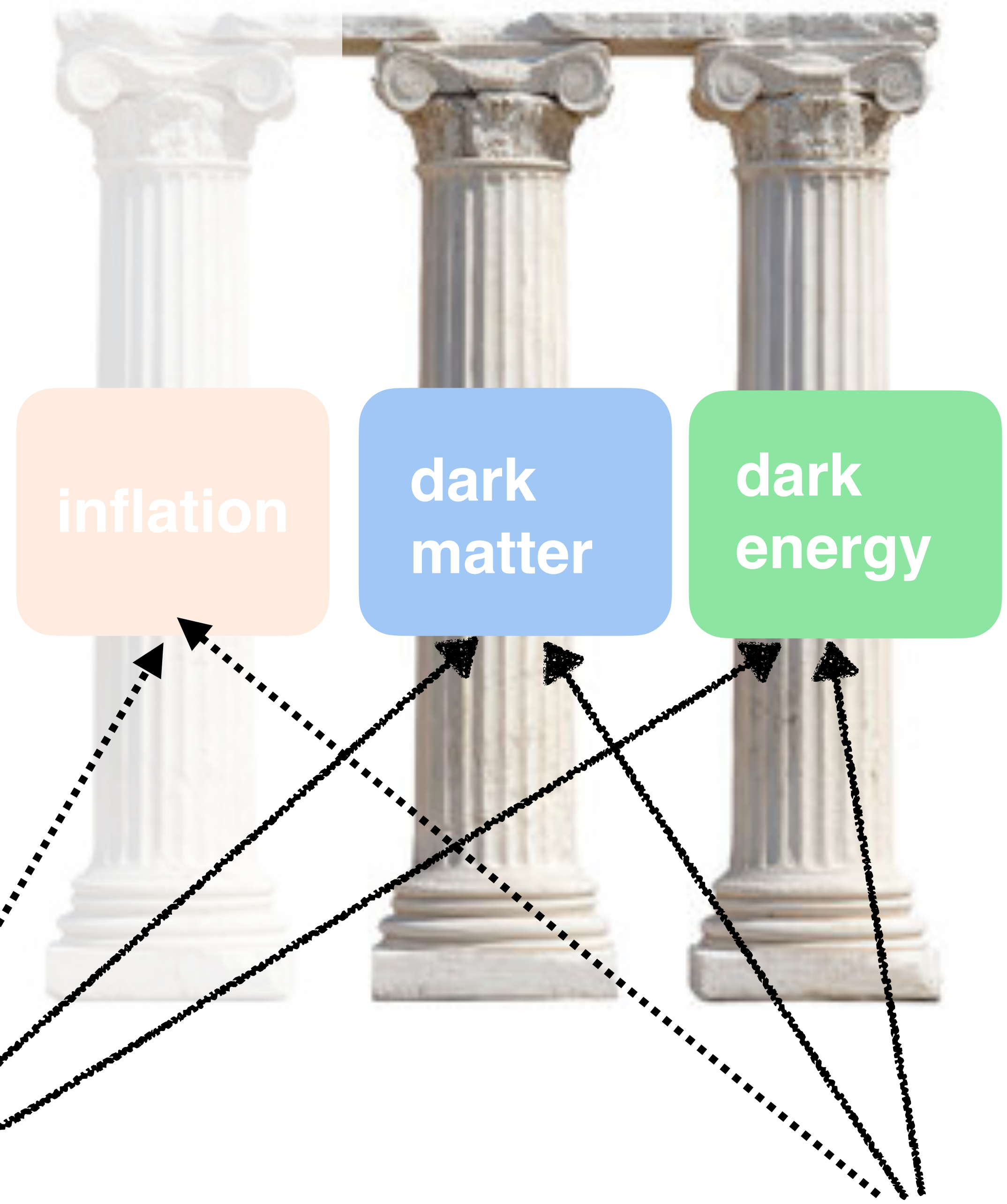
A history of the Universe



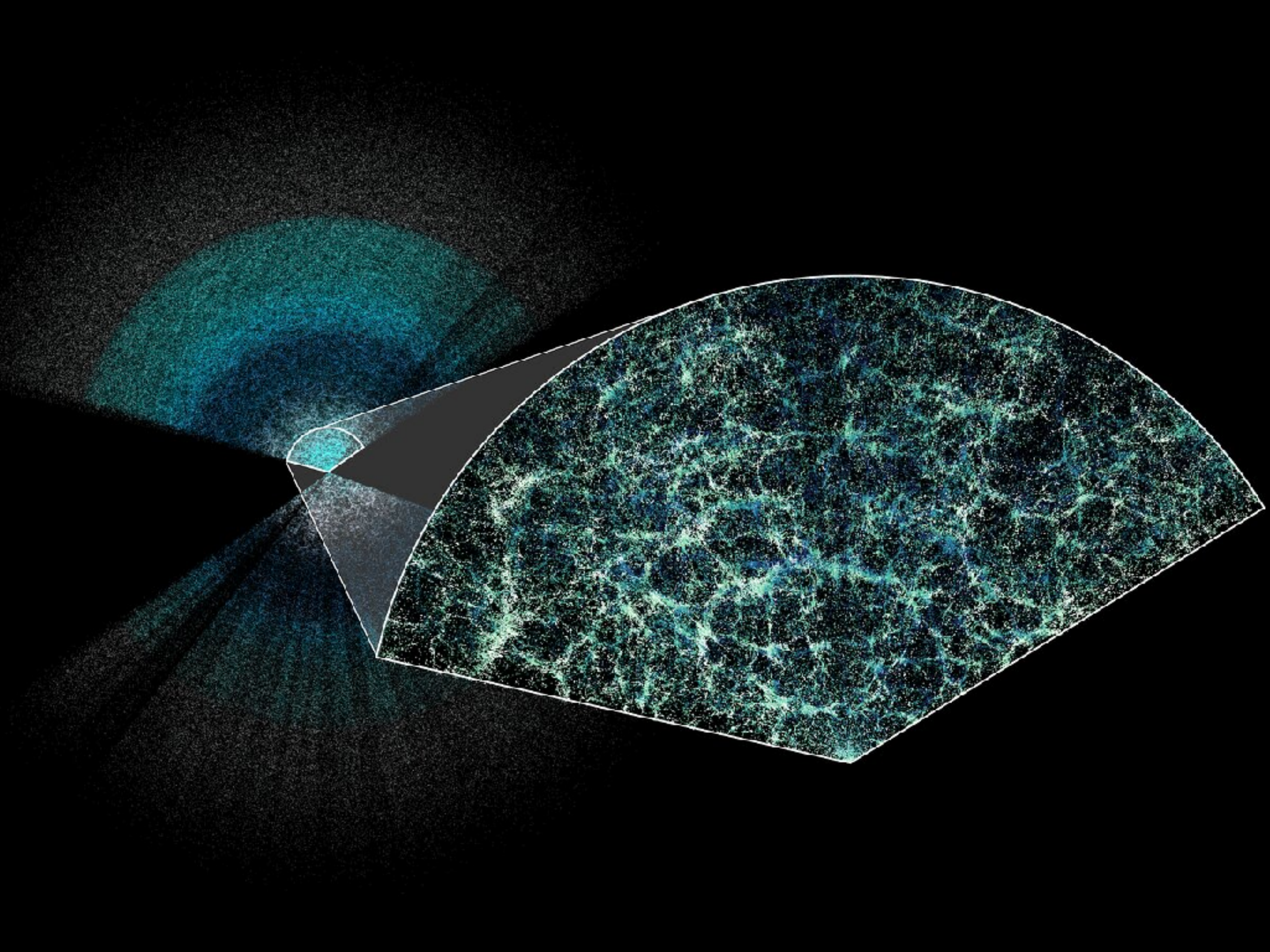
Three fundamental problems

Three fundamental problems



How does the Universe expand?
$H(z)$, $w(z)$, …

How do structures grow?
$f(z)$, $\sigma_8(z)$ …

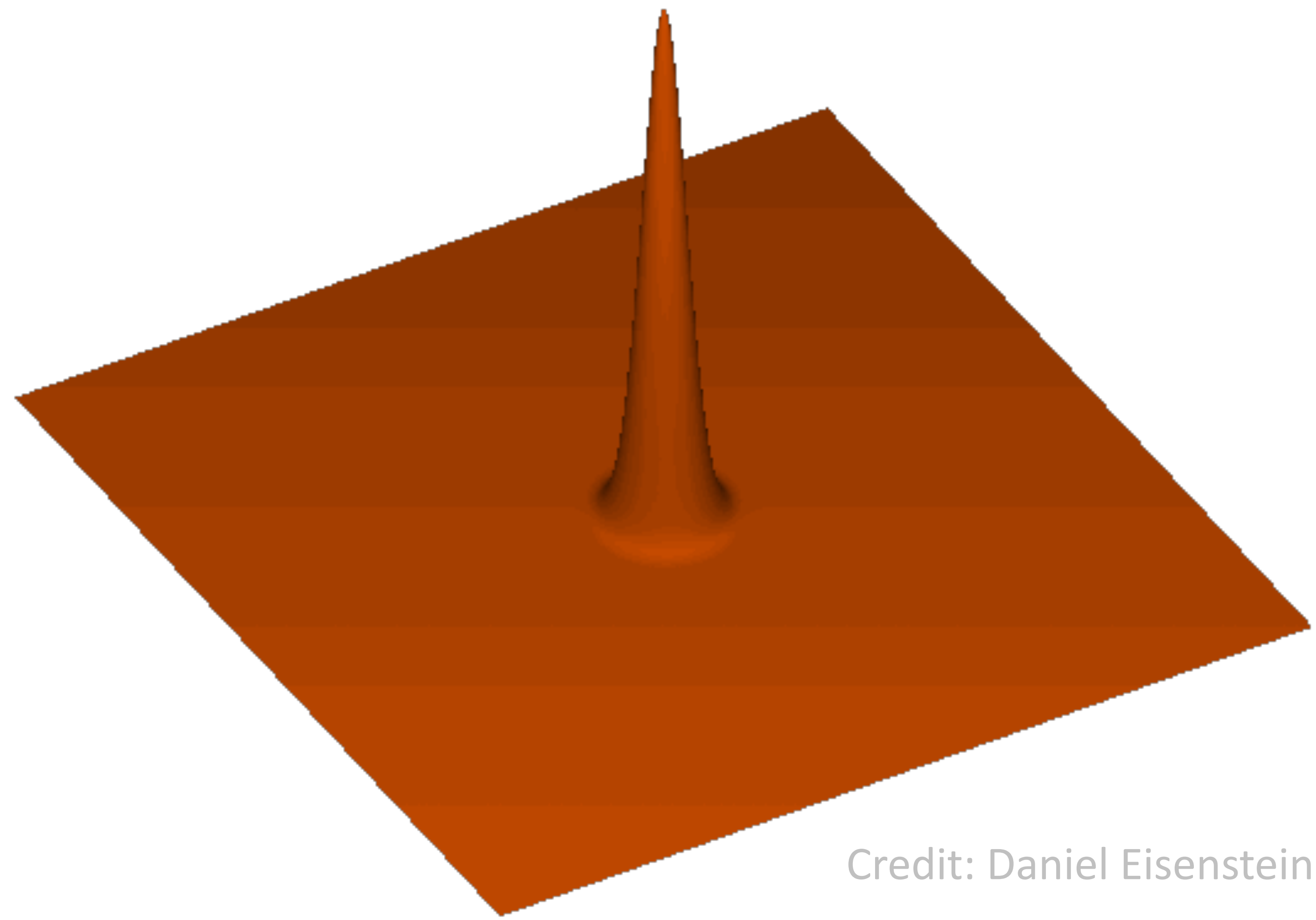


Baryon Acoustic Oscillations (BAO)

Gravity + pressure in primordial plasma → sound waves

When baryons and photons decouple ($z \sim 1100$), sound waves stall

Characteristic scale imprinted in matter distribution at sound horizon scale, $r_{\mathrm{d}} \sim 150$ Mpc



Credit: Daniel Eisenstein

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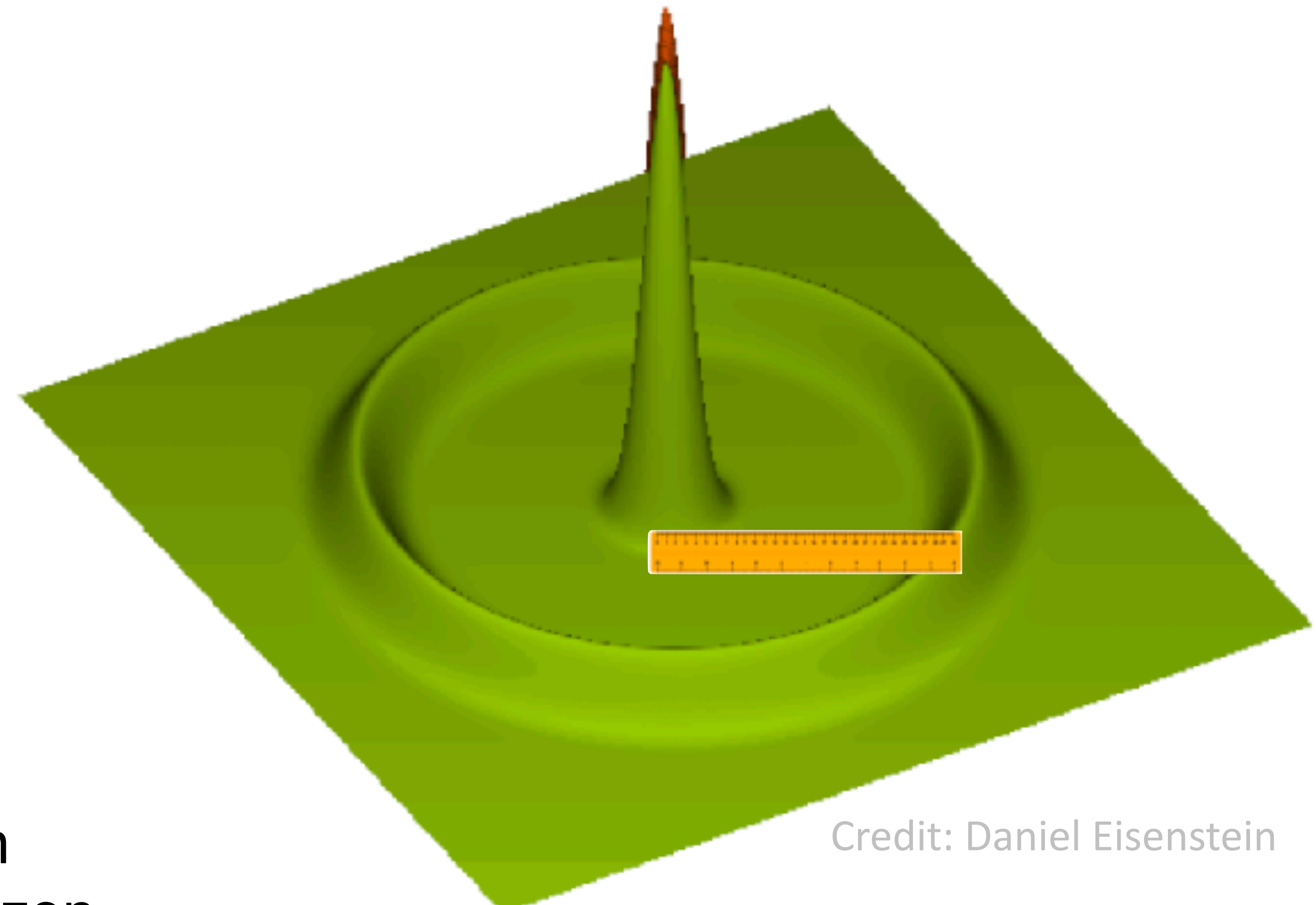

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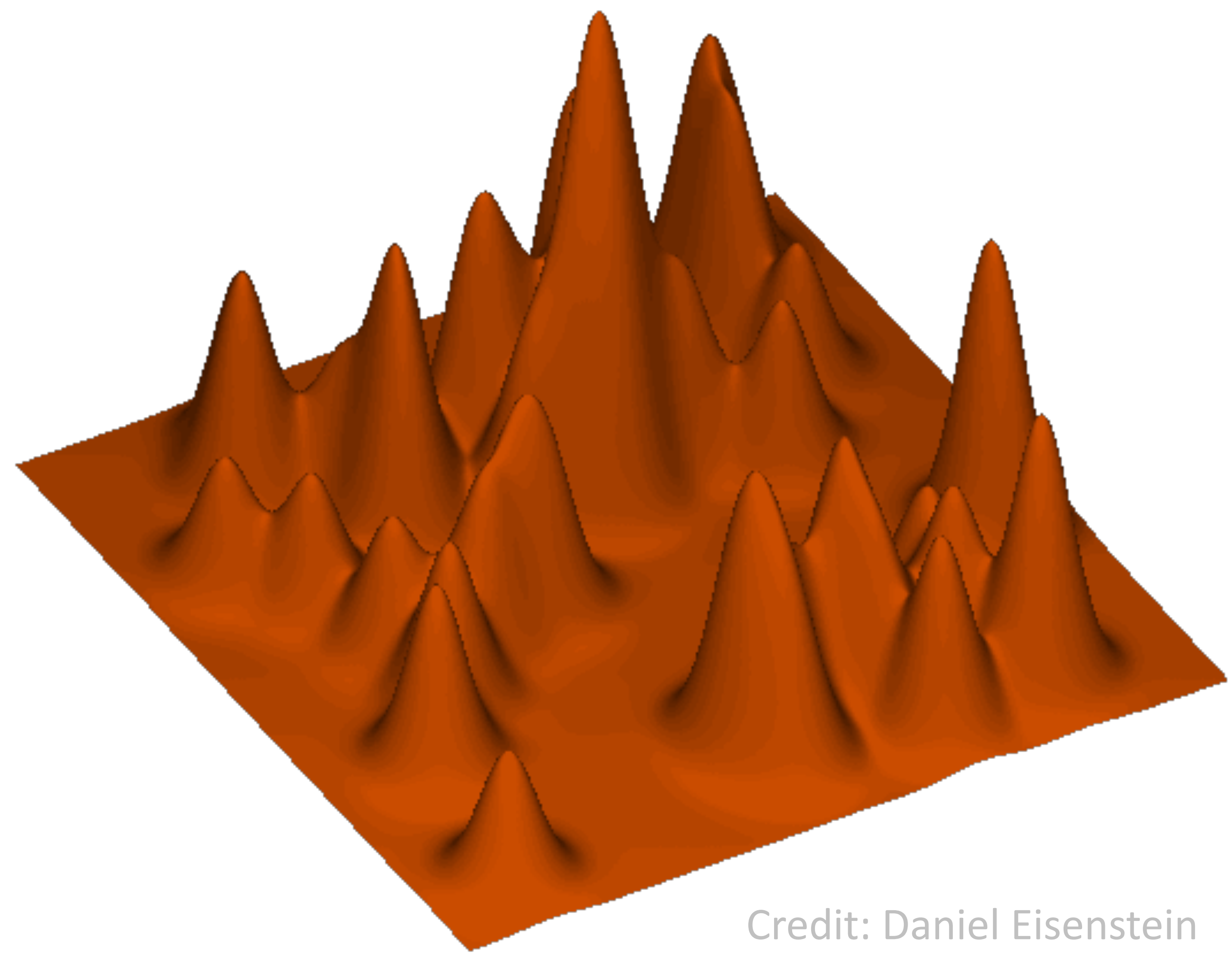

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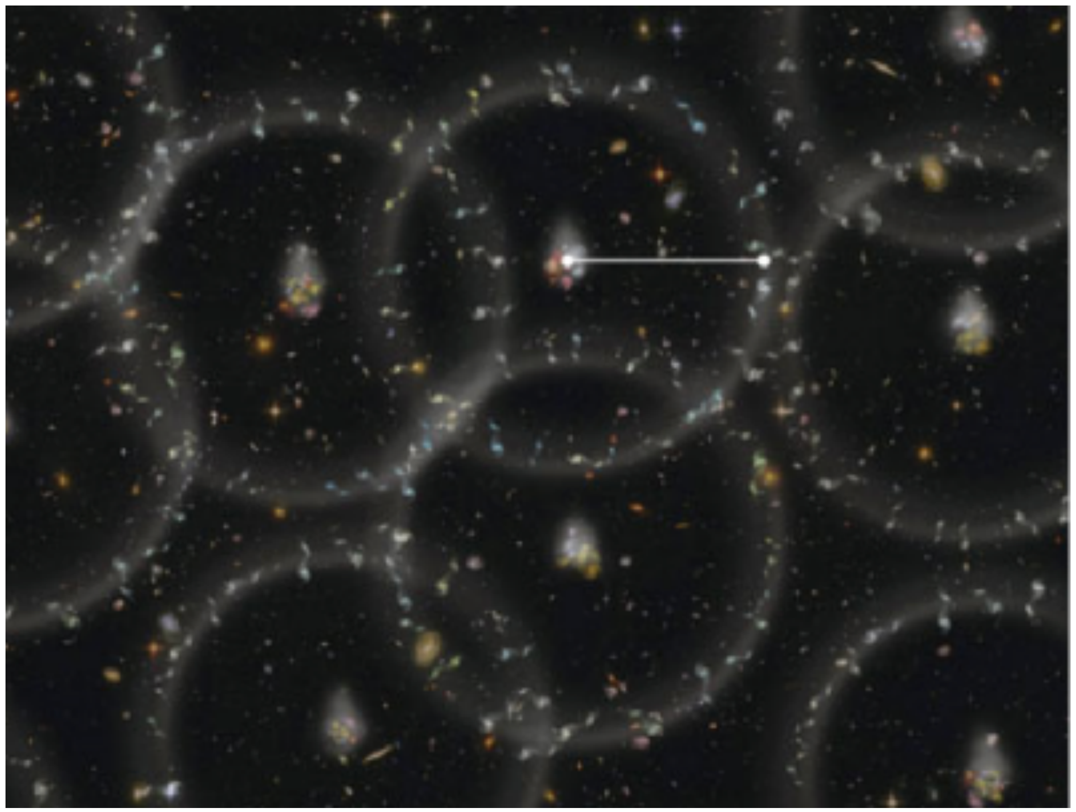
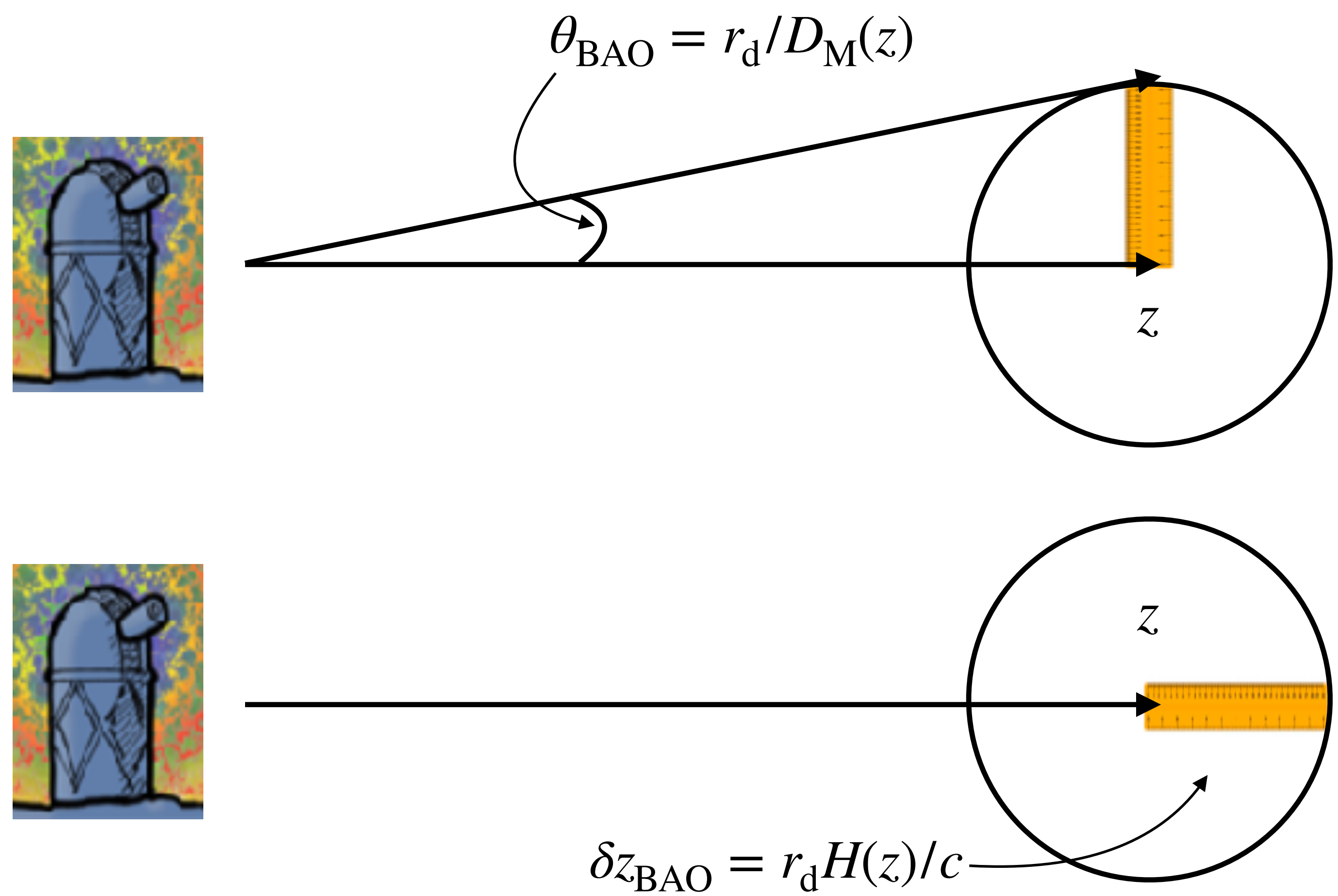
Baryon Acoustic Oscillations (BAO)



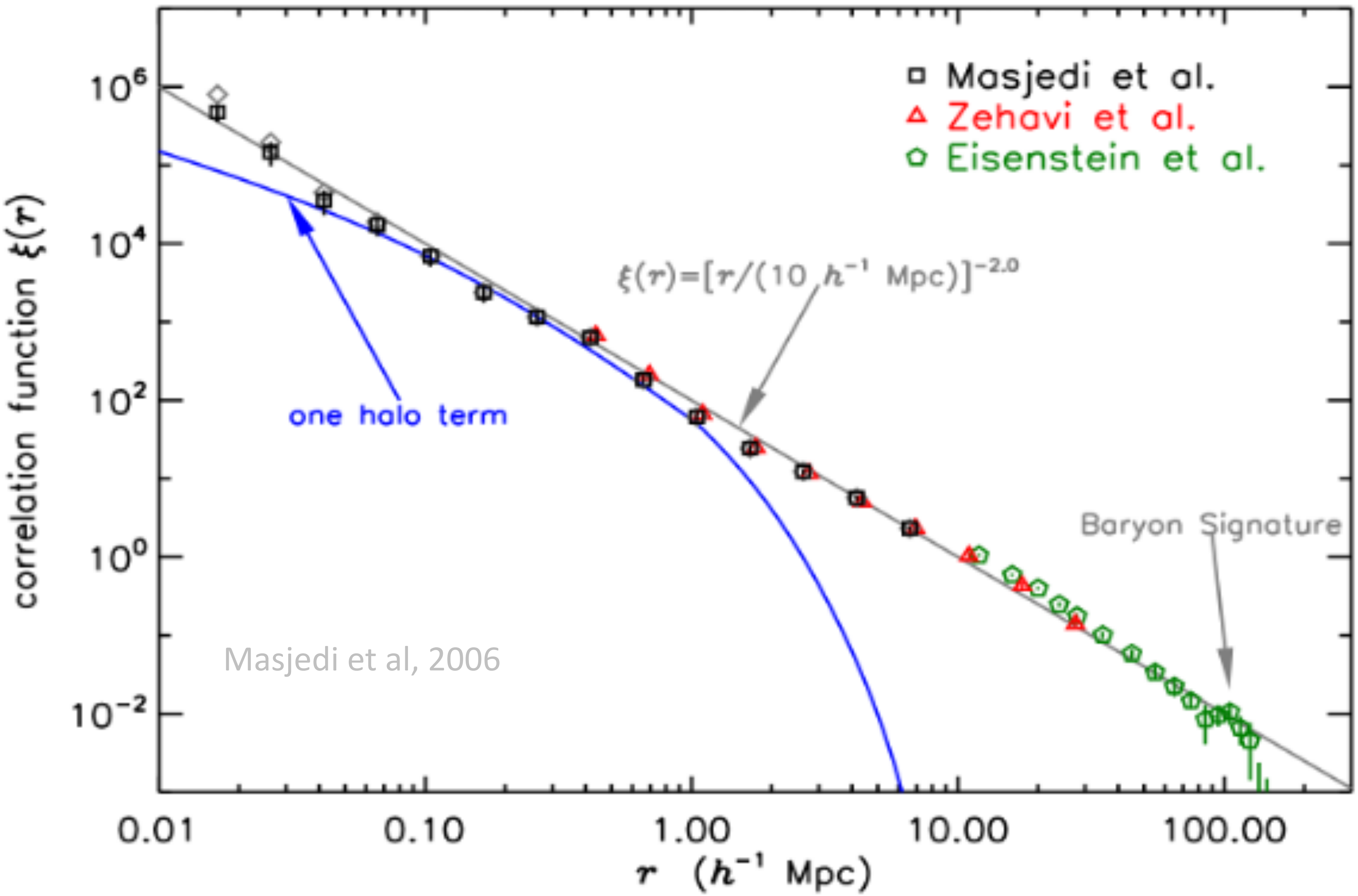


$D_{\mathrm{M}}(z)$ and $H(z)$ encode expansion history of the Universe

$$D_{\mathrm{M}} = \frac{c}{H_0\sqrt{\Omega_{\mathrm{K}}}} \sinh\left[\sqrt{\Omega_{\mathrm{K}}}\int_0^z \frac{dz'}{H(z')/H_0}\right]$$

$$H^2 = H_0^2\left(\Omega_{\mathrm{m}} a^{-3} + \Omega_{\mathrm{K}} a^{-2} + \Omega_{\mathrm{r}} a^{-4} + \Omega_{\Lambda}\right)$$

Baryon Acoustic Oscillations (BAO)



Masjedi et al, 2006

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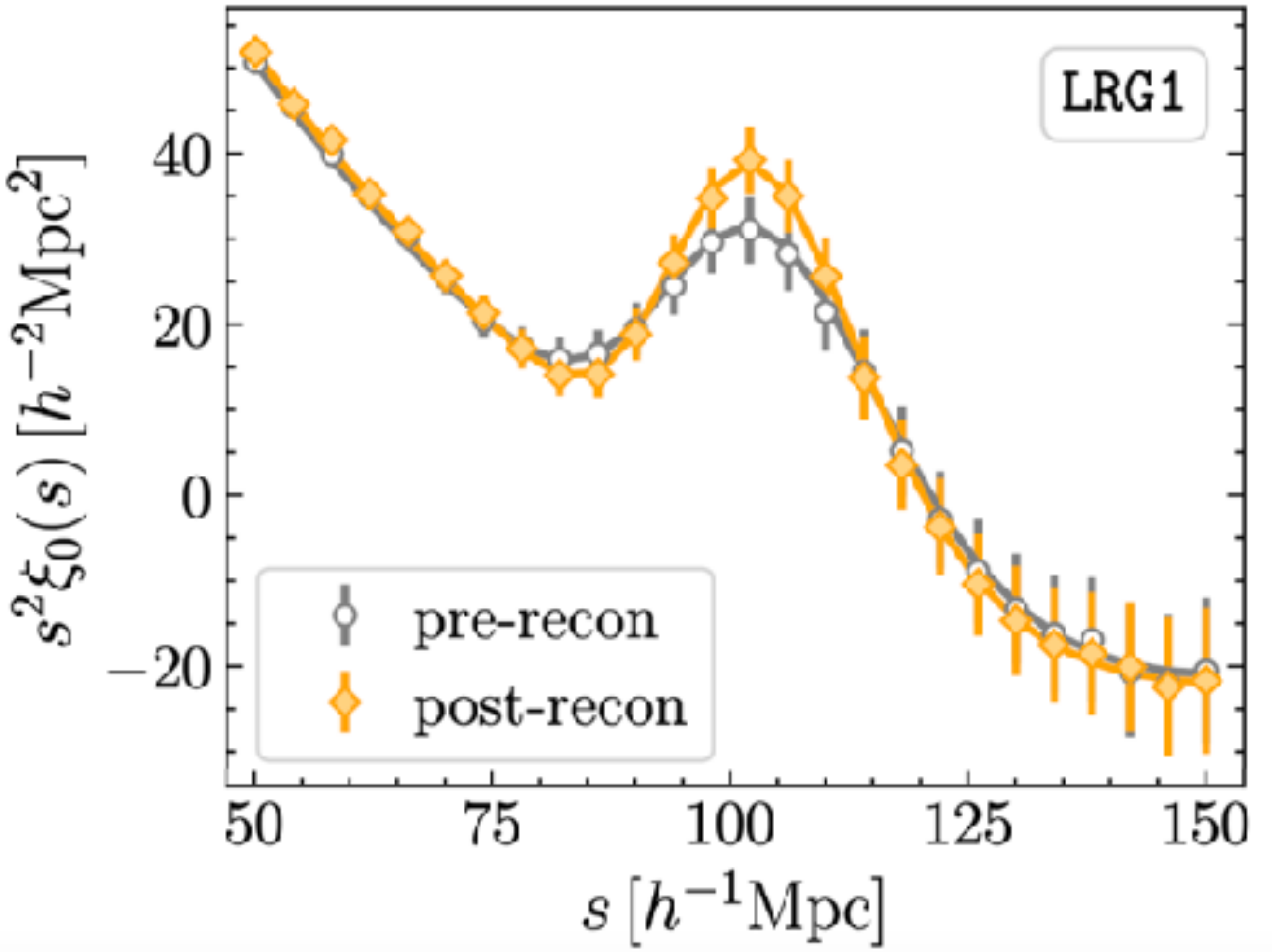
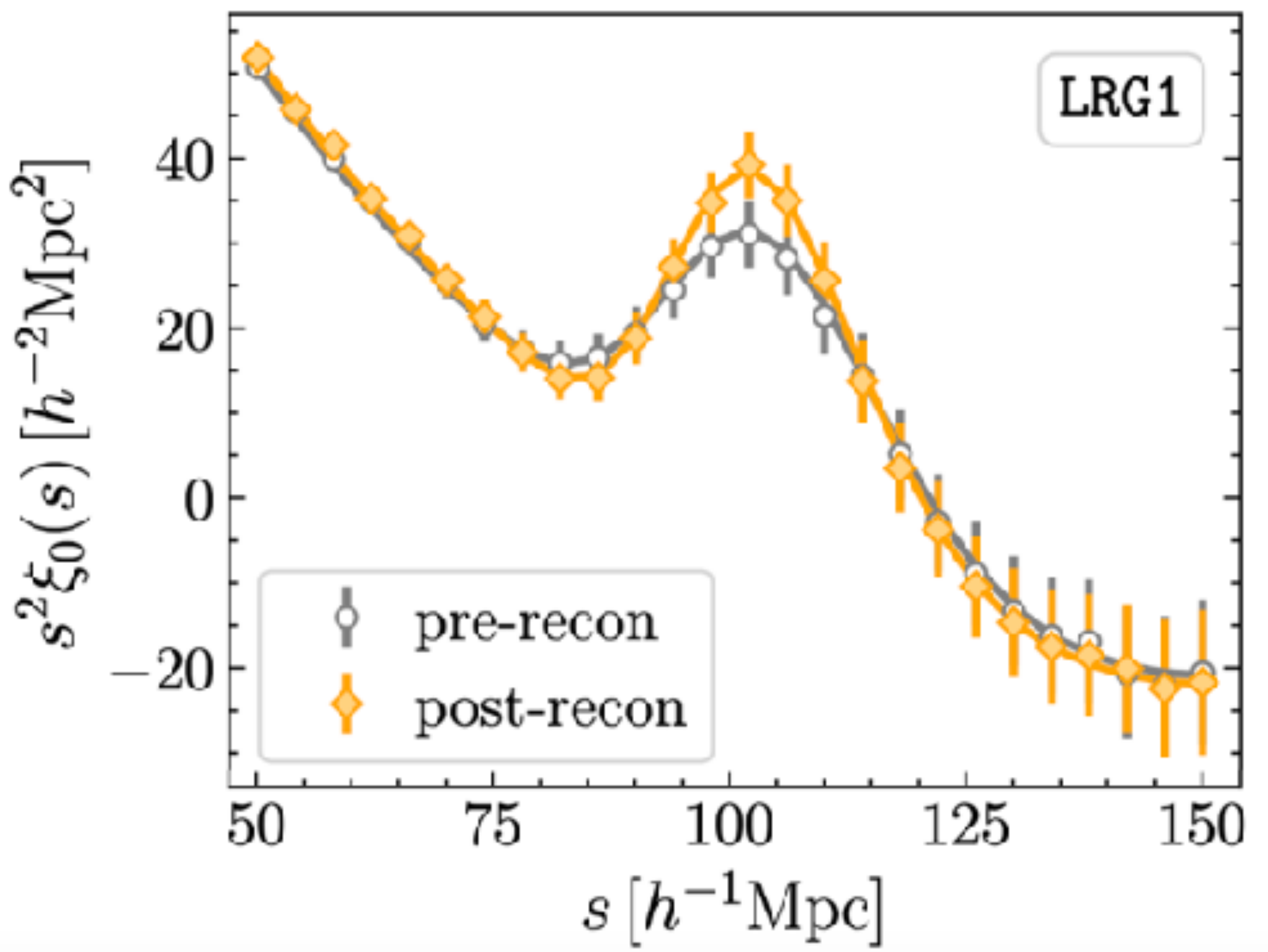
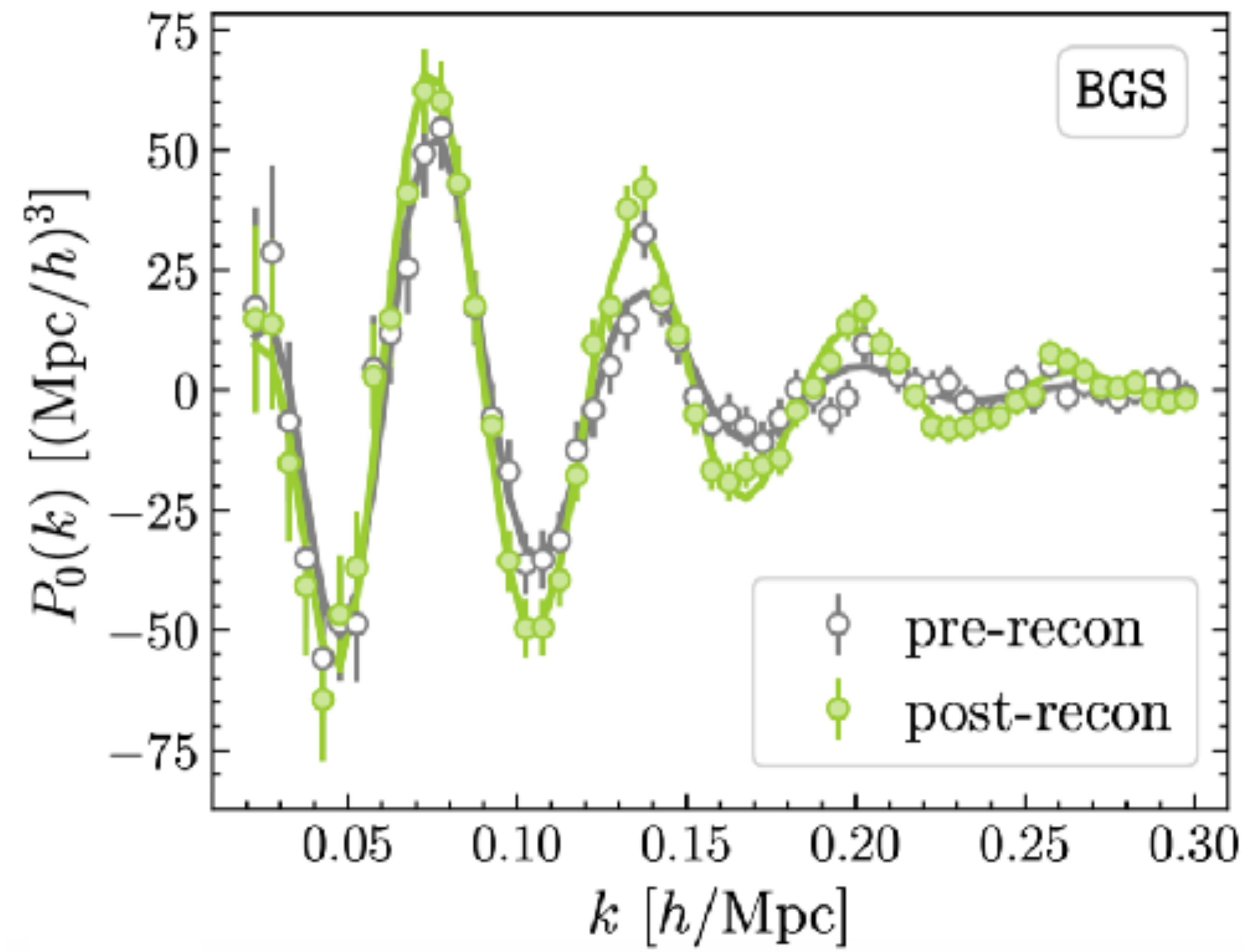
Baryon Acoustic Oscillations (BAO)



A peak in the correlation function …

Baryon Acoustic Oscillations (BAO)

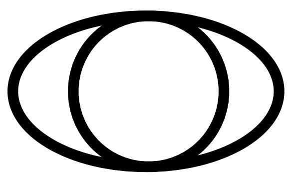




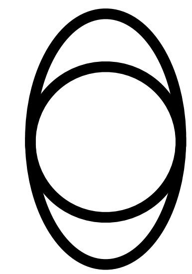
A peak in the correlation function … or wiggles in the power spectrum

BAO measurements

"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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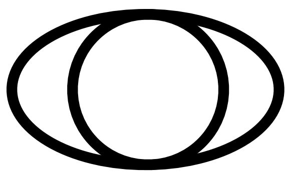
BAO measurements

"Scaling parameters":



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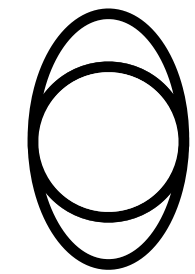
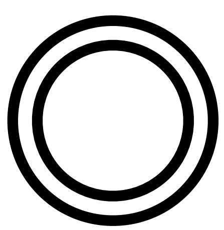


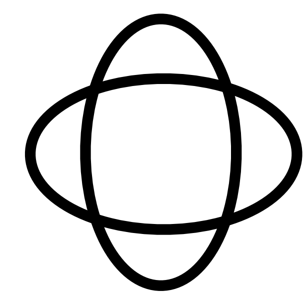
perpendicular std ruler size

line-of-sight std ruler size

OR



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

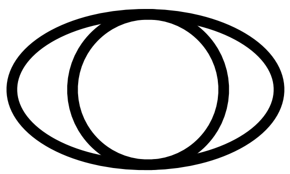


overall scale of std ruler

anisotropy of std ruler

BAO measurements

"Scaling parameters":



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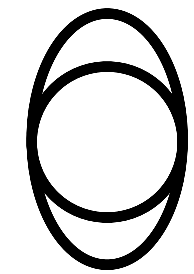
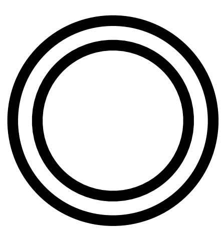


perpendicular std ruler size

line-of-sight std ruler size

OR



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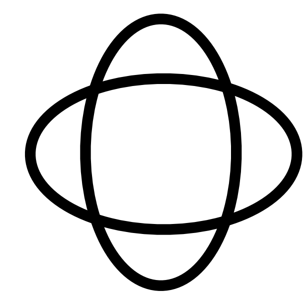

overall scale of std ruler

anisotropy of std ruler

OR

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

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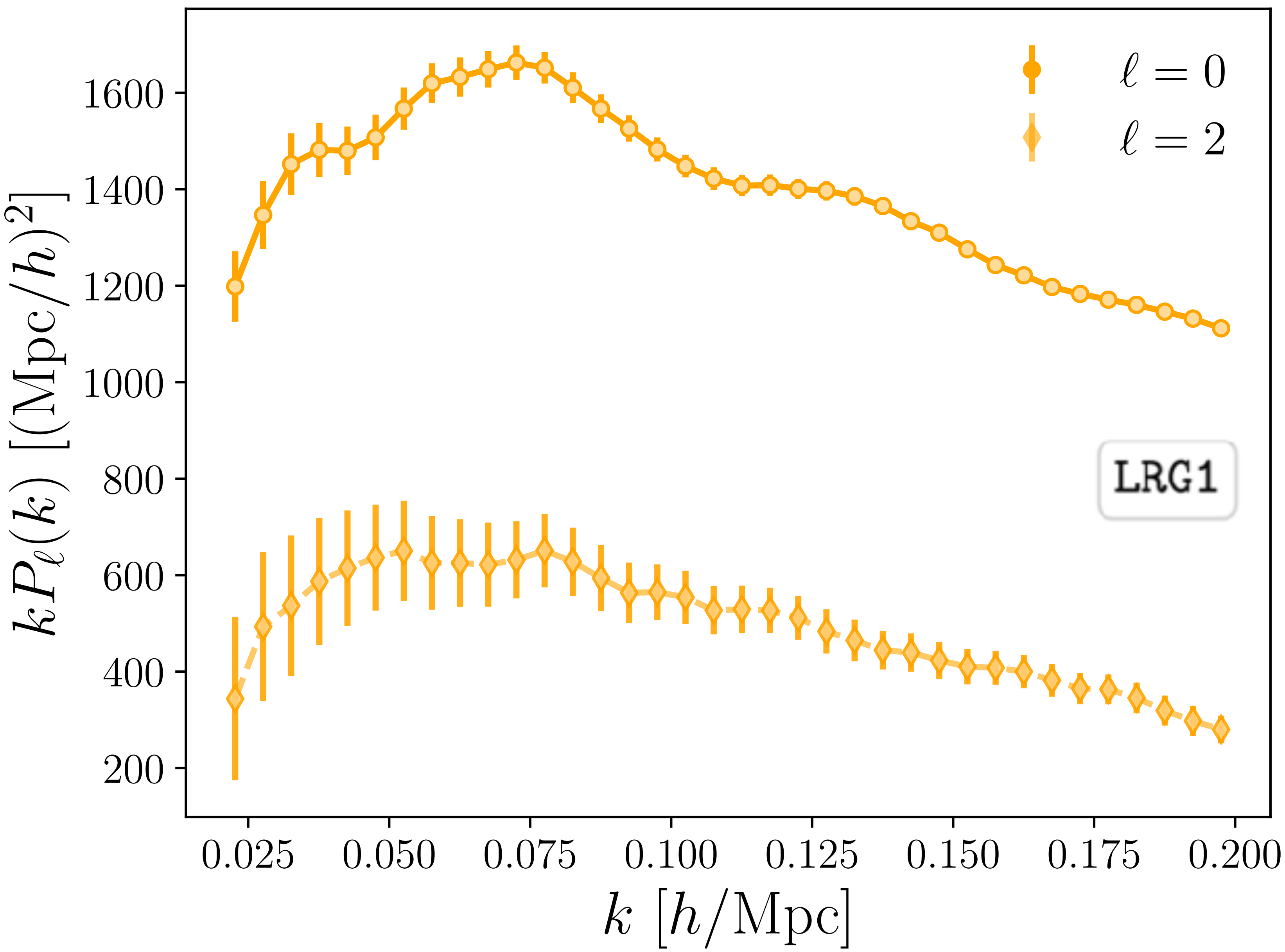
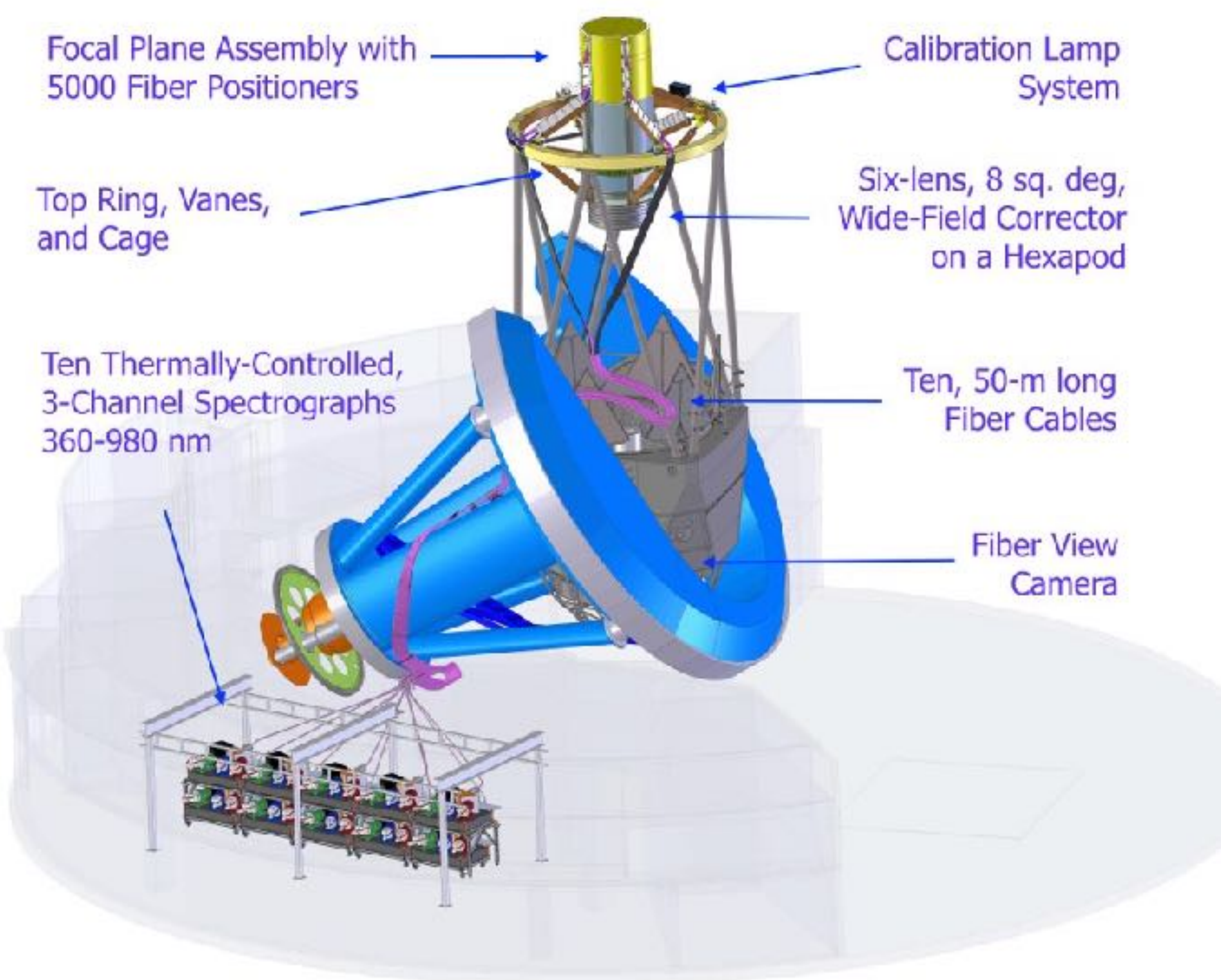
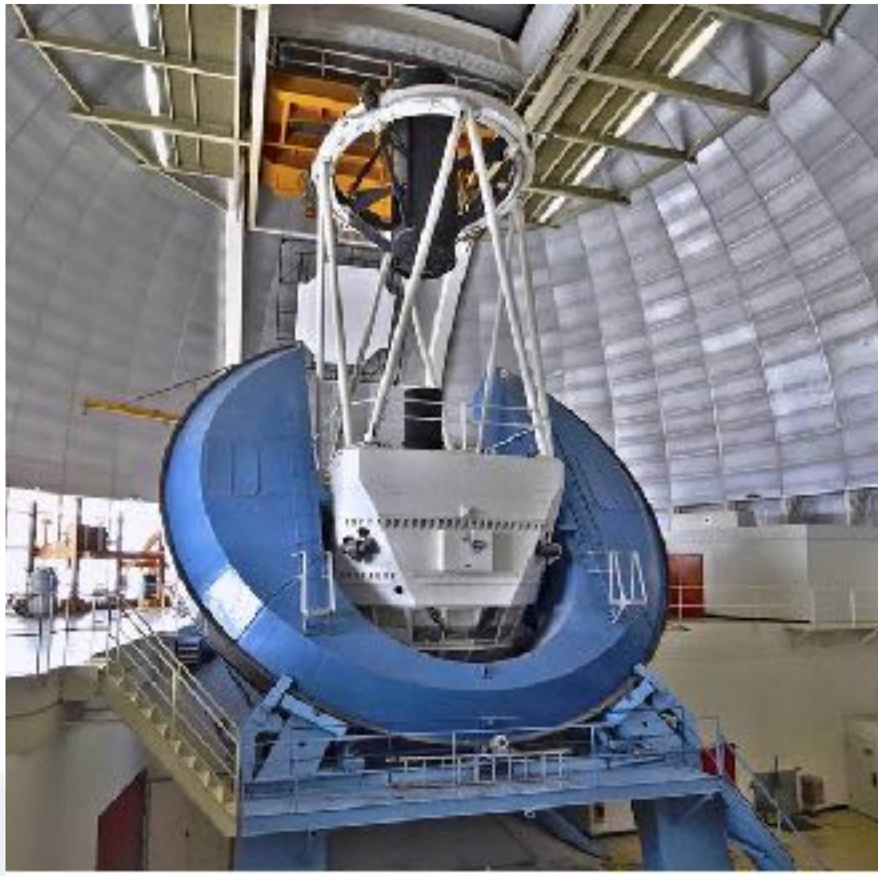
Full shape power spectrum



$$P_{s,g}(\boldsymbol{k}) = P^{PT}_{s,g}(\boldsymbol{k}) + (b + f\mu^2)(b\alpha_0 + f\alpha_2\mu^2 + f\alpha_4\mu^4)k^2 P_{\mathrm{s},b_1^2}(\boldsymbol{k}) + (\mathrm{SN}_0 + \mathrm{SN}_2 k^2\mu^2 + \mathrm{SN}_4 k^4\mu^4),$$

DESI: the instrument





in situ at KPNO

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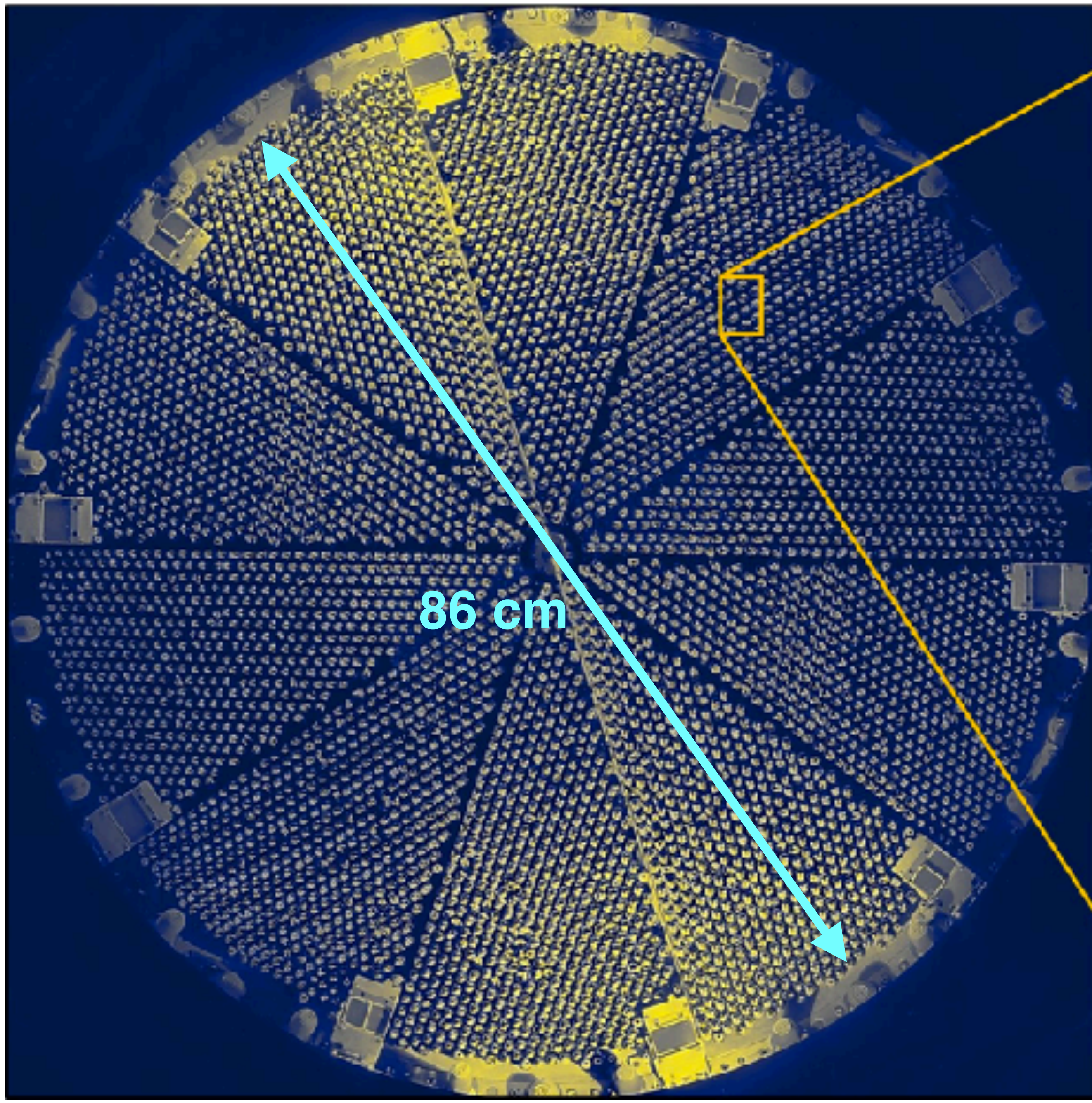

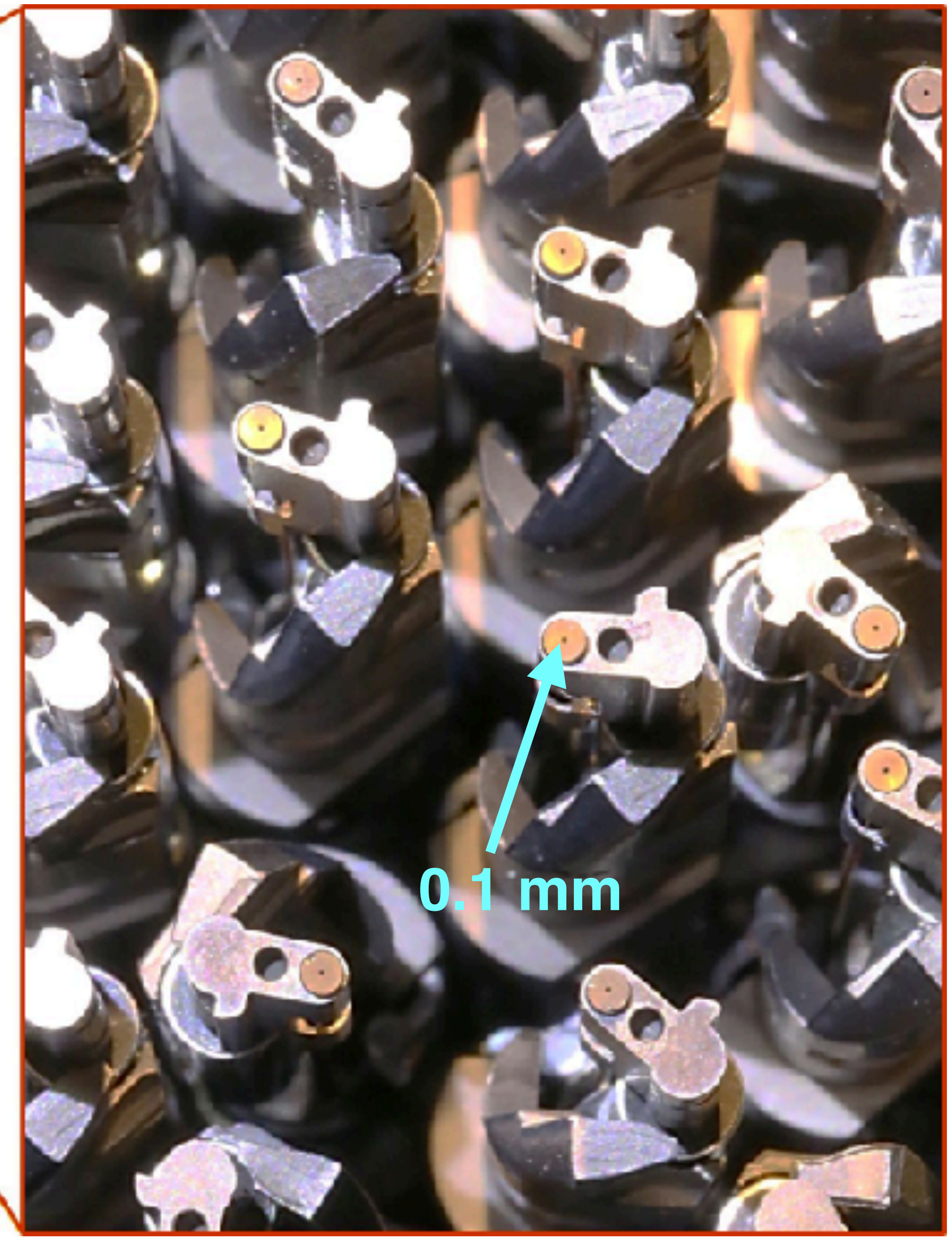

All 5000 fibres can be positioned to accuracy of <5 μm RMS in <120s

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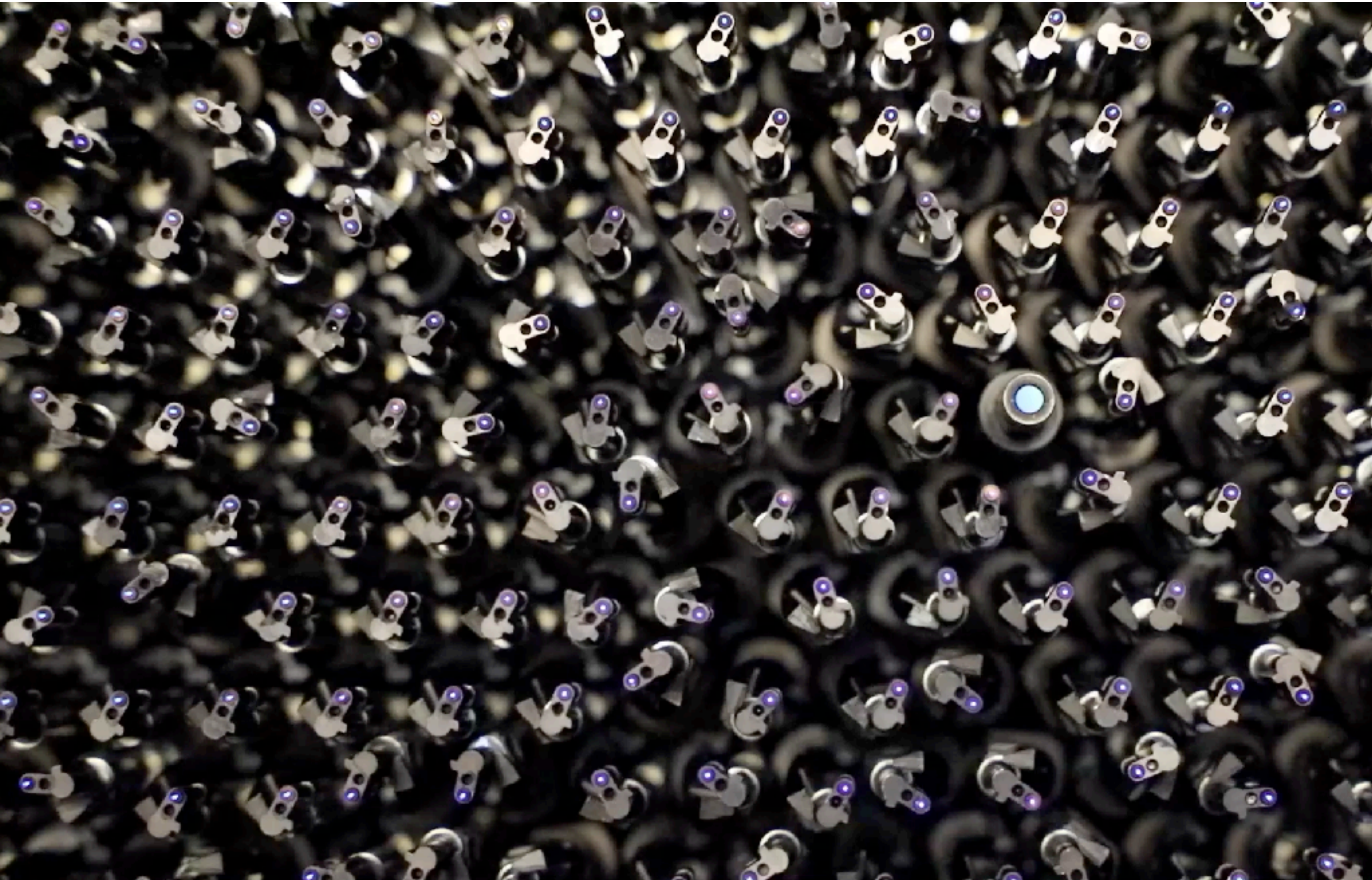
DESI: the instrument



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DESI: the survey

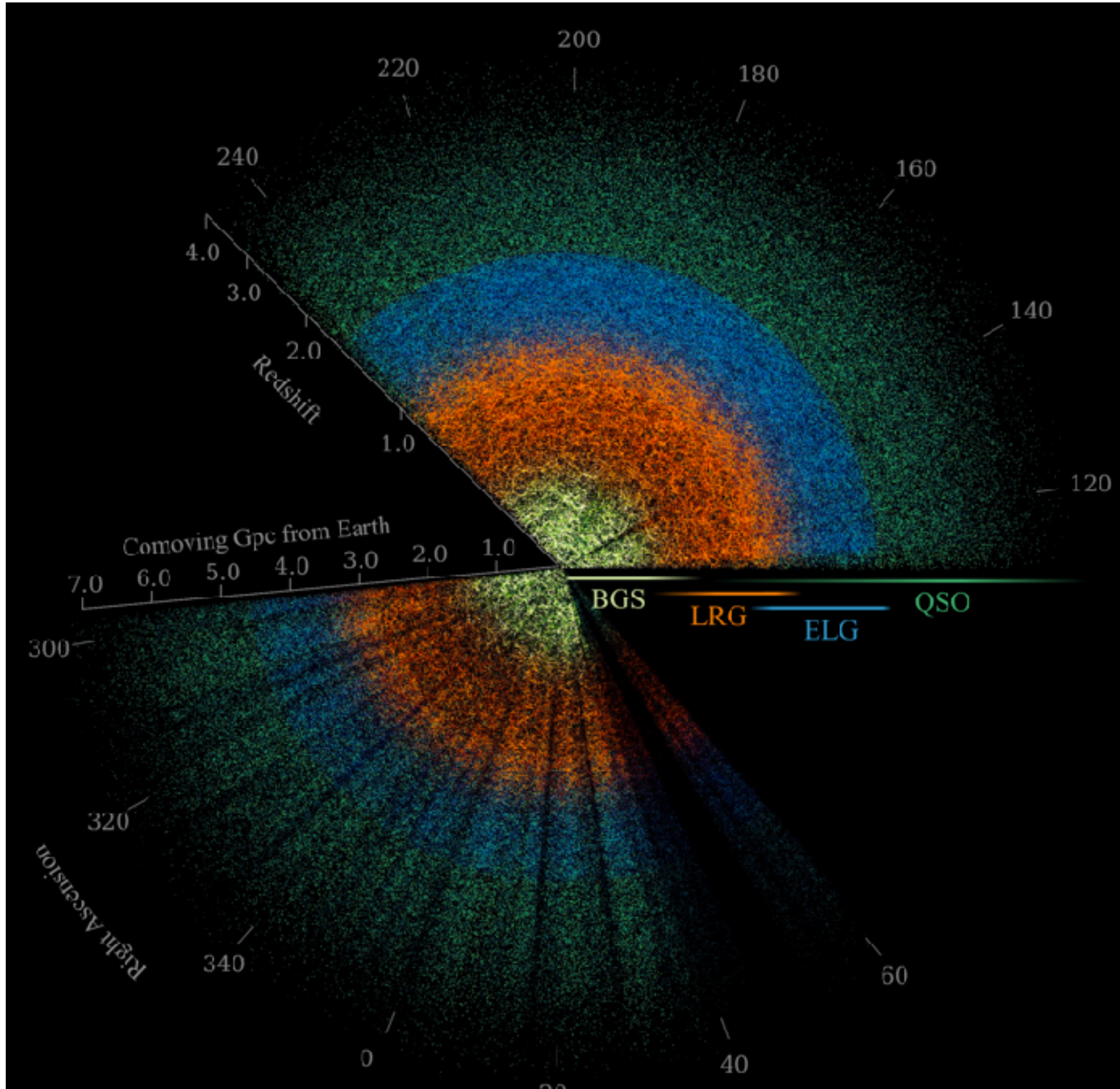
~~30~~ ~~40~~ **50+ million** extragalactic redshifts in ~~5~~ **8** years

Bright Galaxies (BGS)
$0 < z < 0.4$

Luminous Red Galaxies (LRG)
$0.4 < z < 1.1$

Emission Line Galaxies (ELG)
$0.8 < z < 1.6$

Quasars (QSO)
tracers: $0.9 < z < 2.1$
Lya: $z > 2.1$



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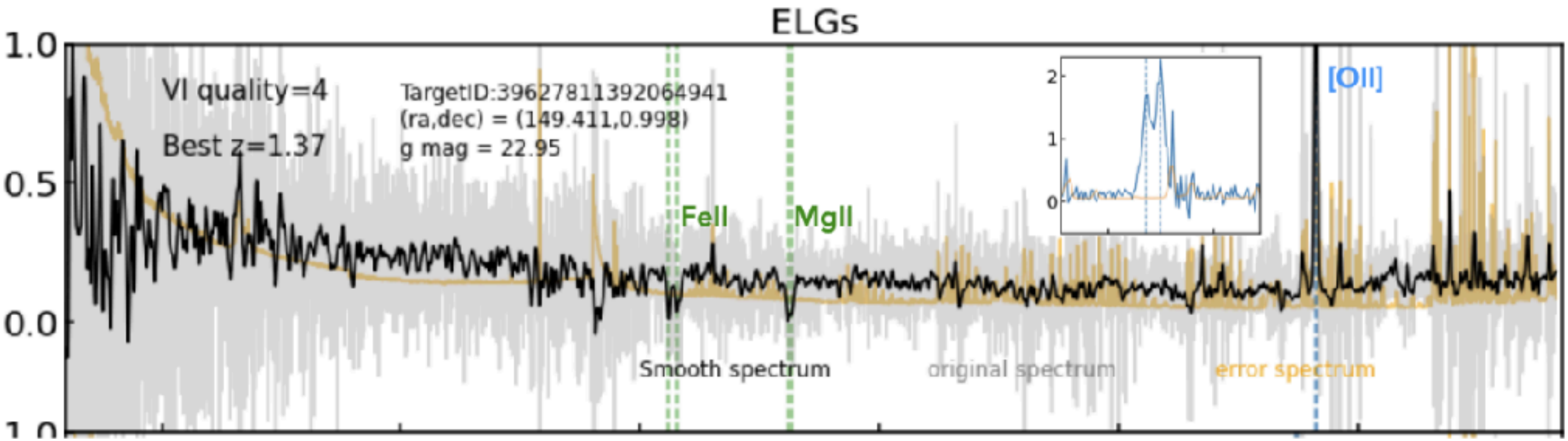
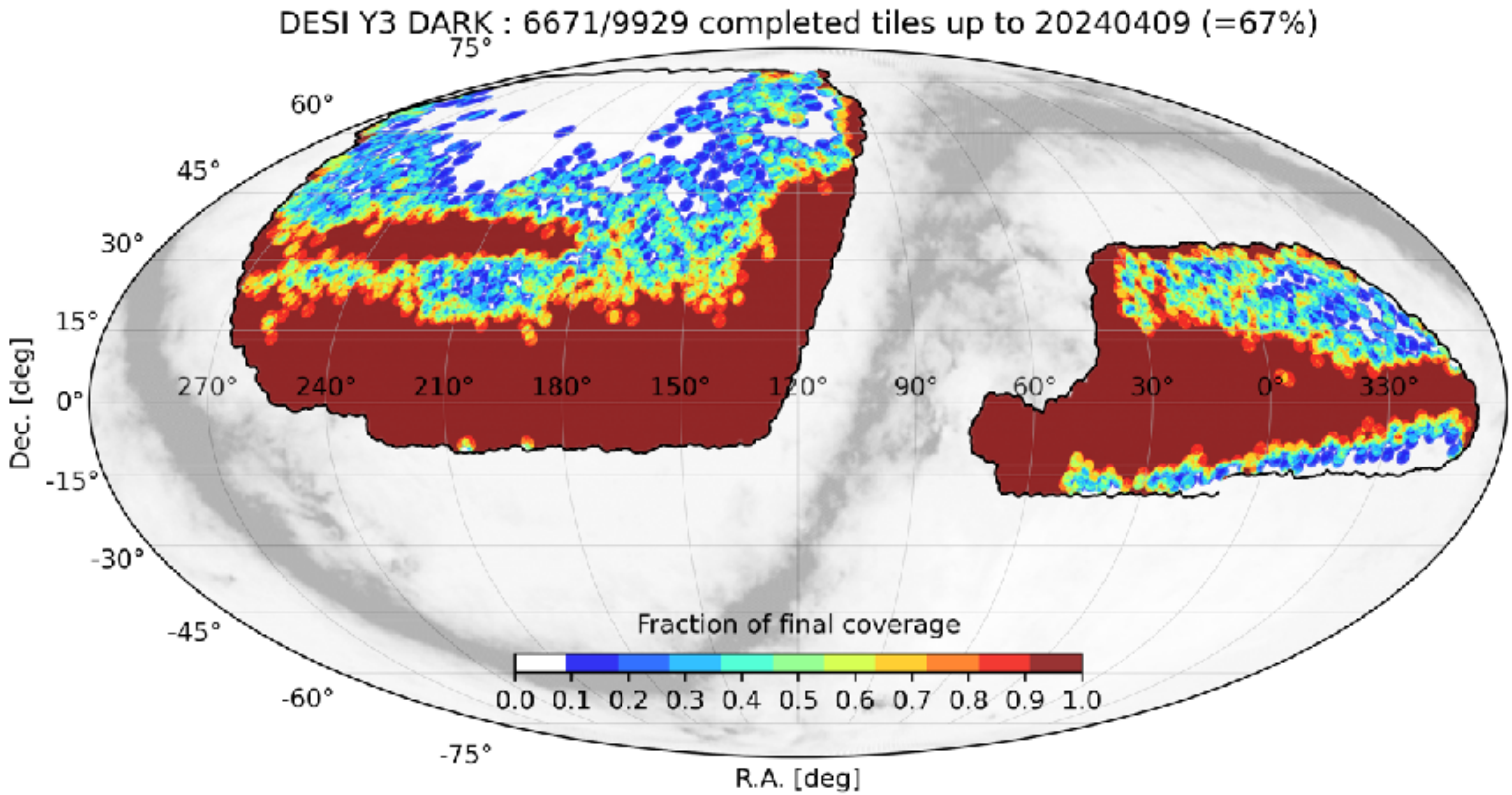
DESI: spectra



Visual Inspection analyses:
Lan et al (2023)
Alexander et al (2023)

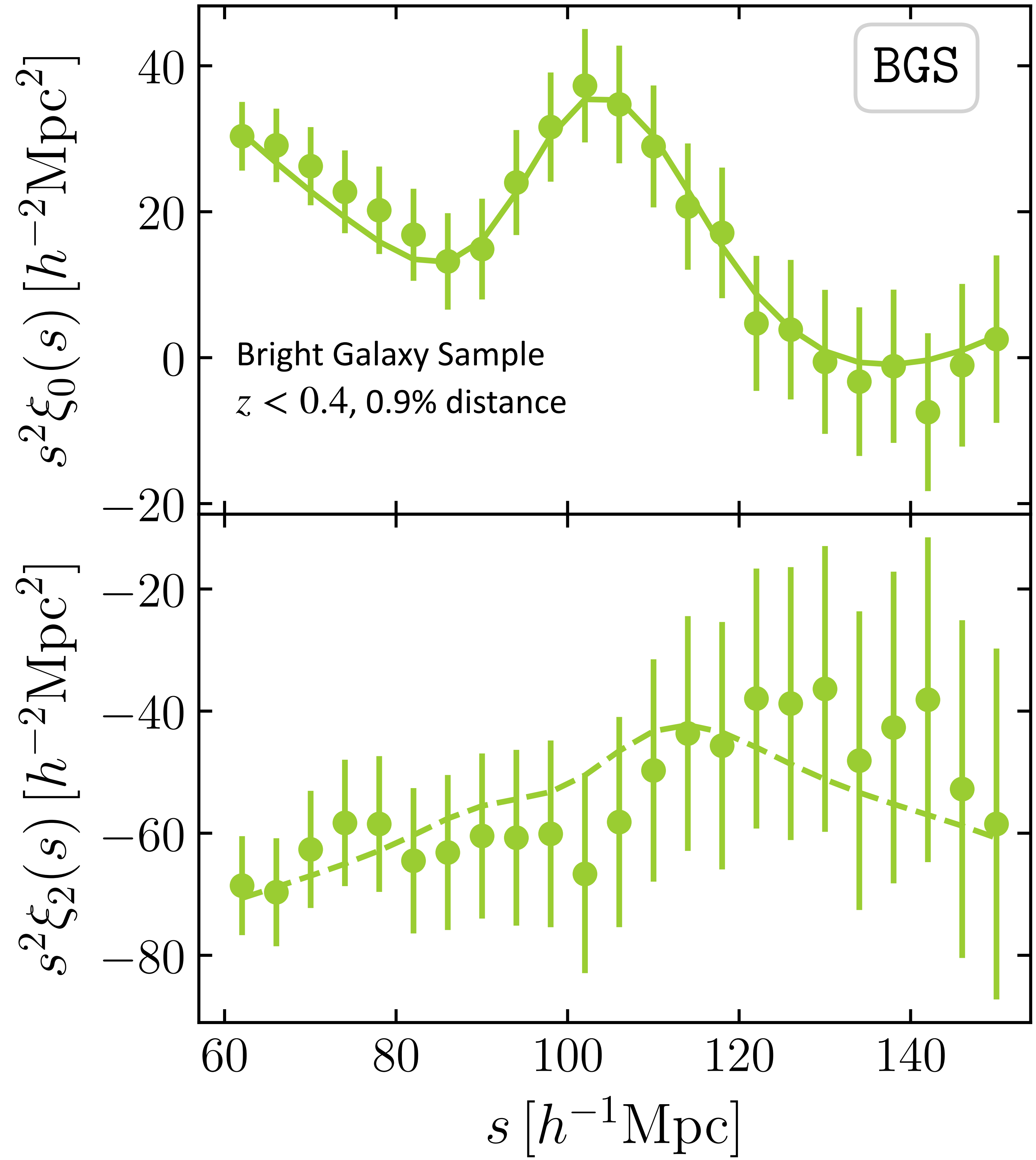
DR2 – 3 years of data

DR2 BAO results: March 2025

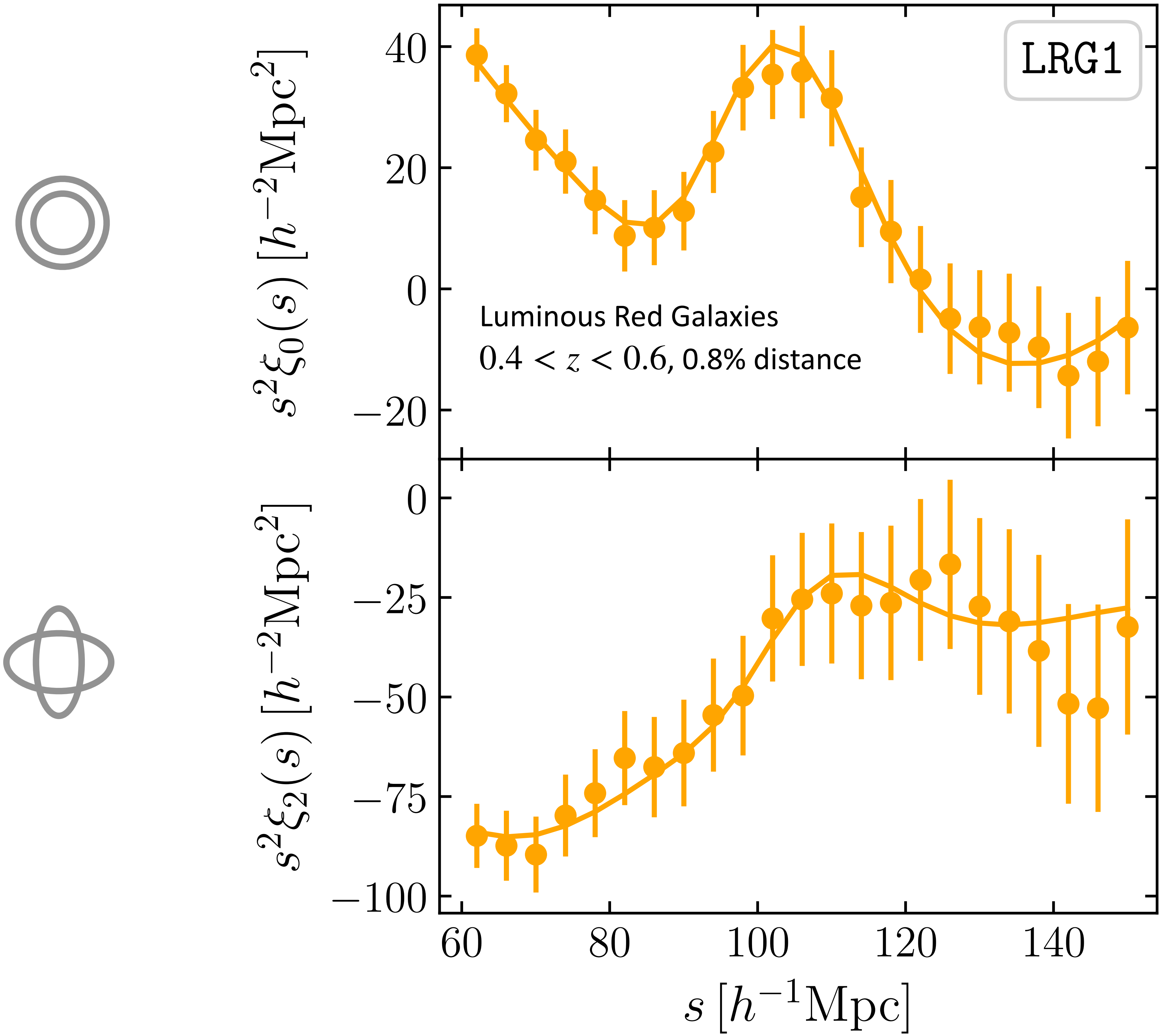


>30 million galaxies and quasars, ~14 million of which are used for cosmology

BAO measurements in DR2



BAO measurements in DR2



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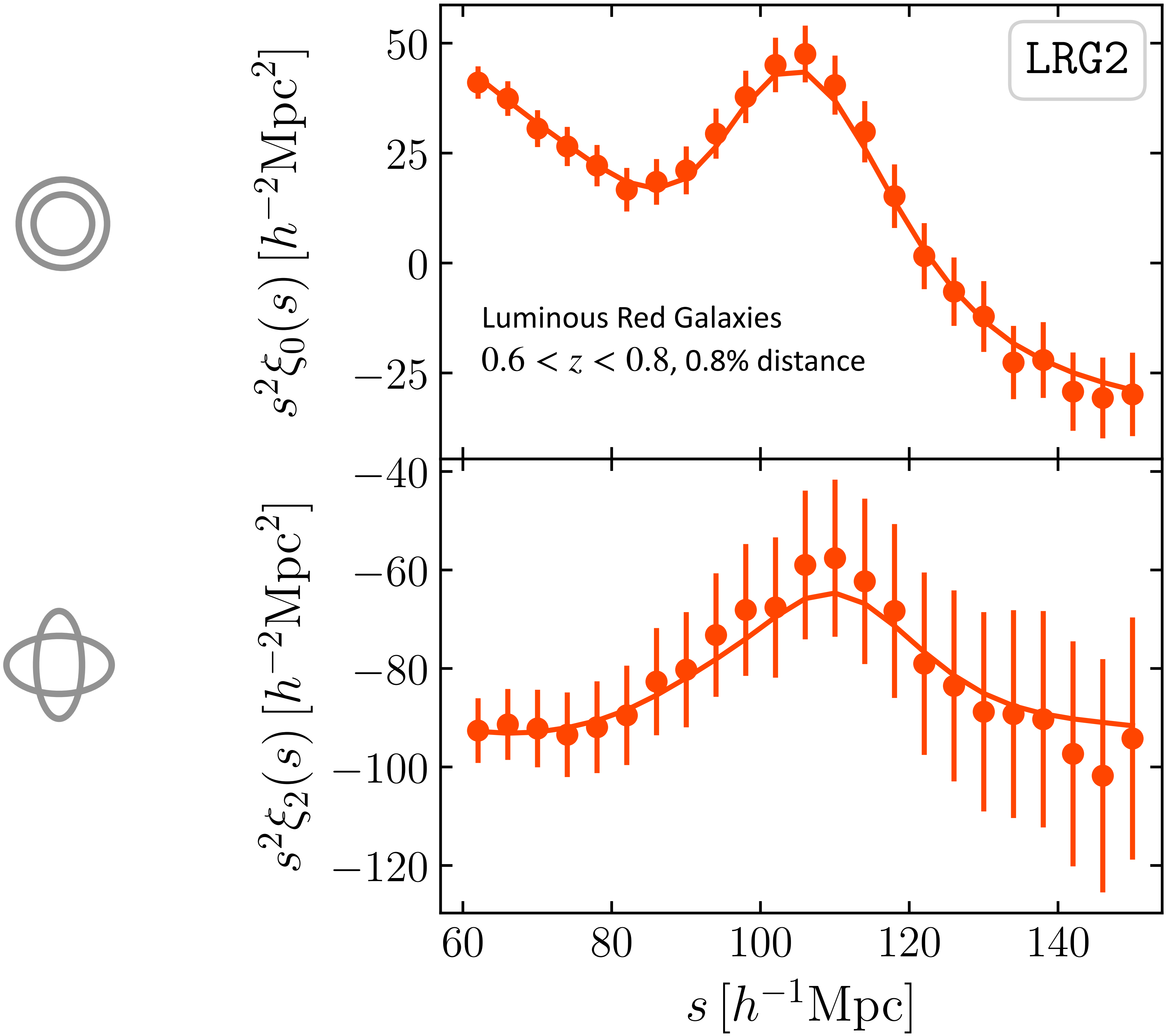
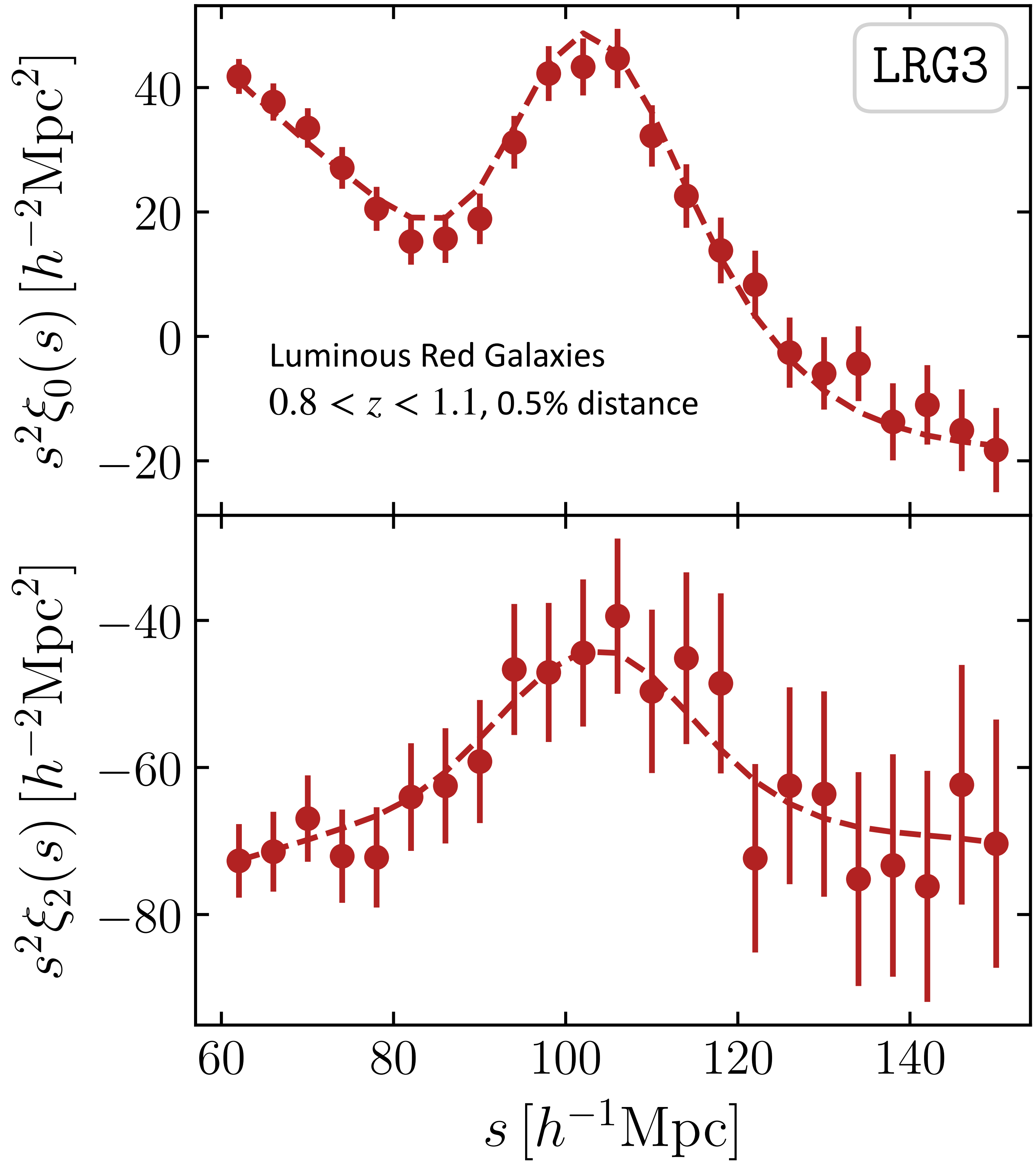


BAO measurements in DR2



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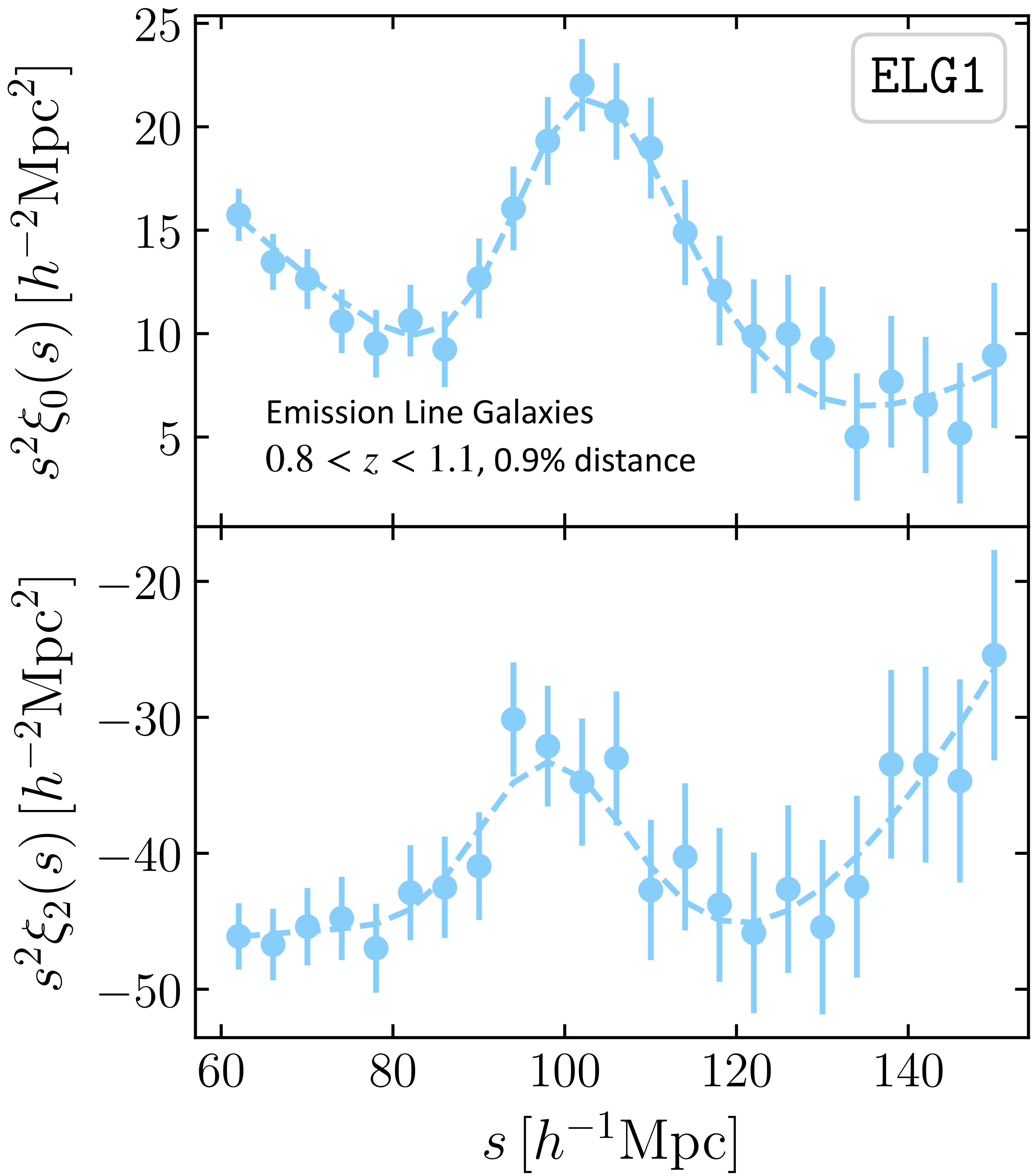

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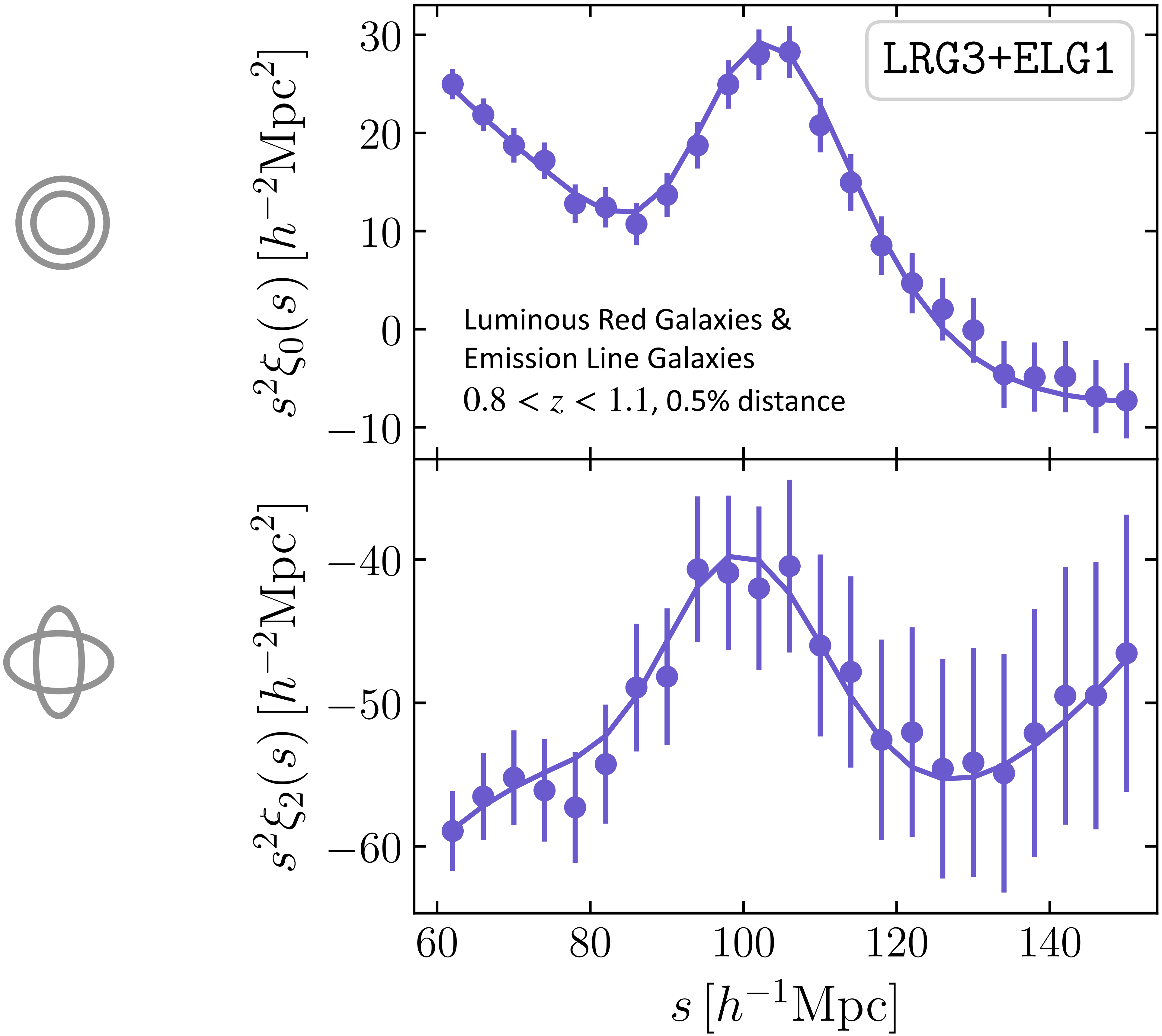

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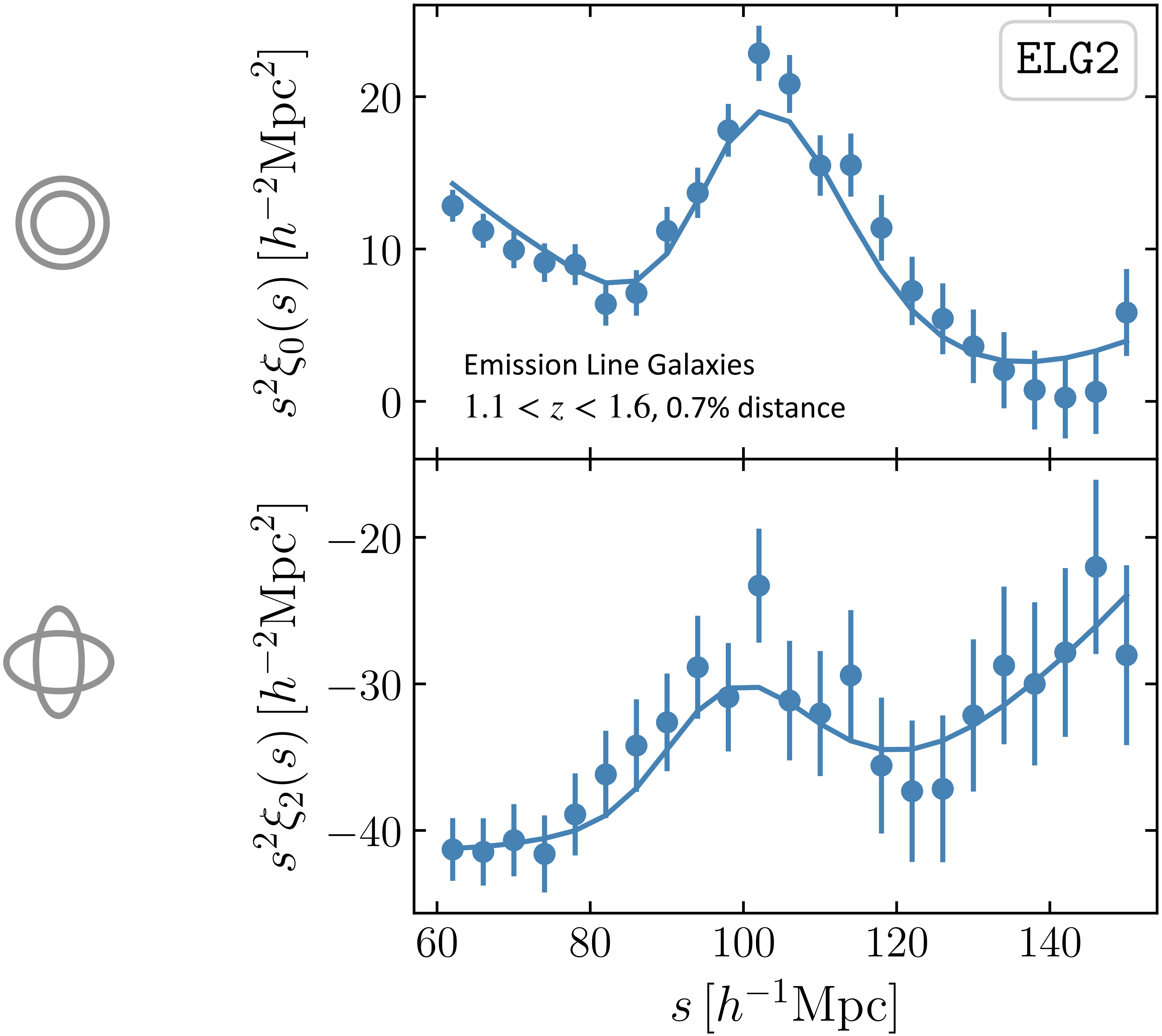

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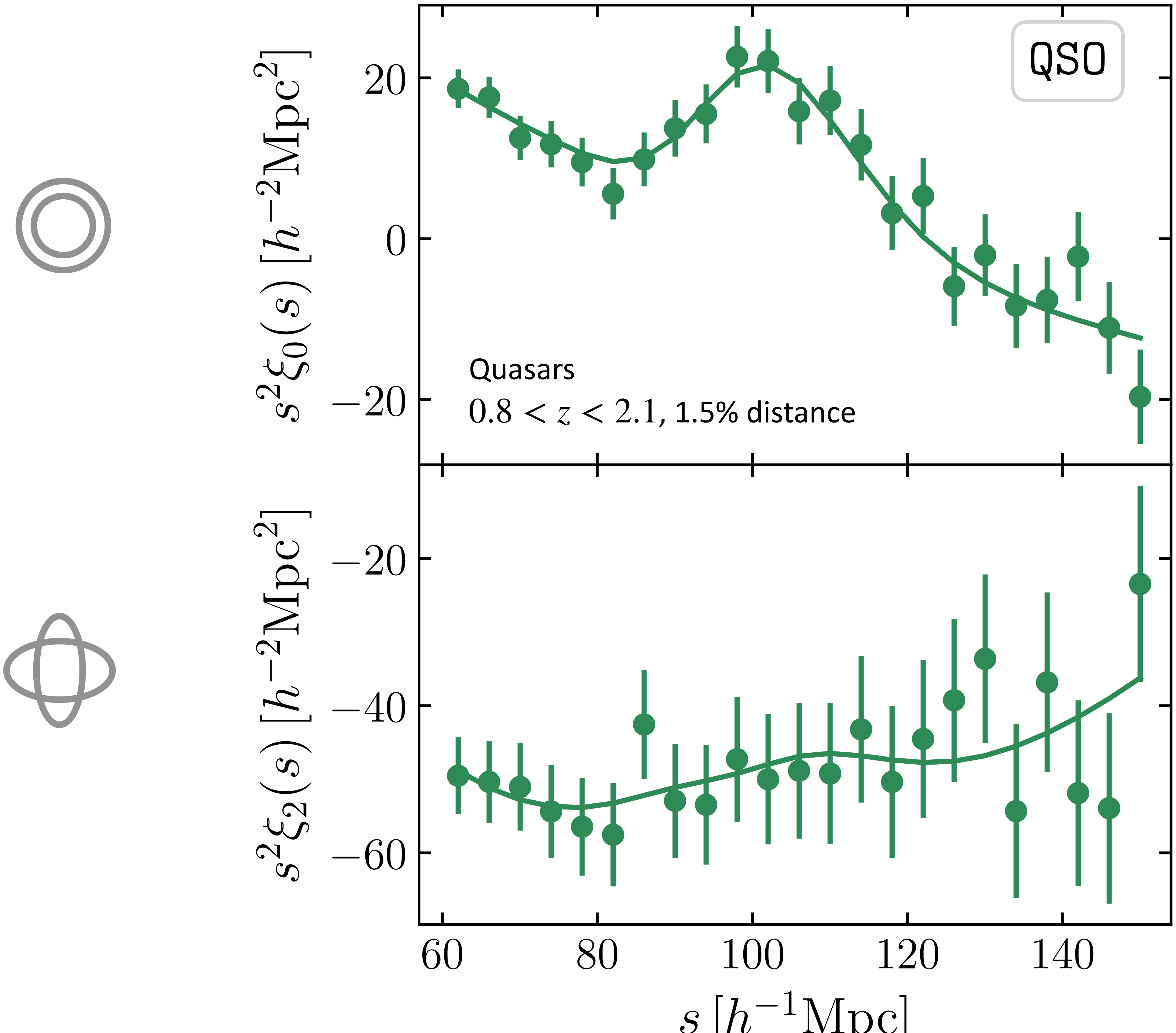

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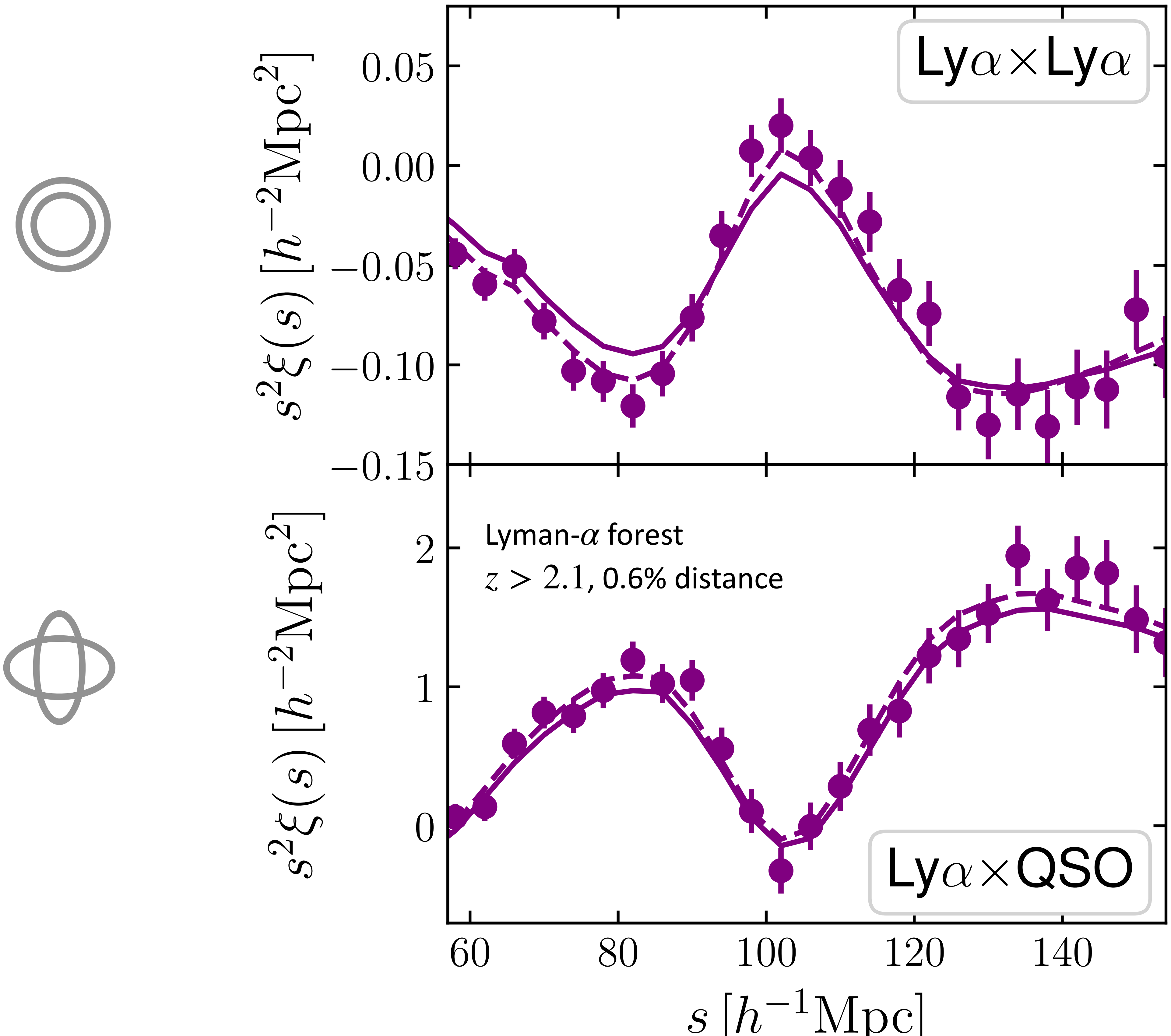
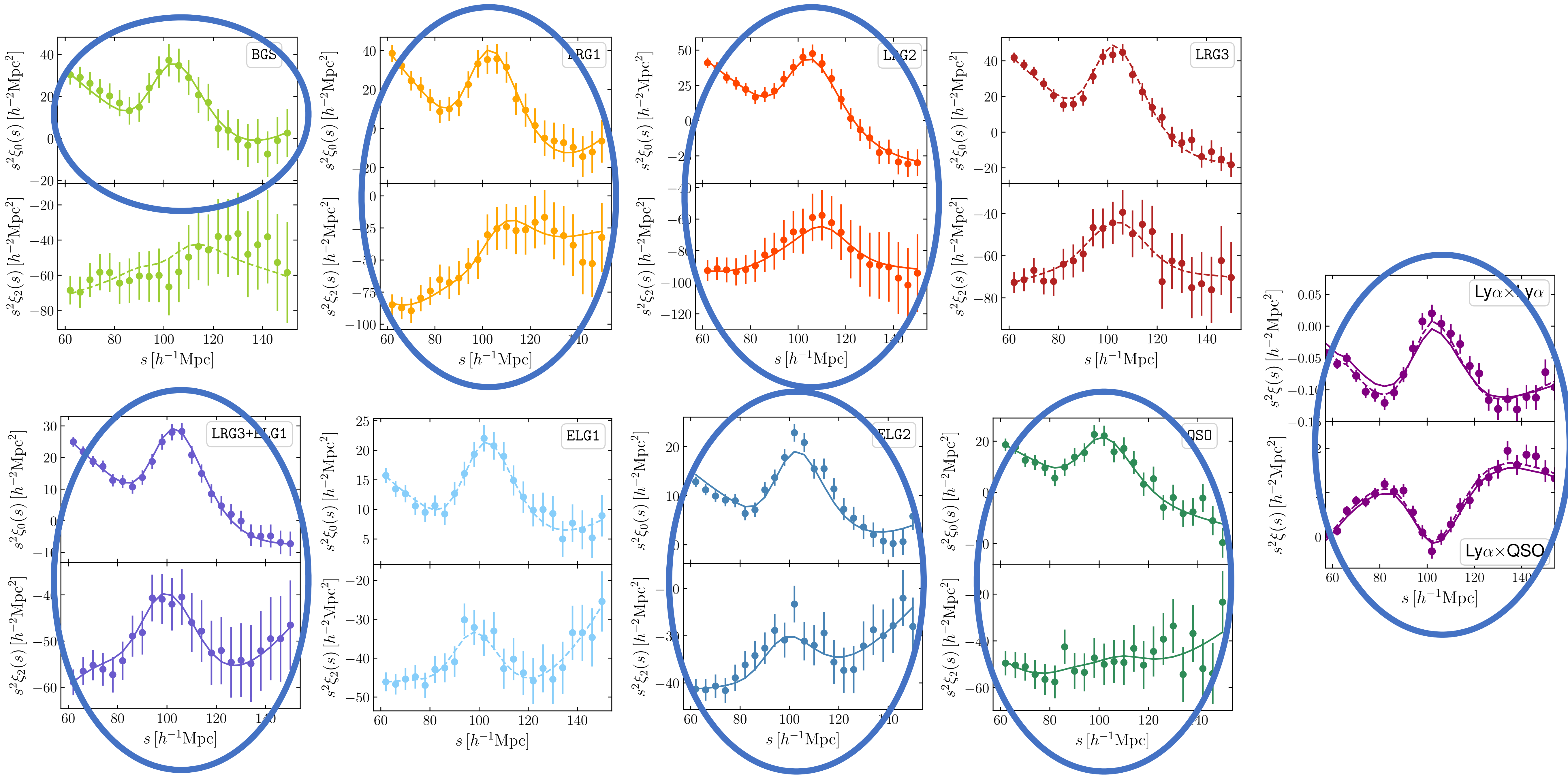
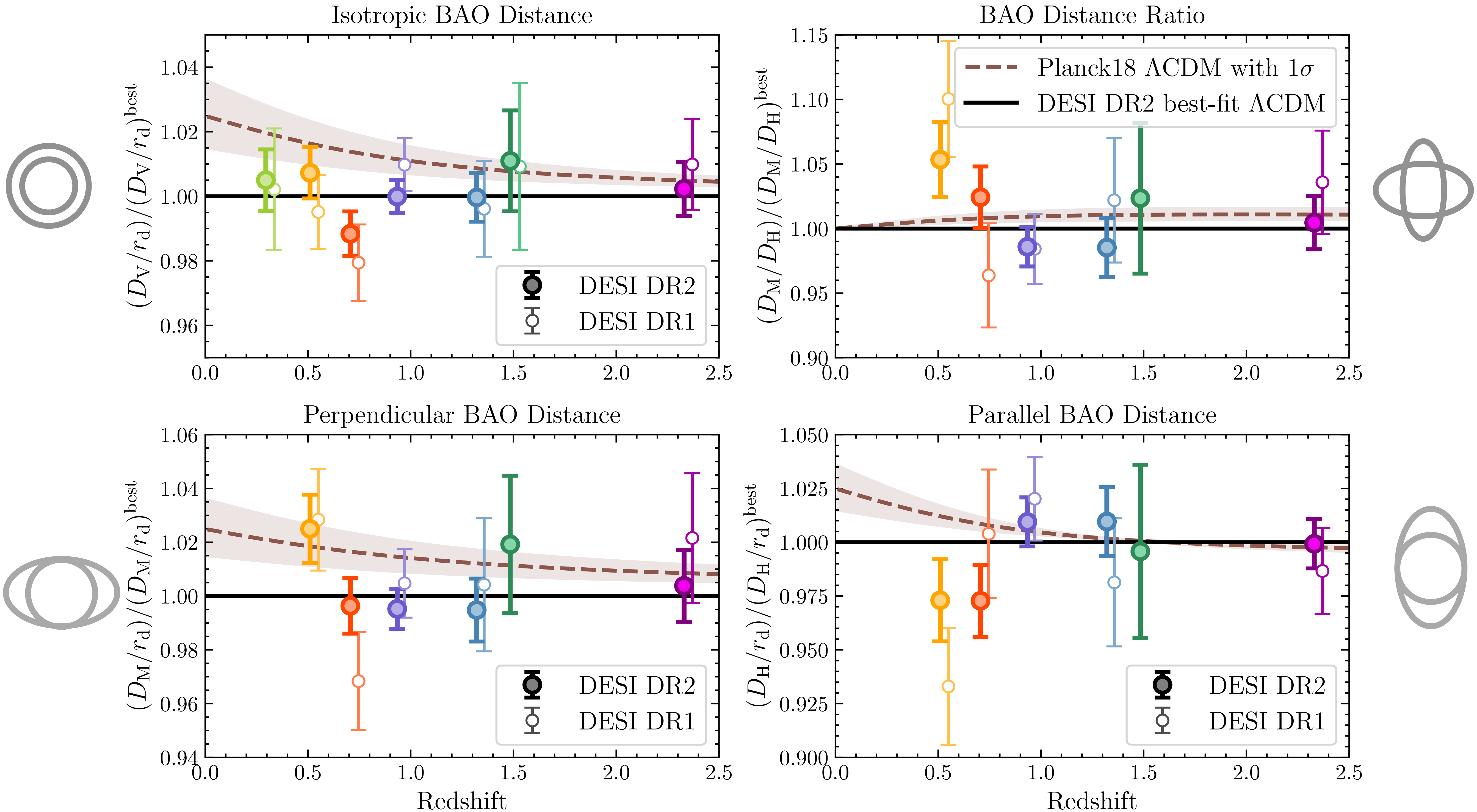


BAO measurements in DR2



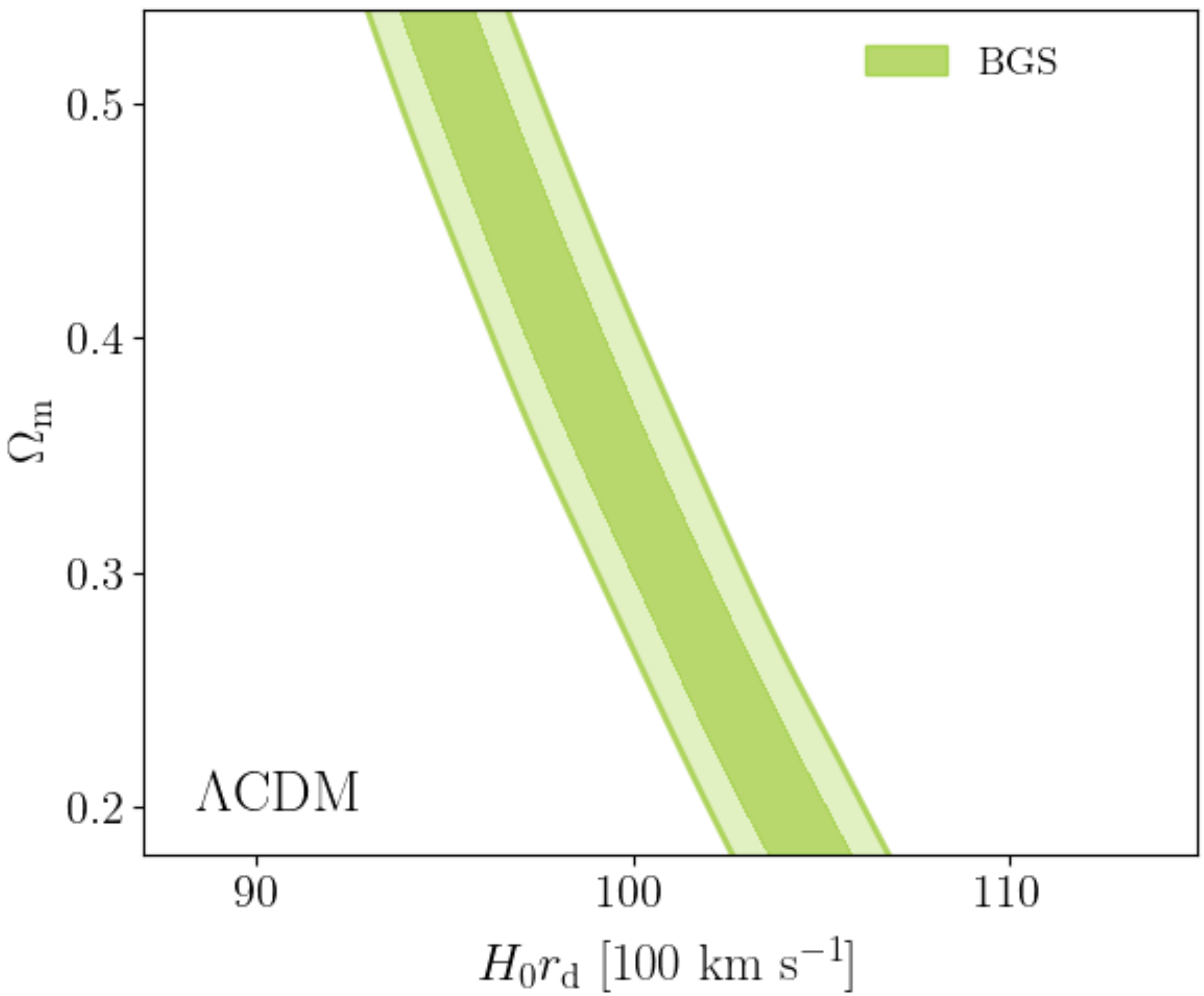
= used for cosmology inference

Distances from BAO



Flat ΛCDM

Flat ΛCDM model



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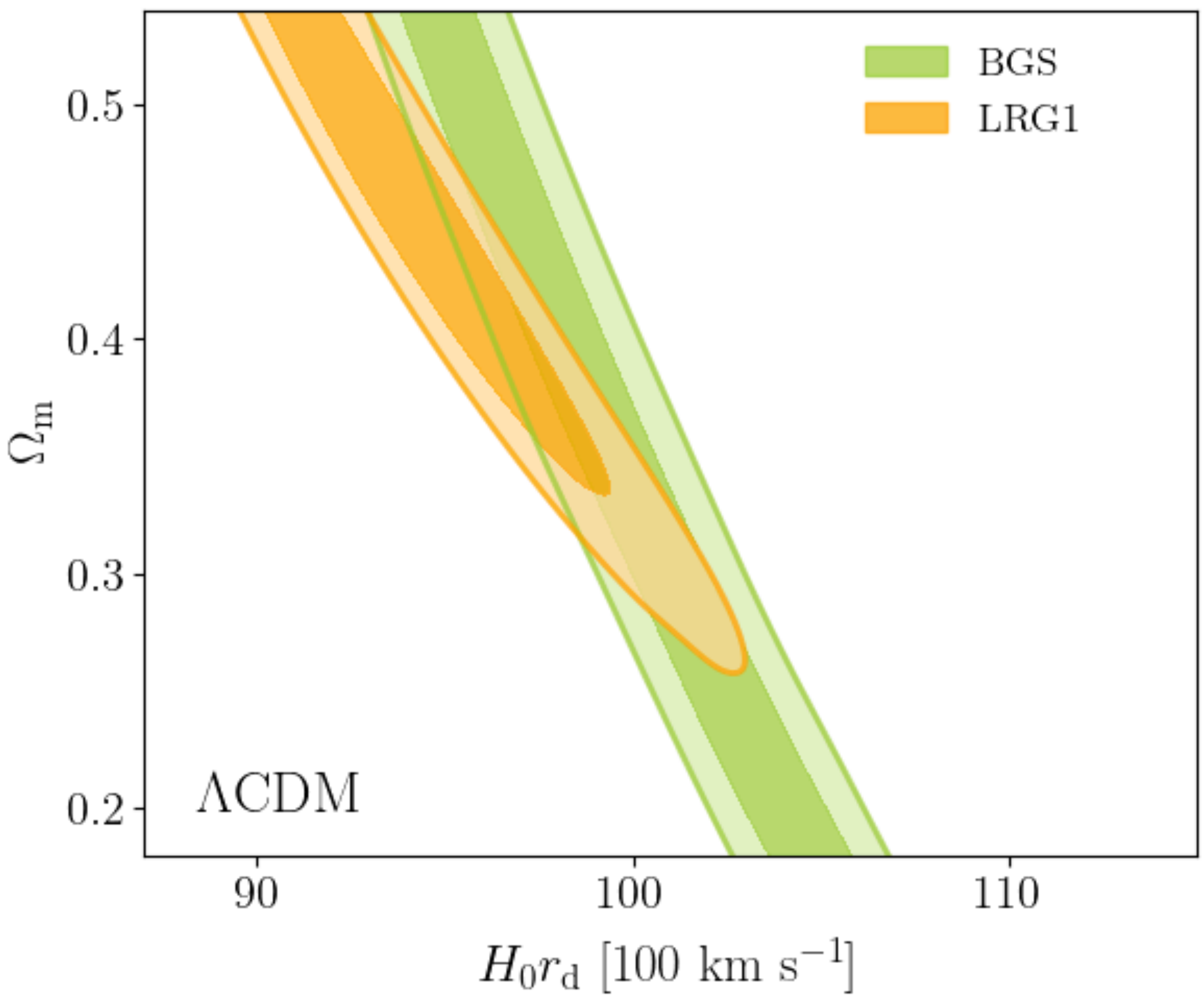

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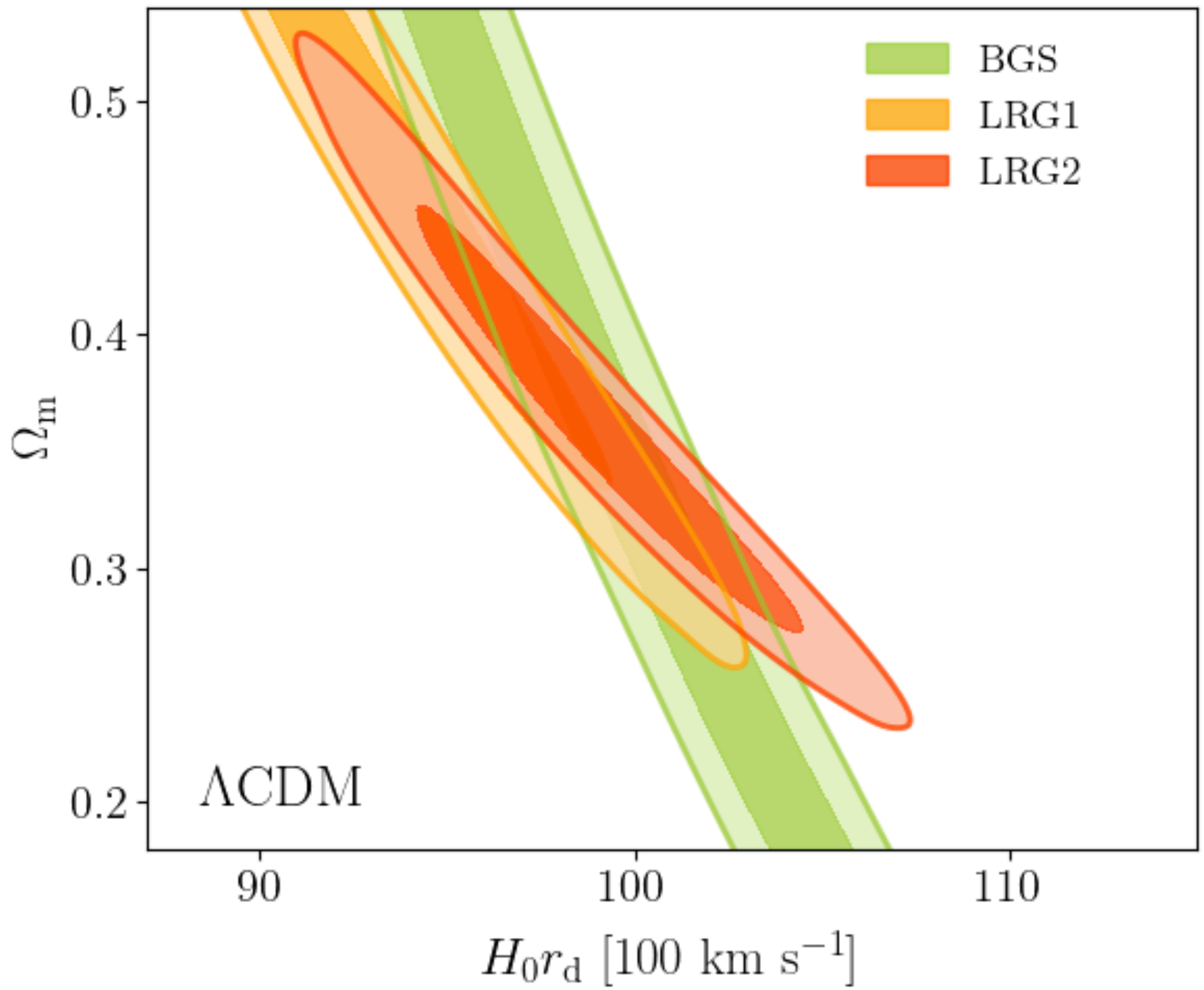
Flat ΛCDM model



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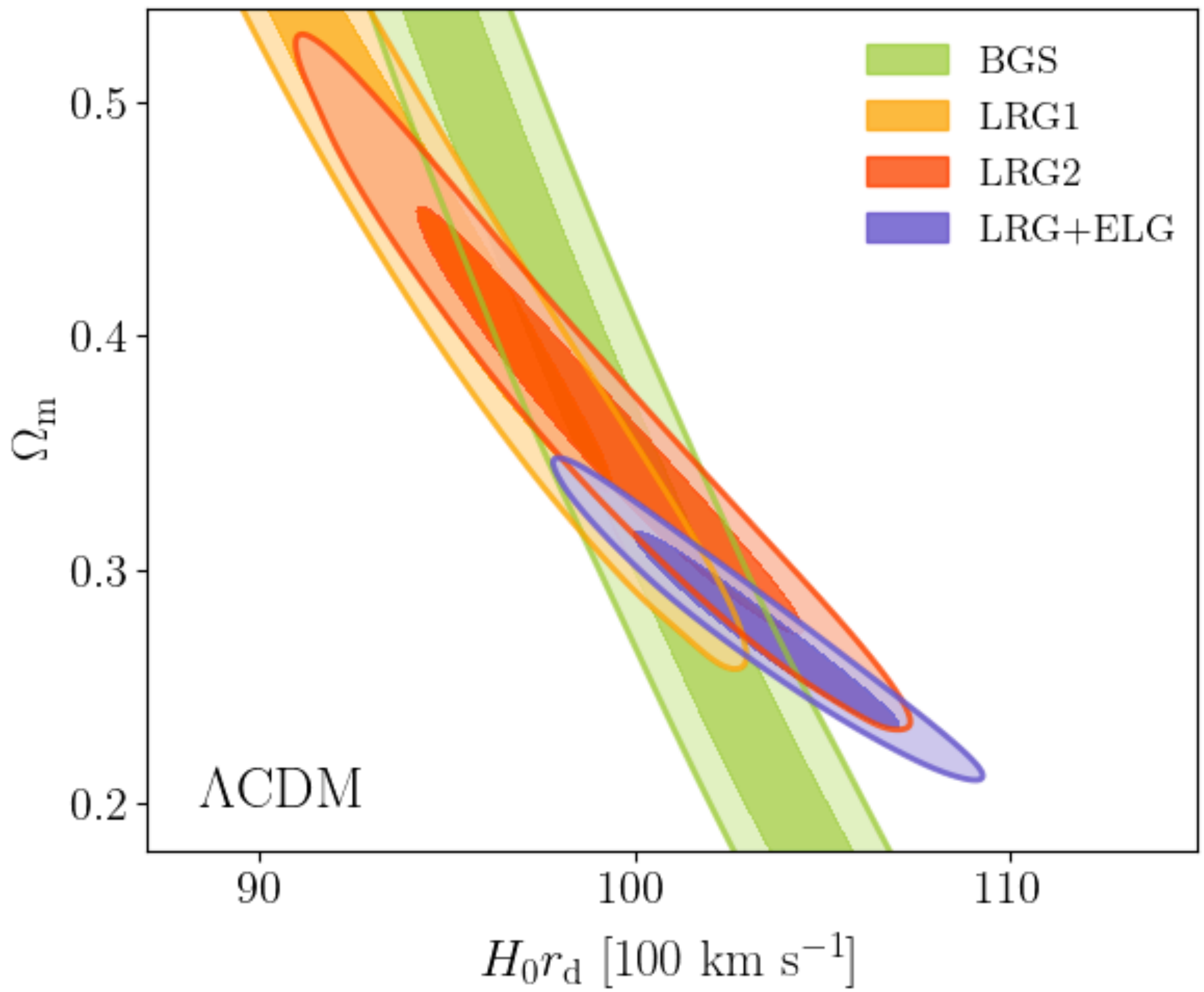

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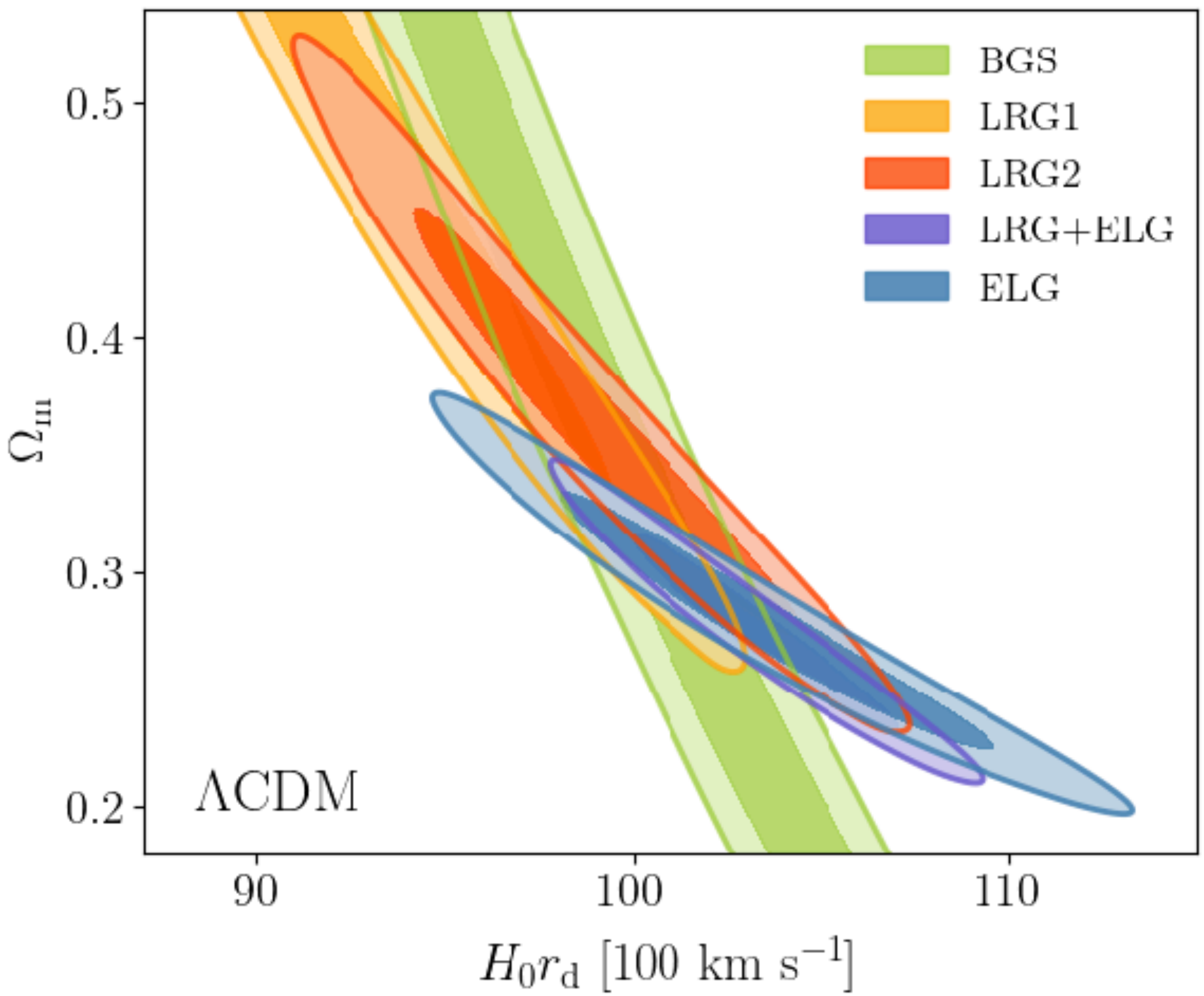
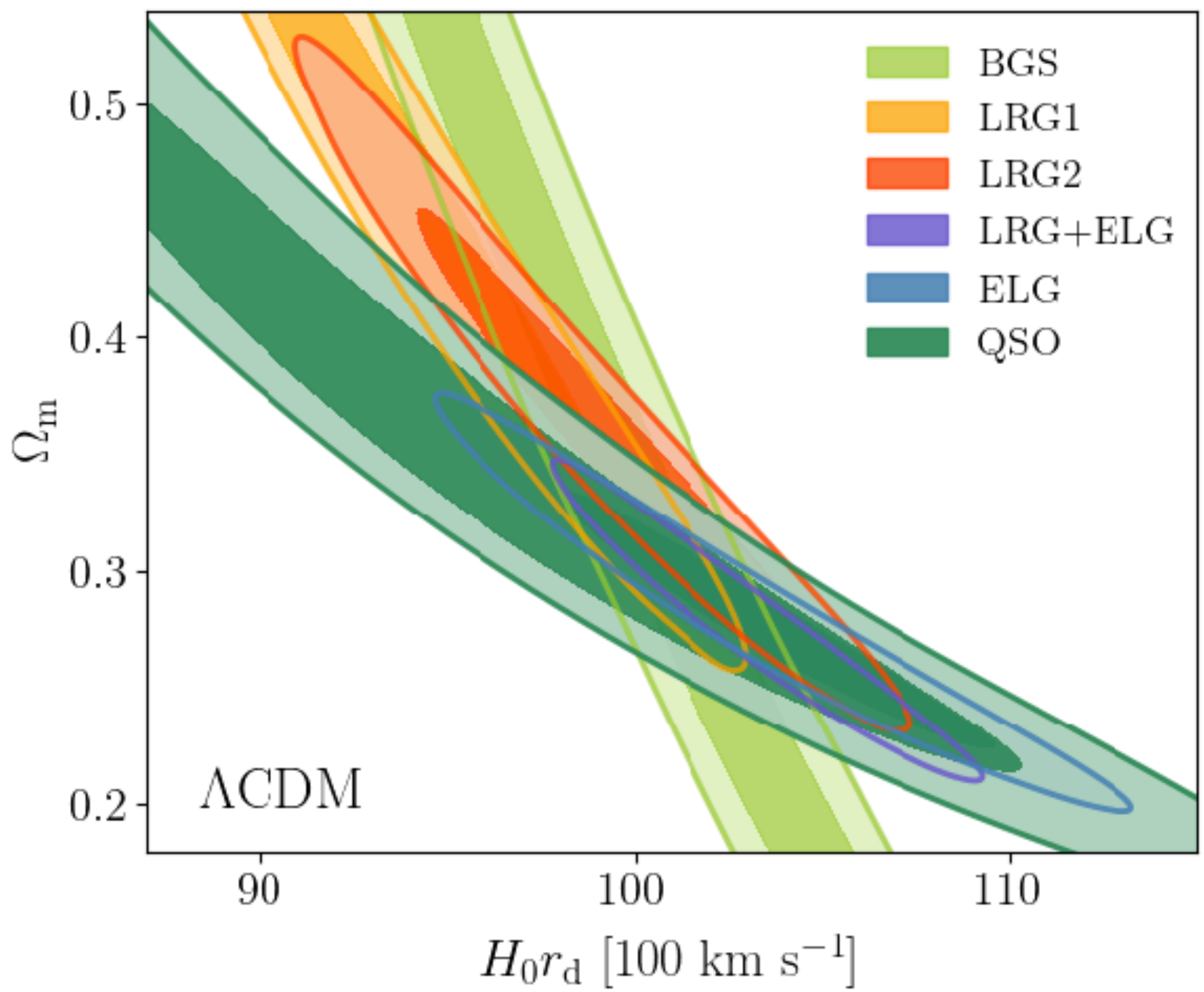
Flat ΛCDM model



Flat ΛCDM model



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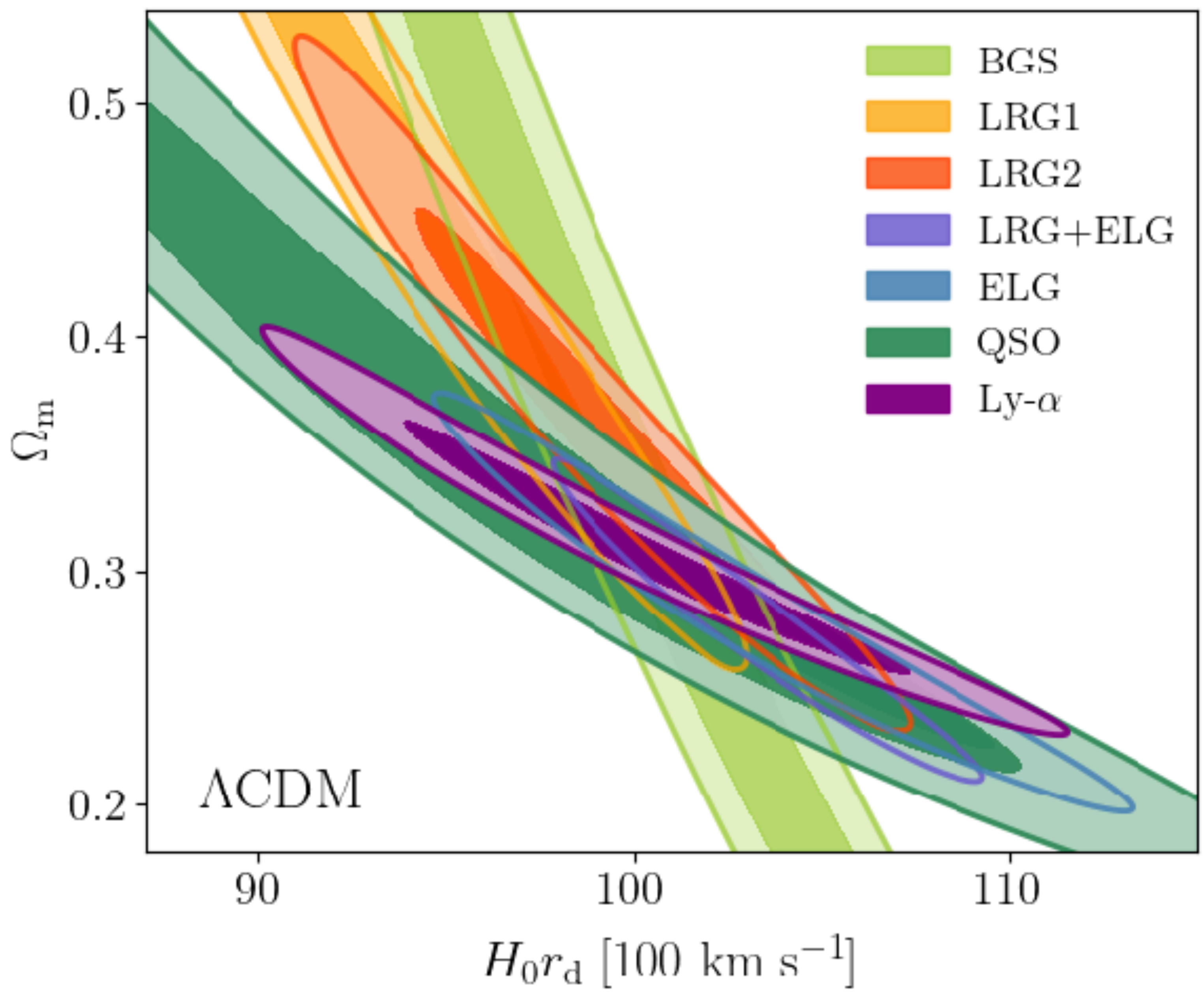
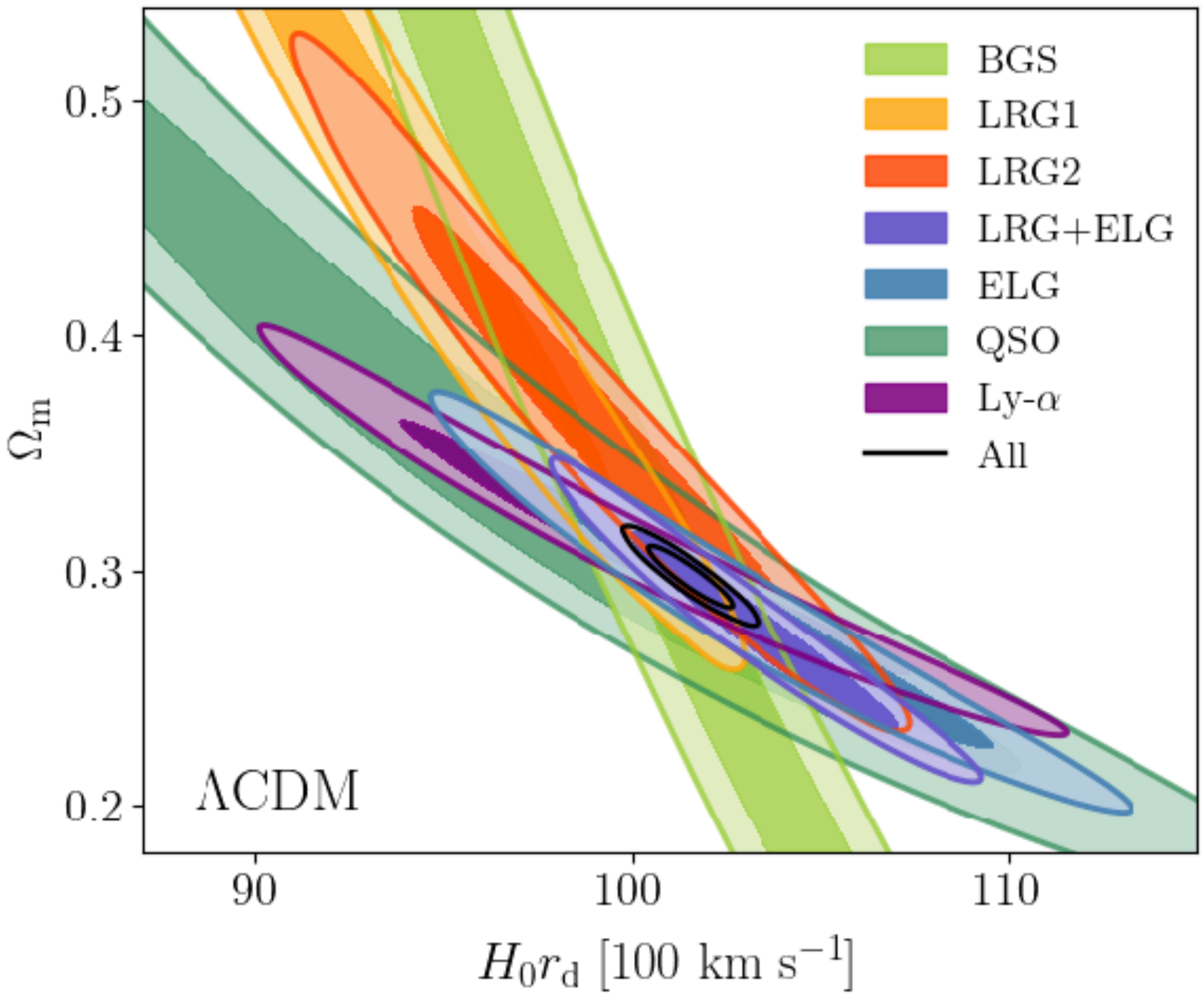


Flat ΛCDM model



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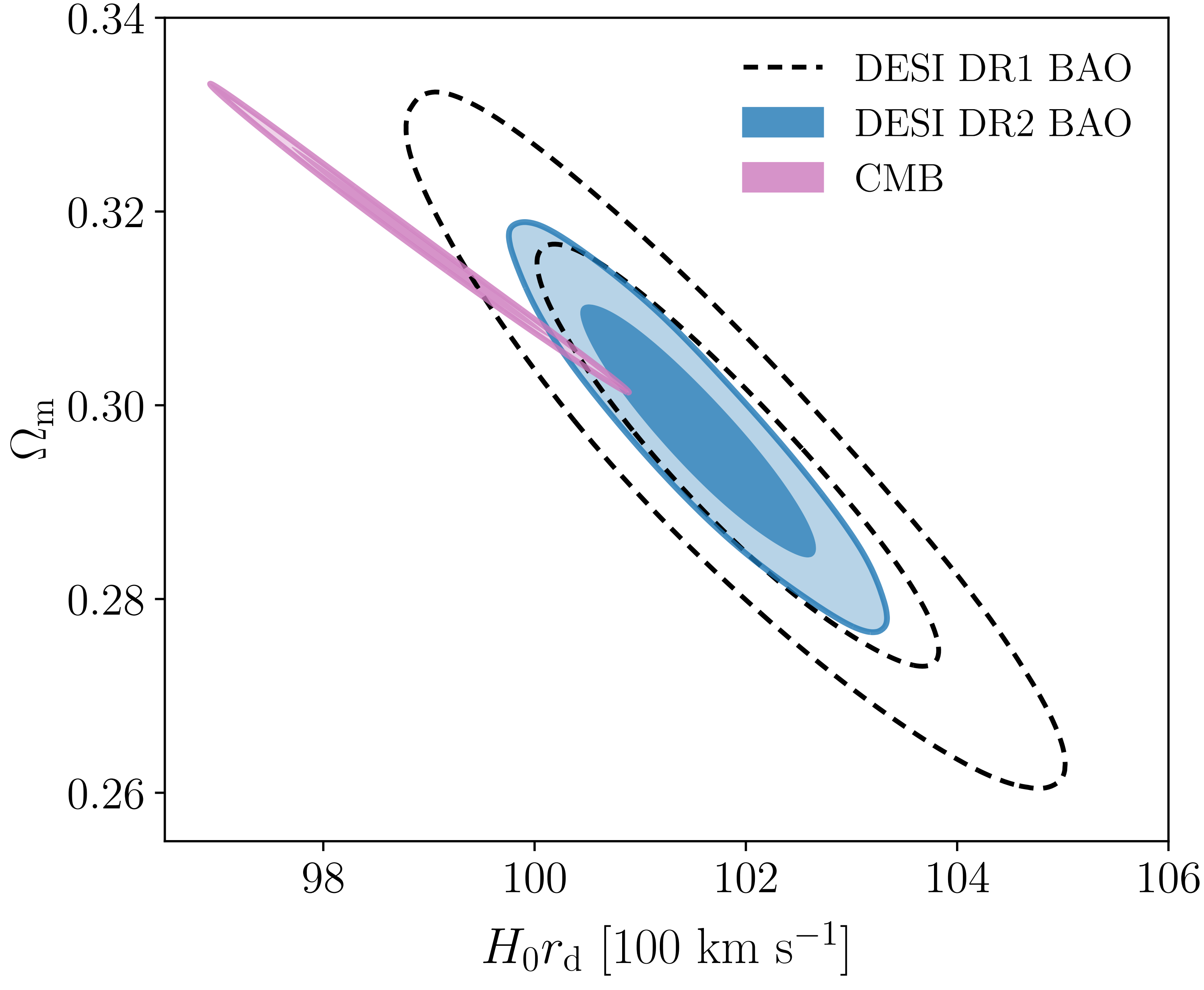
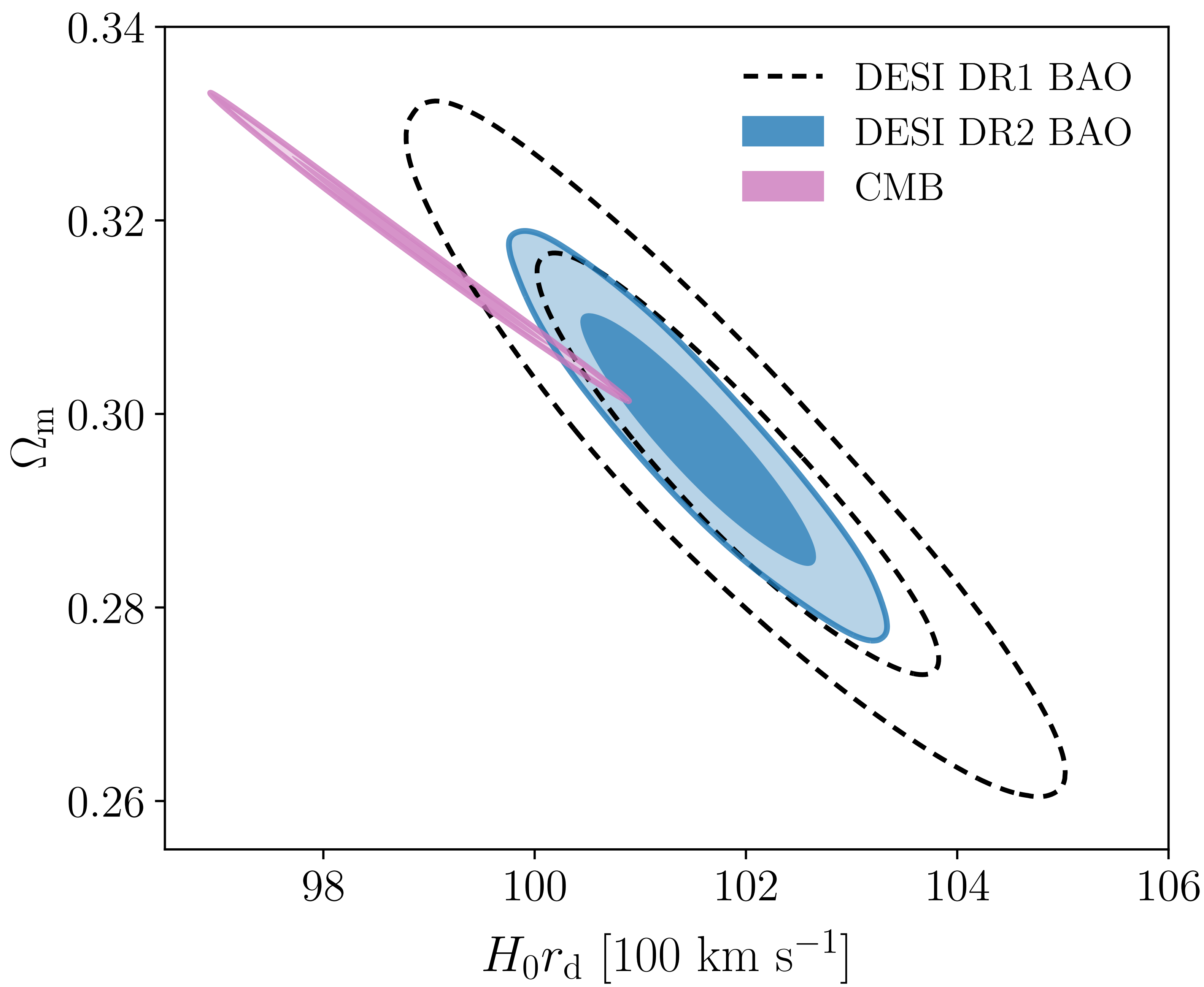


Flat ΛCDM model

- DR2 agrees beautifully with DR1
- DR2 is 40% more precise
- There is a $\sim 2.3\sigma$ **discrepancy** between DESI BAO and CMB
- The discrepancy has **increased** in DR2
- DESI BAO and CMB still agree very well on the acoustic angular scale θ_*
- The discrepancy is roughly in $\Omega_\mathrm{m} h^2$

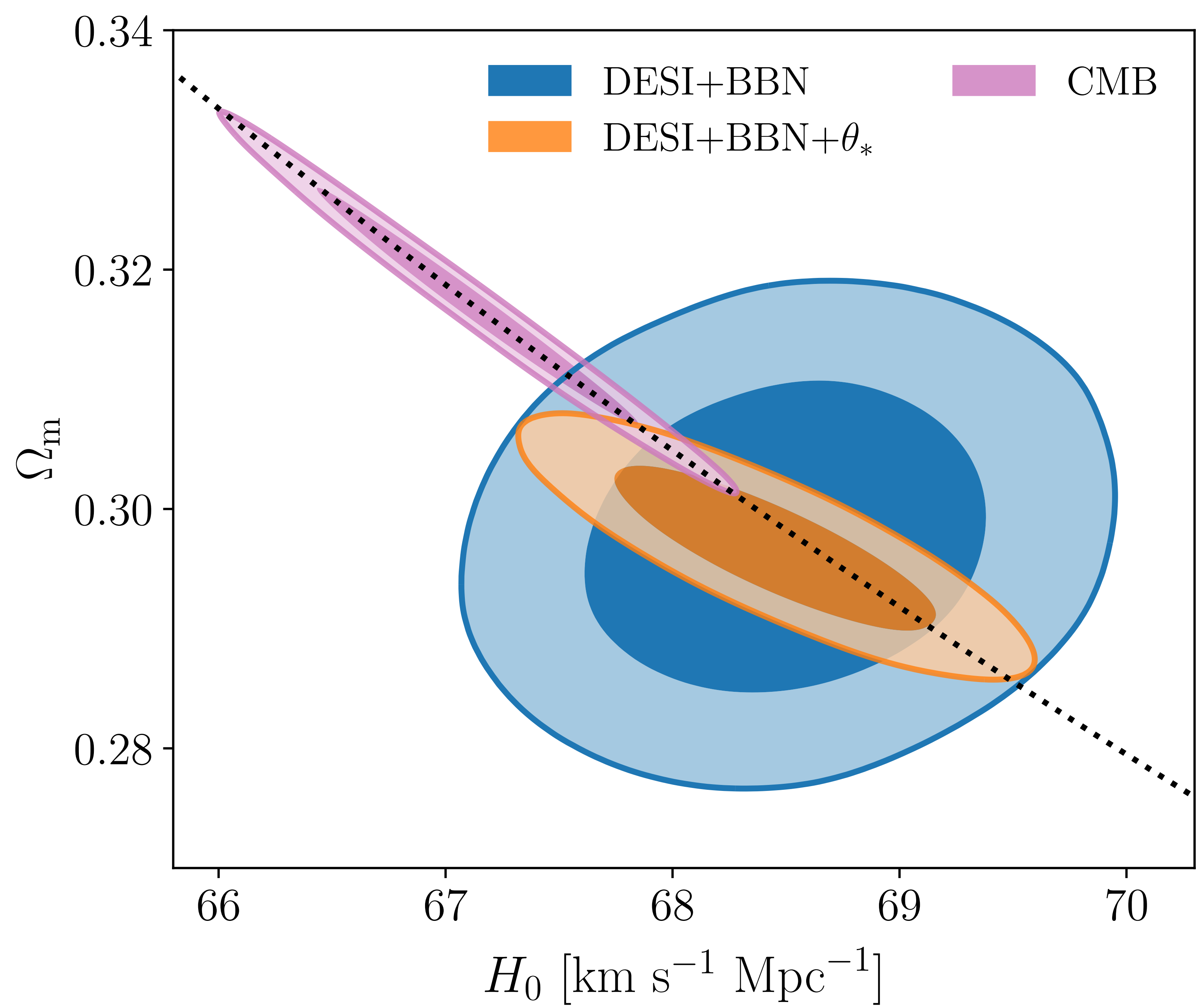


Flat ΛCDM model

Can calibrate sound horizon r_d with a BBN prior

Calibrated BAO then prefers slightly larger H_0 than Planck,
$H_0 = 68.5 \pm 0.6\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$

(again, very consistent in θ_* but slightly shifted in $\Omega_\mathrm{m} h^2$ …)



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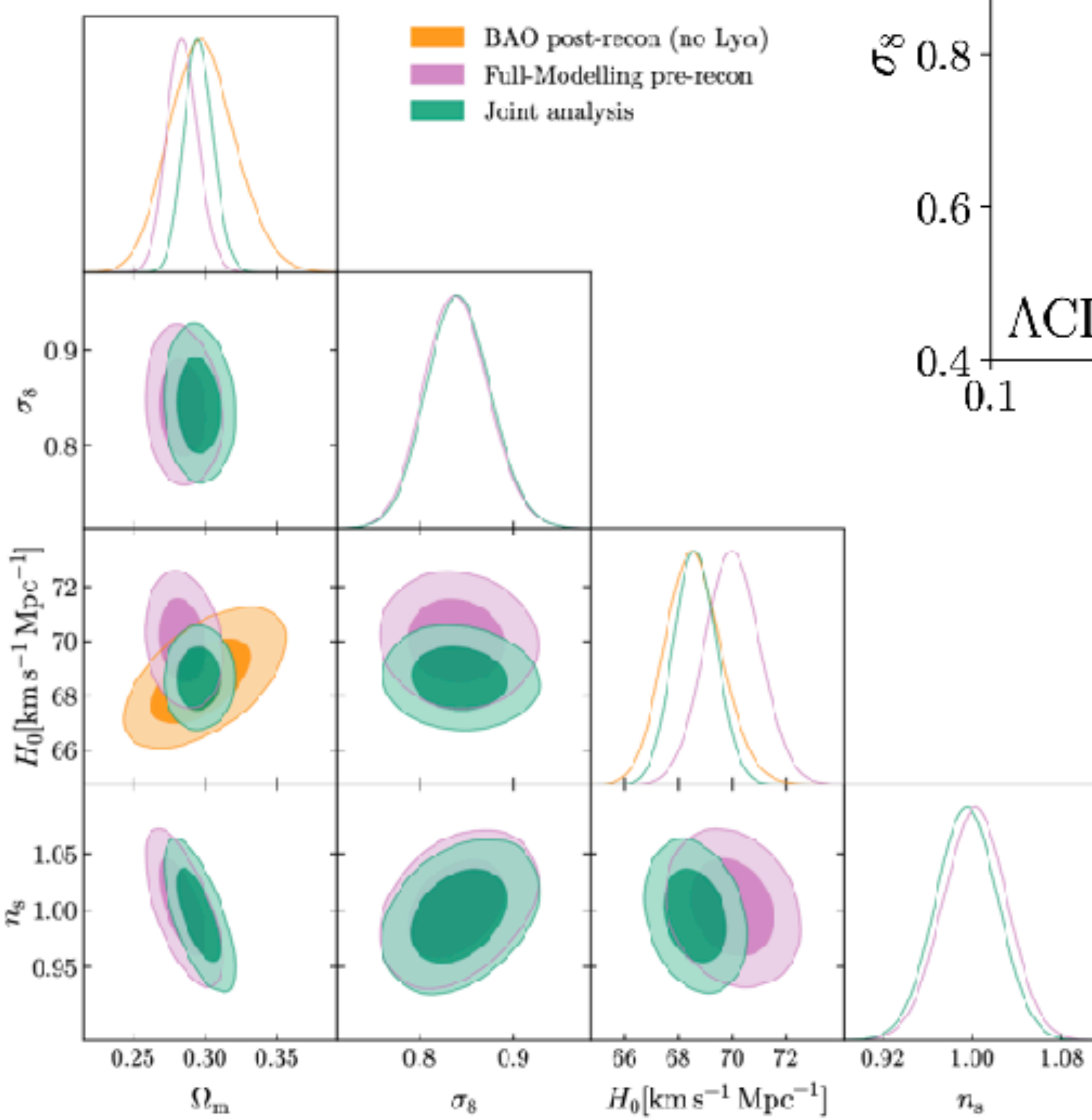
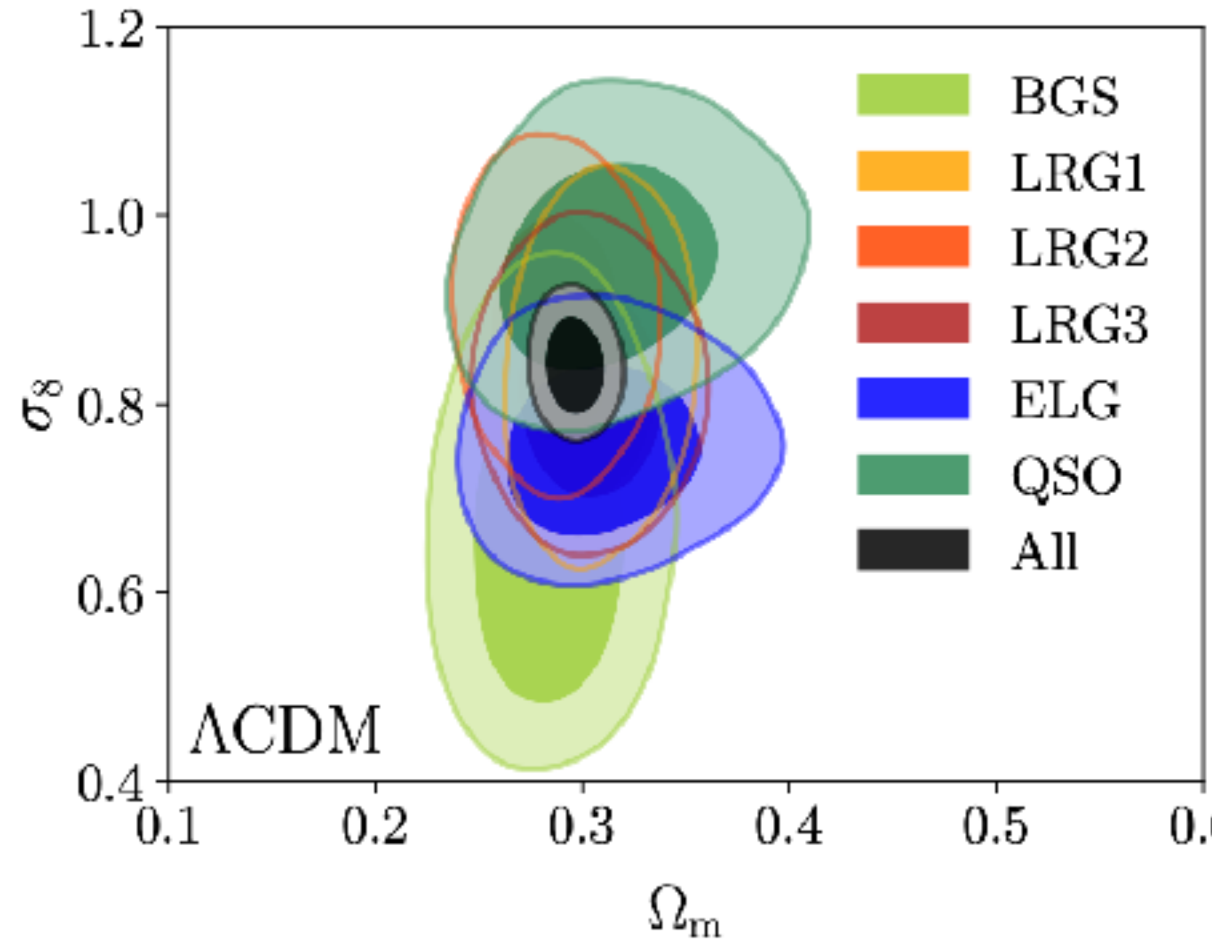
Flat ΛCDM model (perturbations)

Similarly, from full-shape we can measure growth of perturbations …





DESI DR1 results:
Adame et al (2025), arXiv:2411.12021
Adame et al (2025), arXiv:2411.12022

$$\Sigma m_\nu$$

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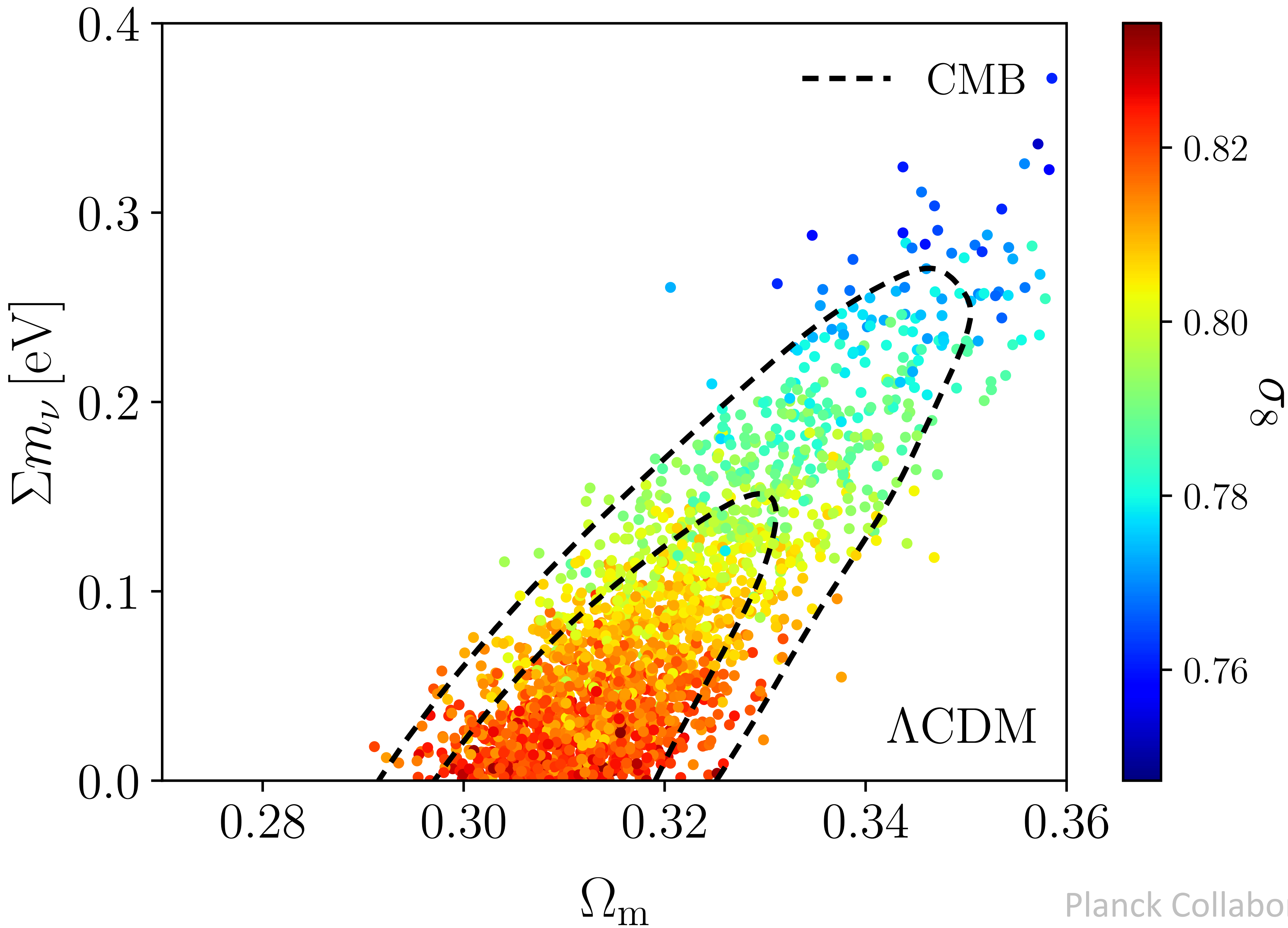
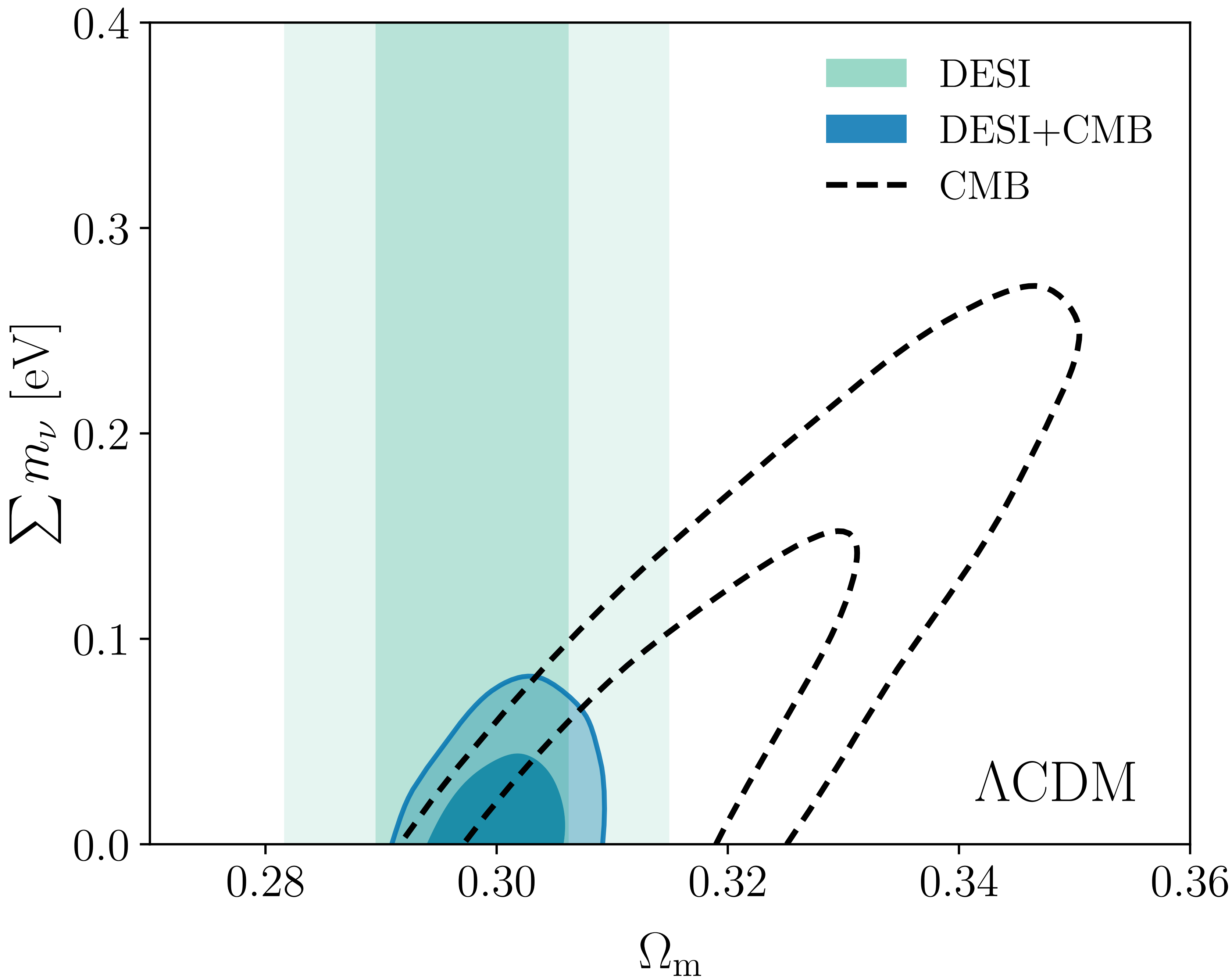
DESI and the neutrino mass scale



Planck Collaboration 2018

$\Sigma m_\nu < 0.260$ eV (95 % CL, TTTEEE)

DESI and the neutrino mass scale



$\Sigma m_\nu < 0.064$ eV (95 % CL)

DESI and the neutrino mass scale

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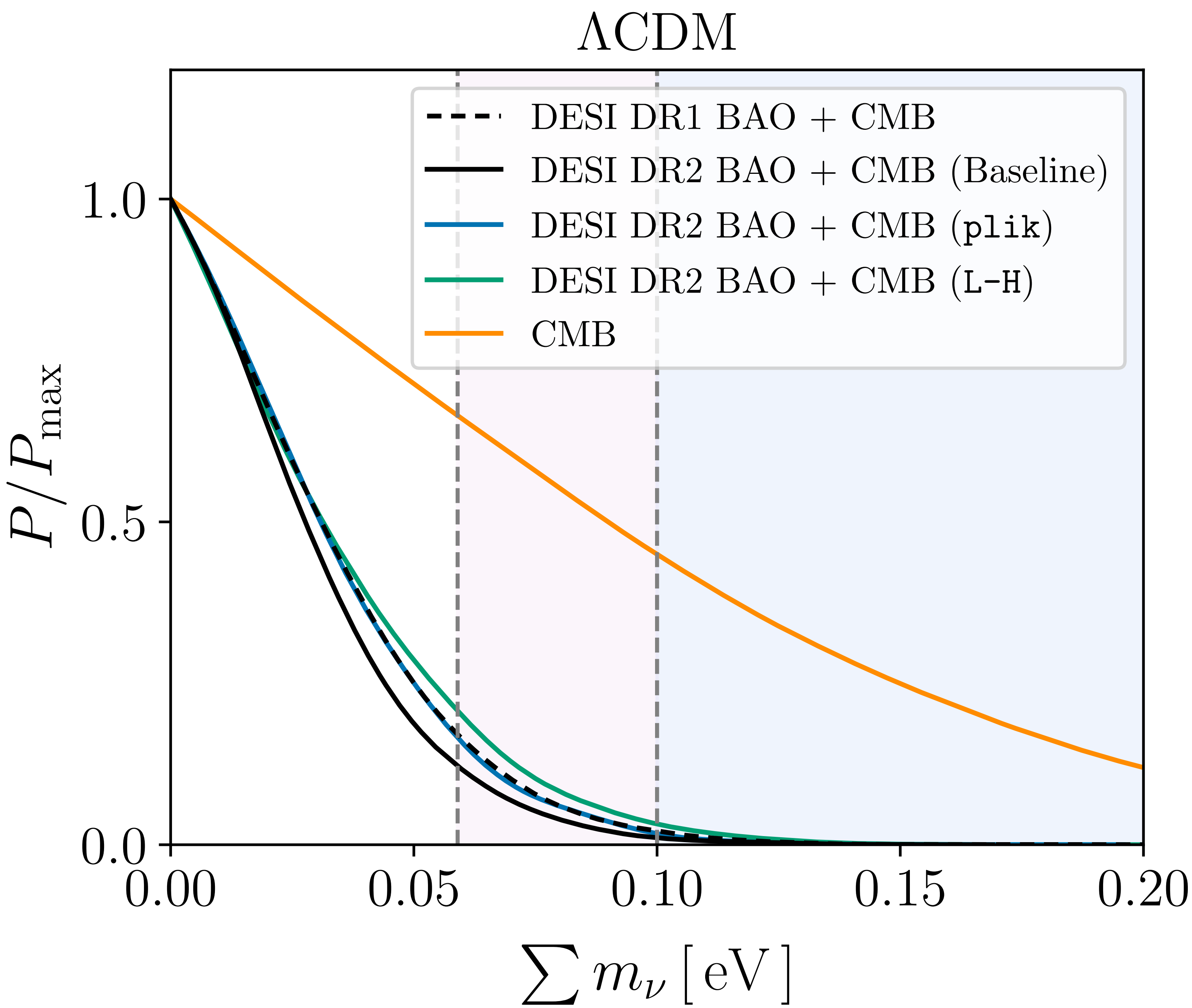
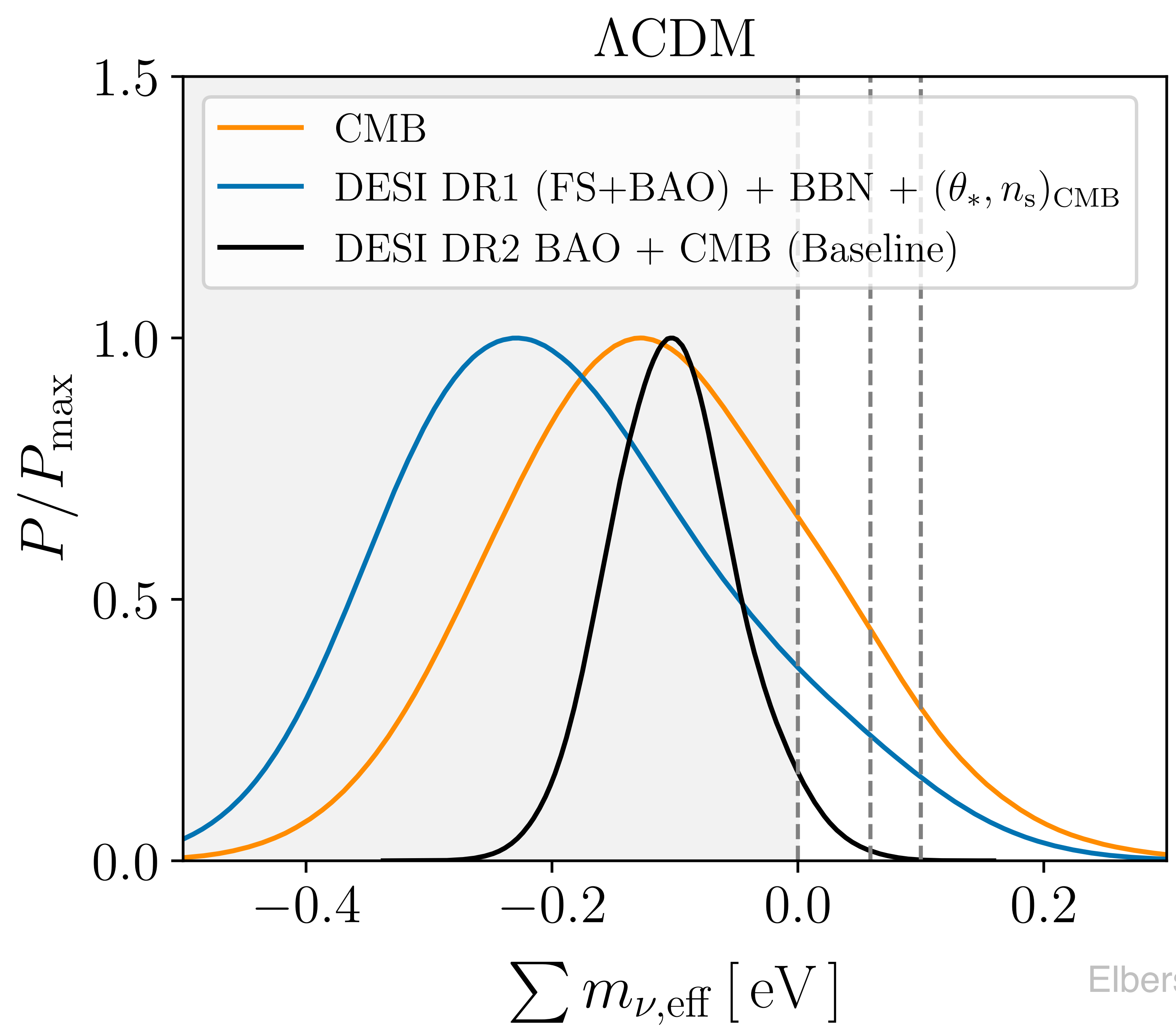


Uncomfortably close to terrestrial lower bound?

DESI and the neutrino mass scale



Elbers et al (2025)

If allowed, data would prefer even smaller (negative!) **effective** masses …

Dark energy $w(z)$

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DESI BAO and Dark Energy

"Equation of state" governs effect of DE on expansion:

$$w = \frac{P_{\mathrm{DE}}}{c^2 \rho_{\mathrm{DE}}}$$

Allow equation of state to vary with time, $w = w(a)$. Baseline analysis uses the "**CPL parametrisation**"

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

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

Remember: CPL is useful as it can match many physical models, but it is not to be taken too literally!

DESI BAO and Dark Energy

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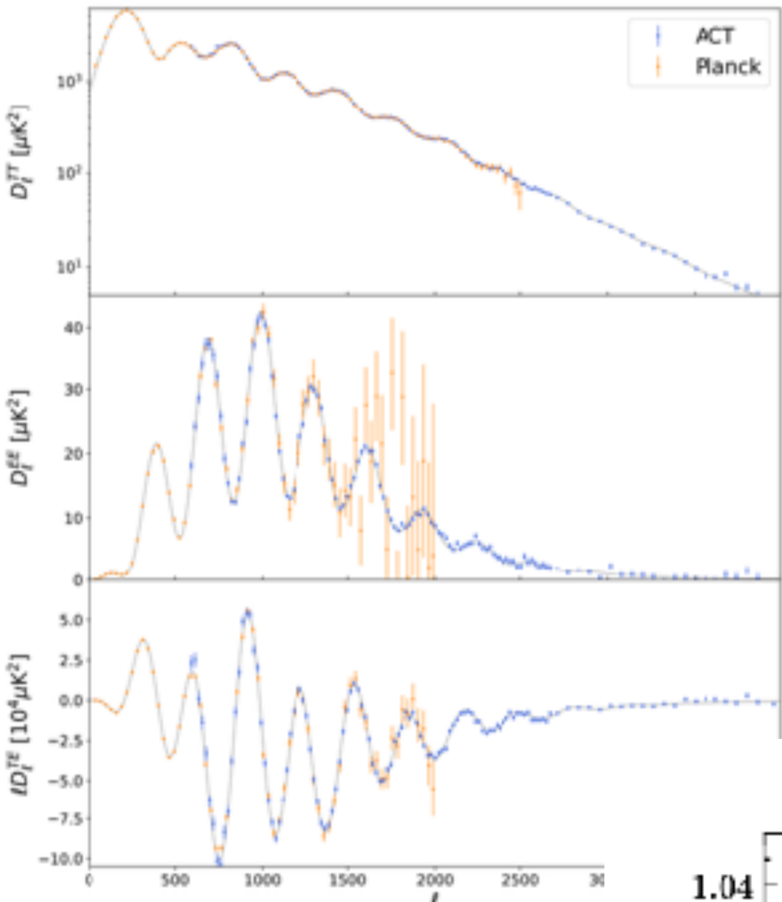
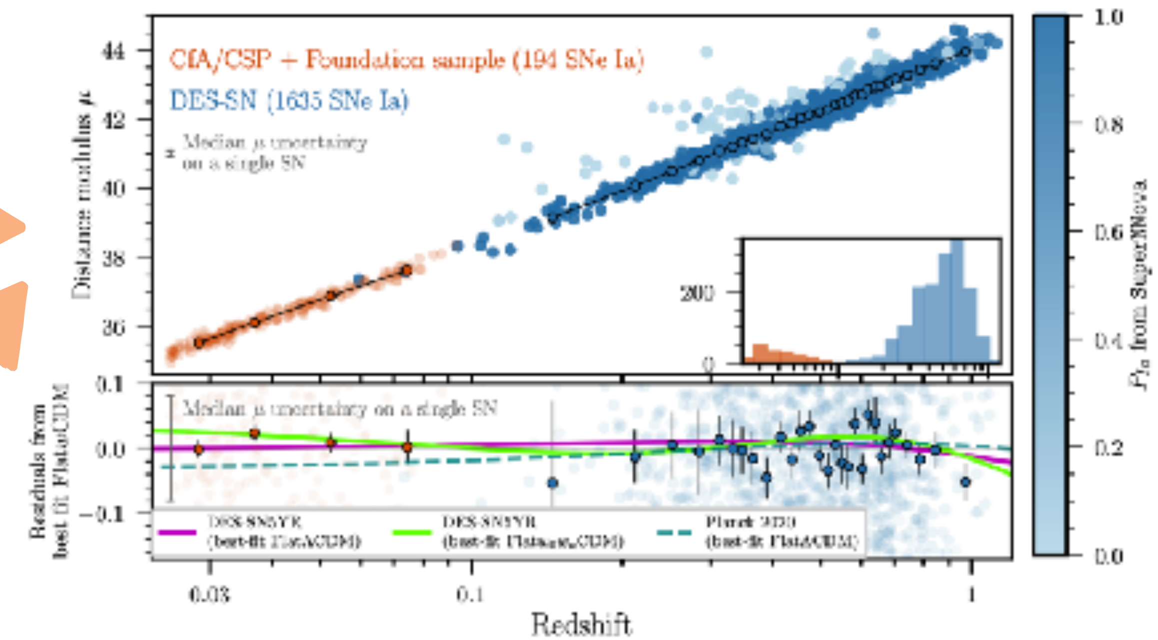
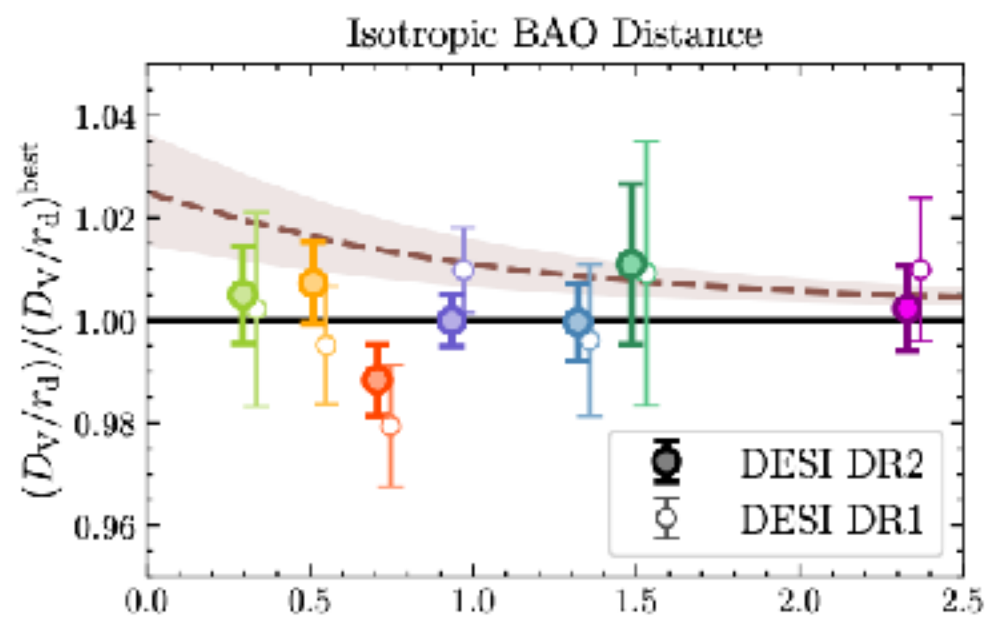


CMB



SNIa



BAO

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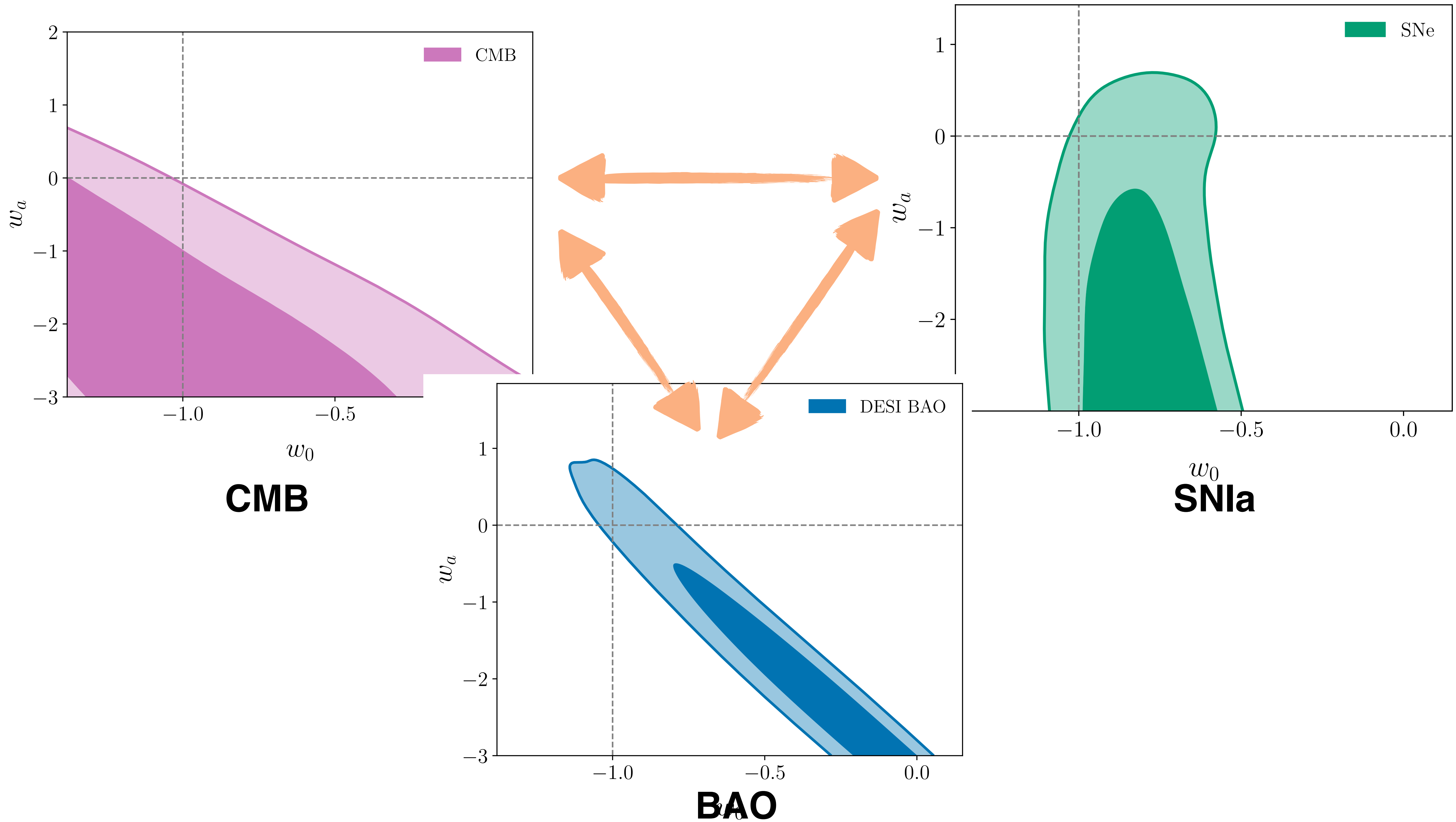
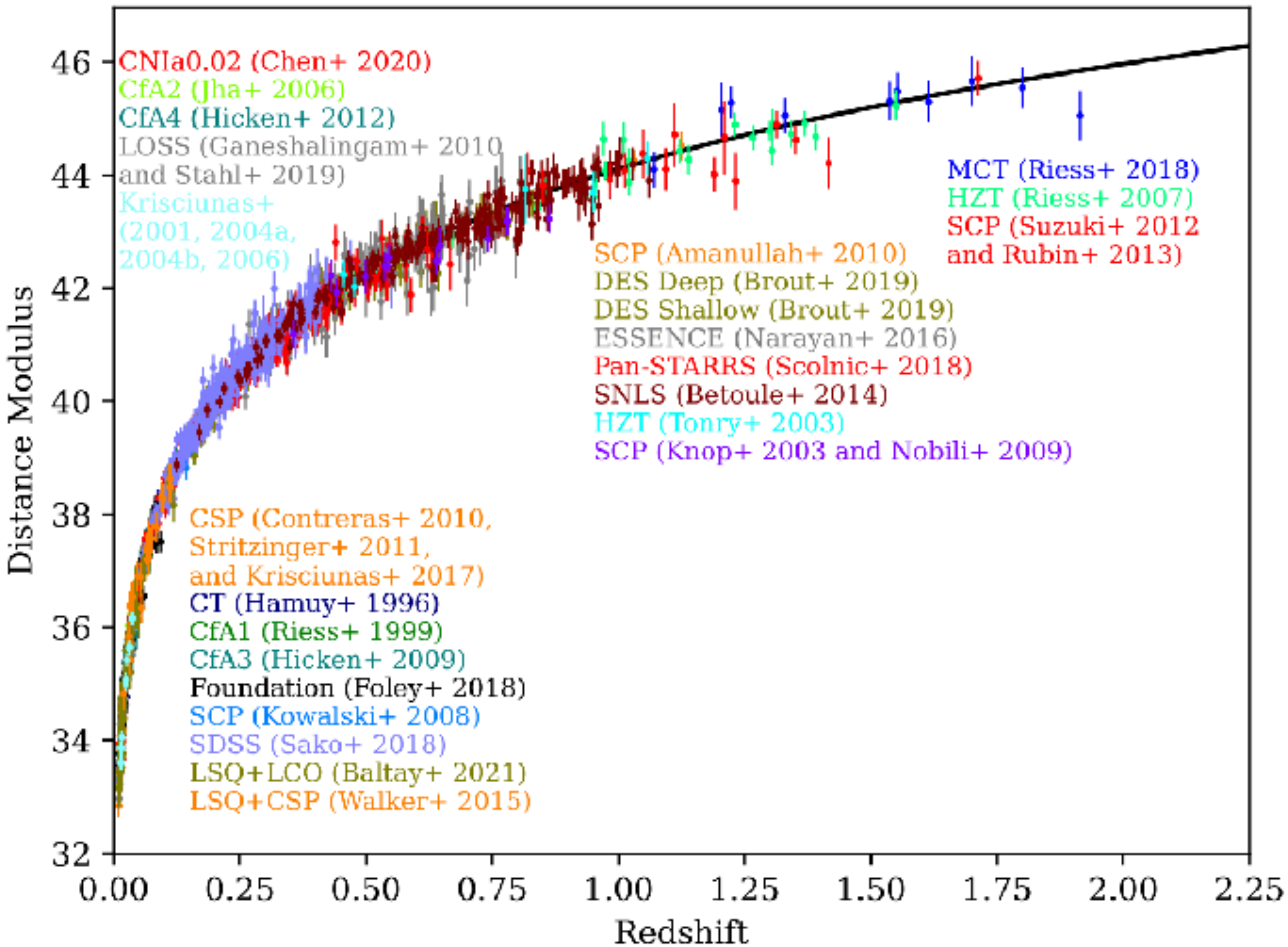
DESI BAO and Dark Energy



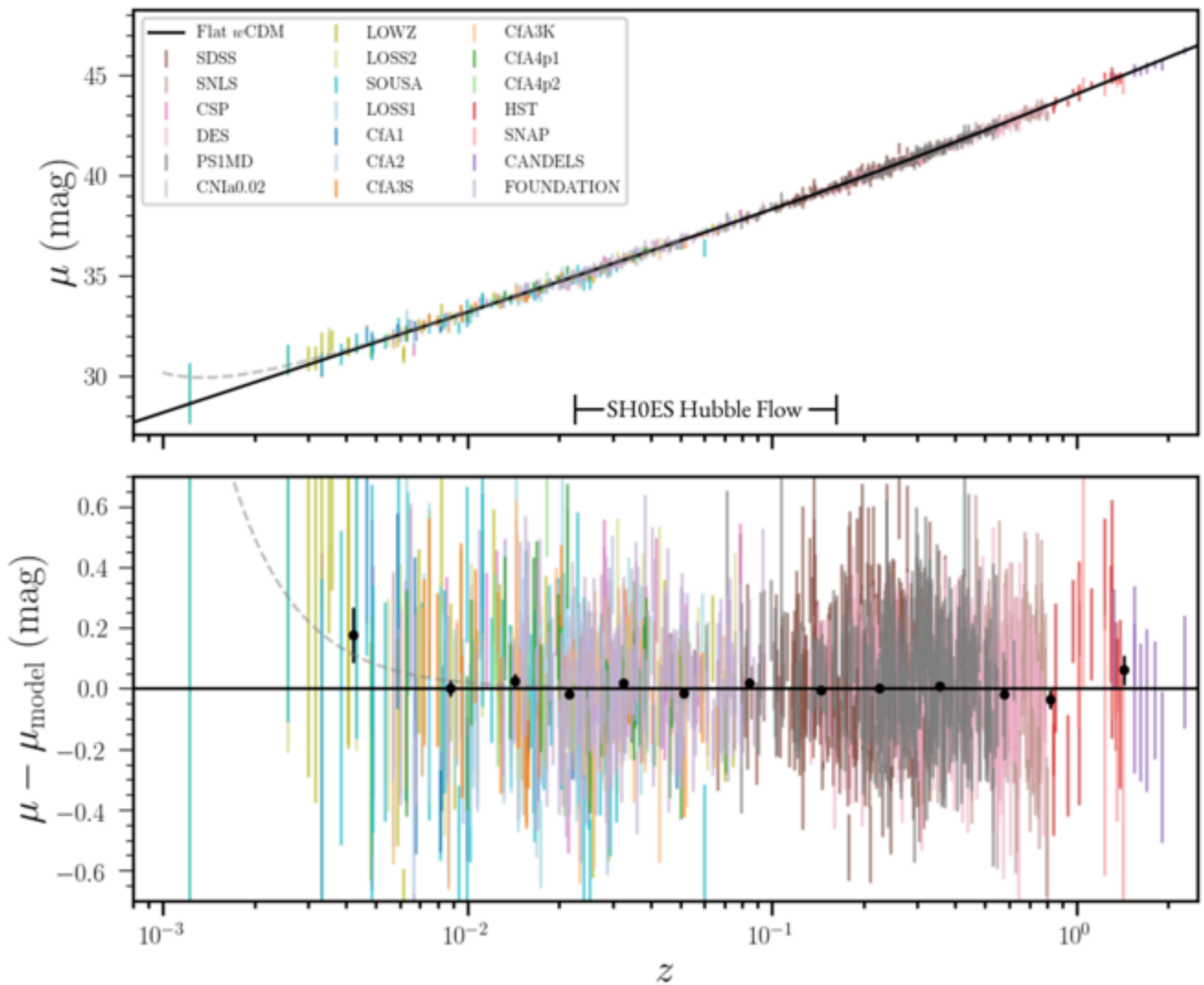
Very hard to say much with 1 probe alone – combinations essential!

A comment on SN datasets



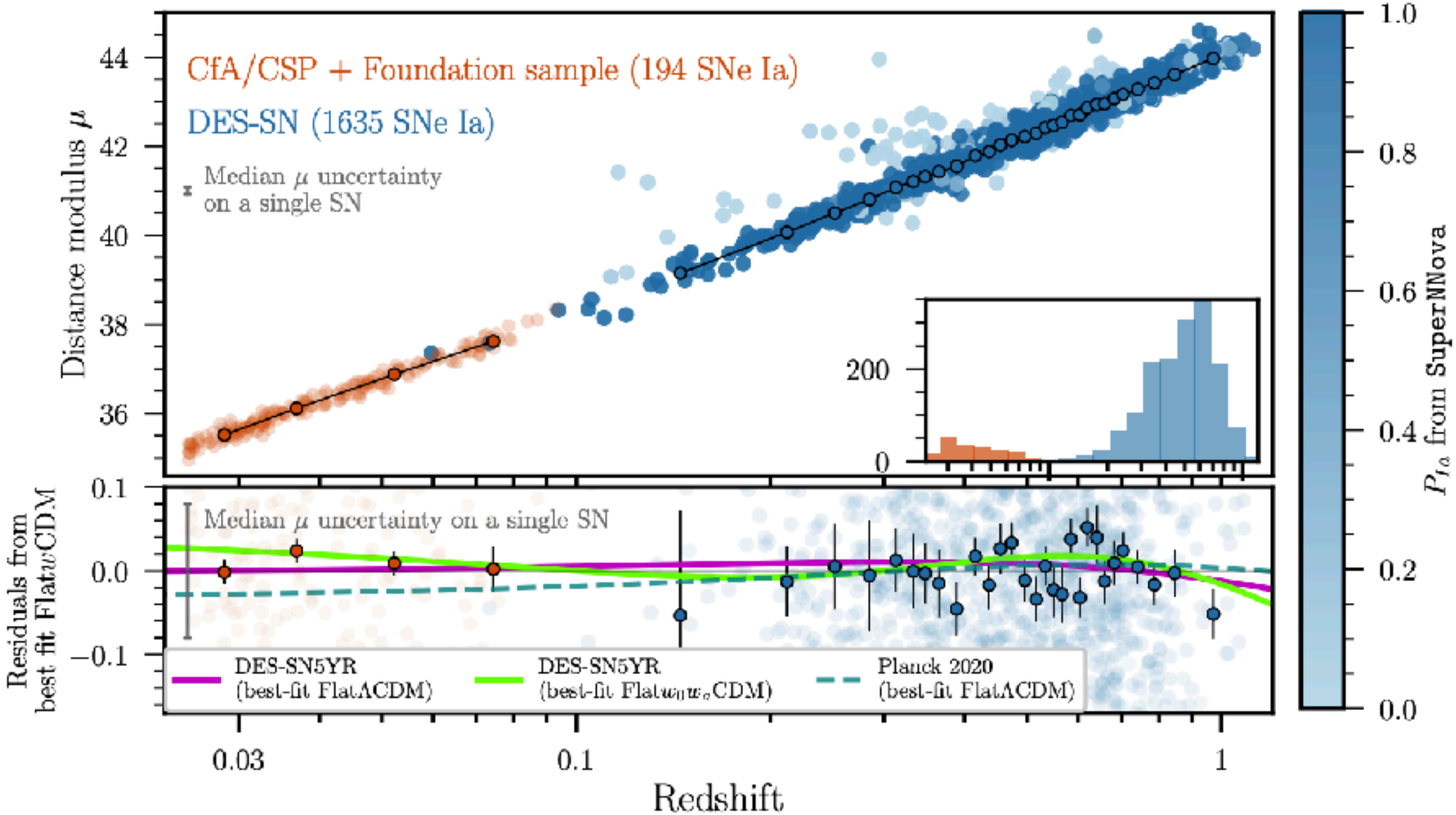
Rubin et al, 2311.12098 (Union3)

A comment on SN datasets



Brout et al, 2202.04077 (Pantheon+)

A comment on SN datasets



DES Collaboration, 2401.02929

DESI BAO and Dark Energy

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Level of discrepancy with ΛCDM cosmological constant DE from

DESI + CMB: 3.1σ

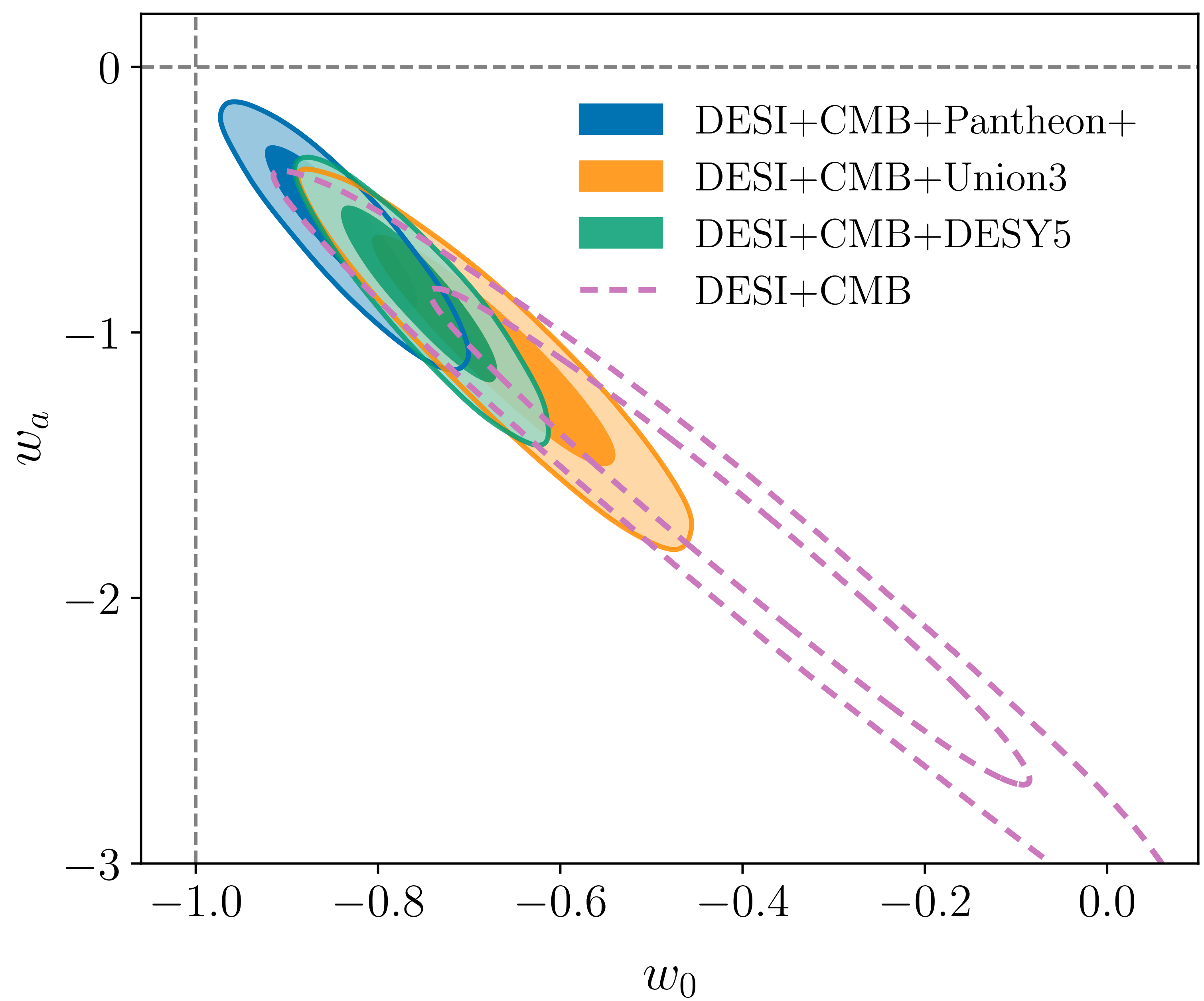
+ Pantheon+: 2.8σ

+ Union3: 3.8σ

+ DES-SN5YR: 4.2σ

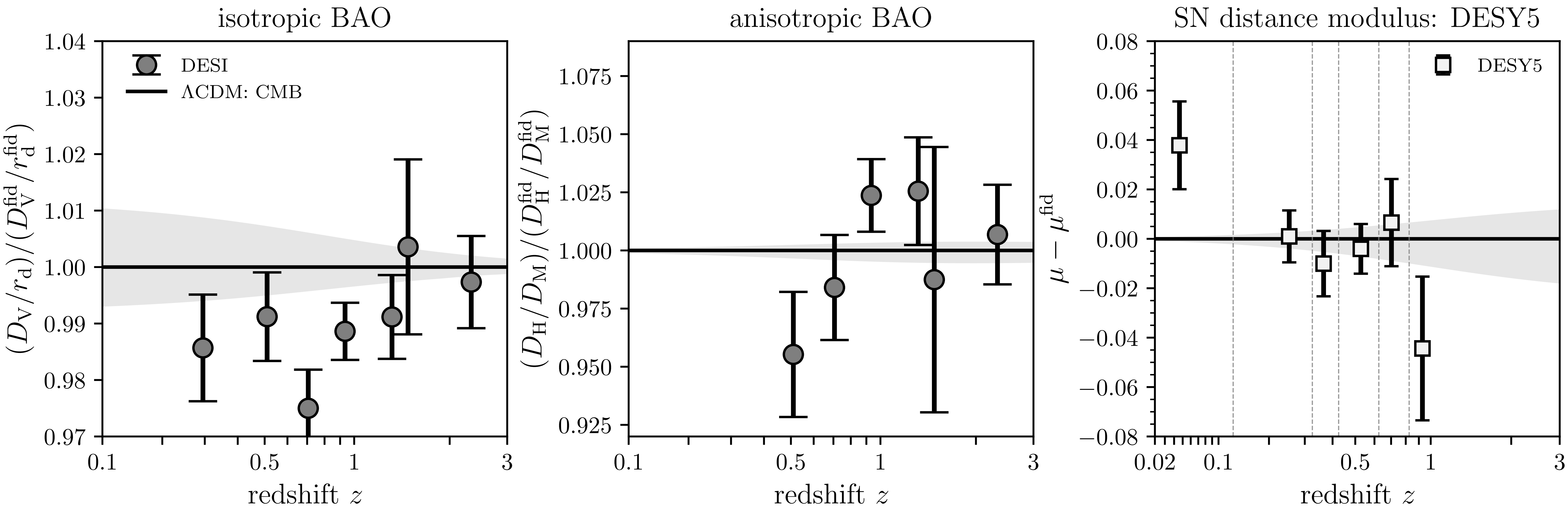
*deliberately frequentist statistic! Other metrics in paper

Hints of dark energy **weakening**



DESI BAO and Dark Energy

Understanding **why** the data pulls away from ΛCDM:



CMB can be encapsulated in 3 parameters: $(\theta_*, \omega_{bc}, \omega_b)$

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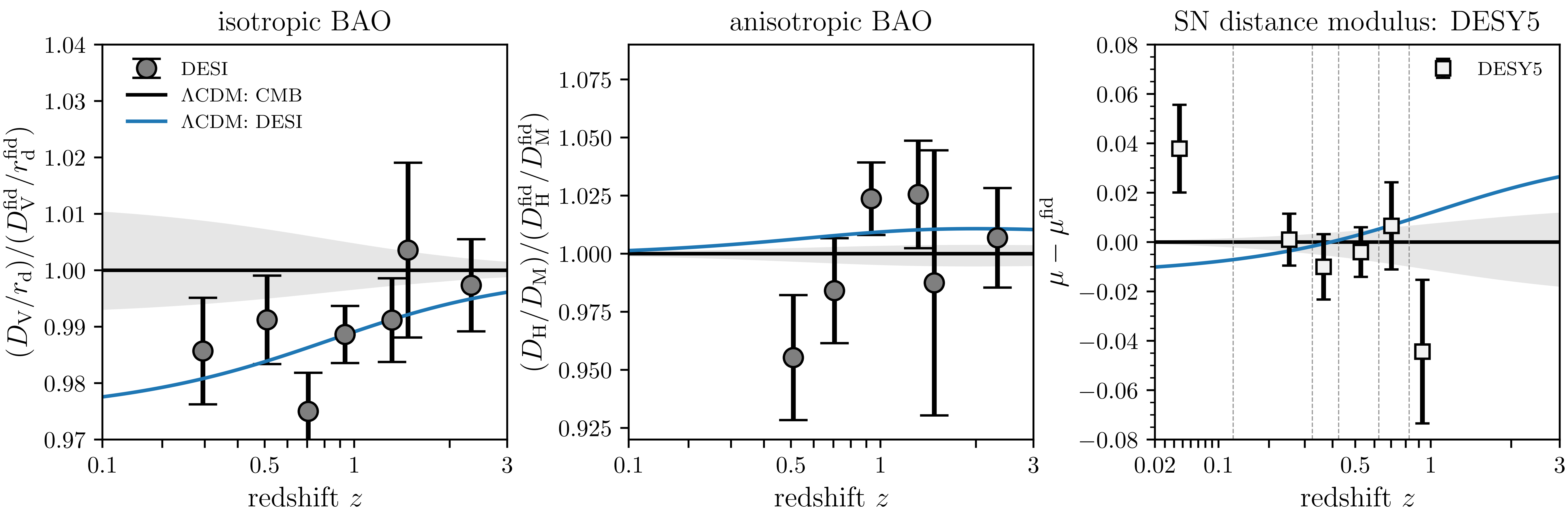

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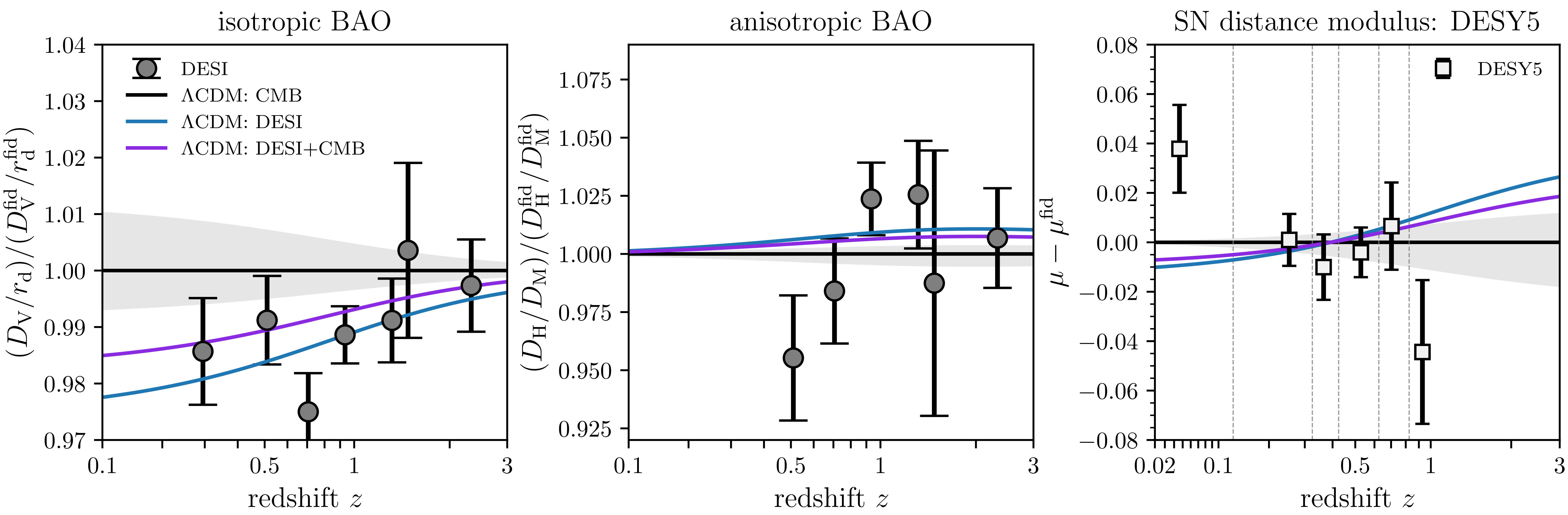

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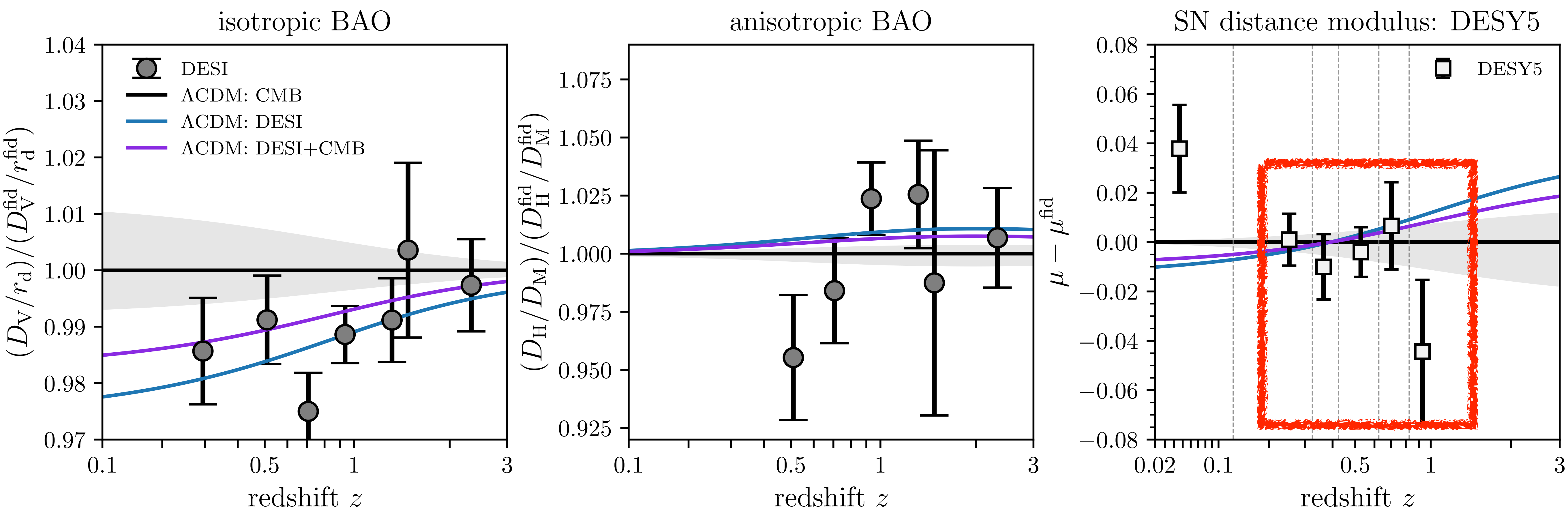
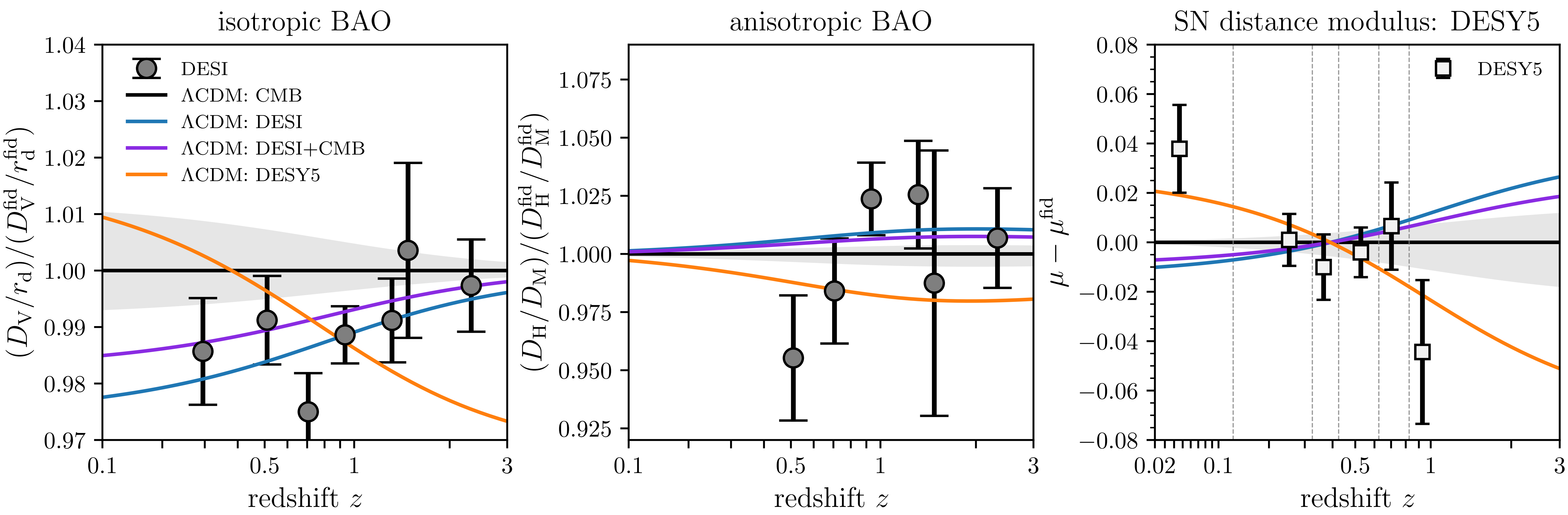


BAO and SN distances agree in the range of redshift overlap!

CMB can be encapsulated in 3 parameters: $(\theta_*, \omega_{bc}, \omega_b)$

DESI BAO and Dark Energy

Understanding **why** the data pulls away from ΛCDM:



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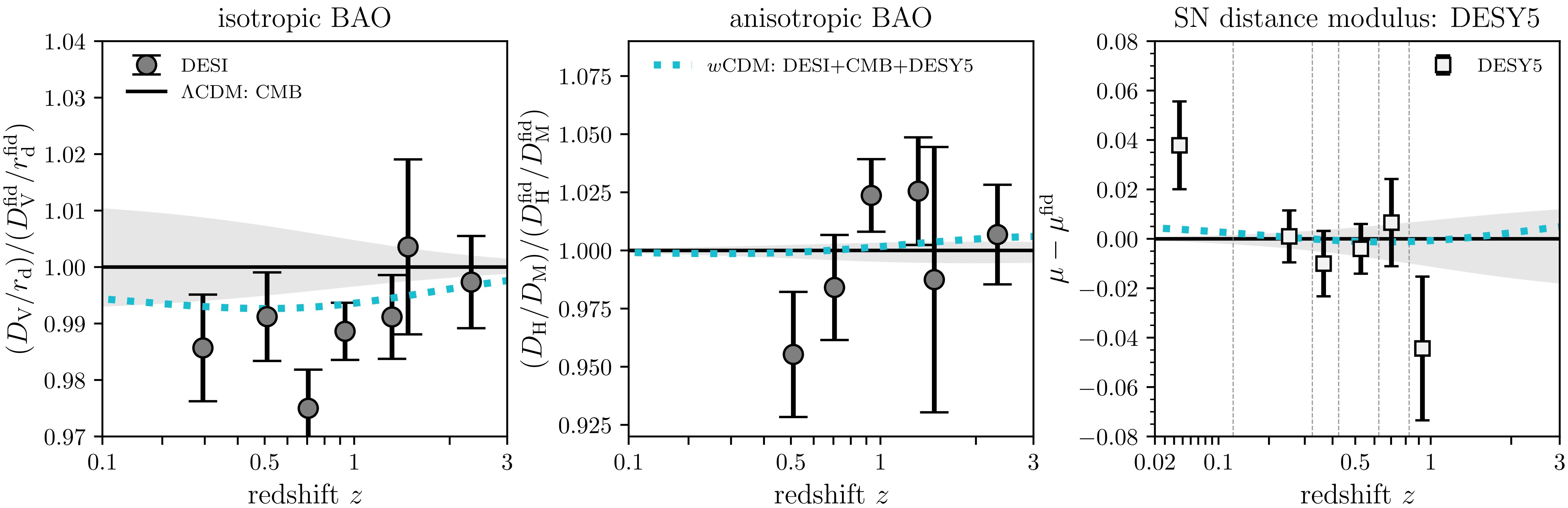

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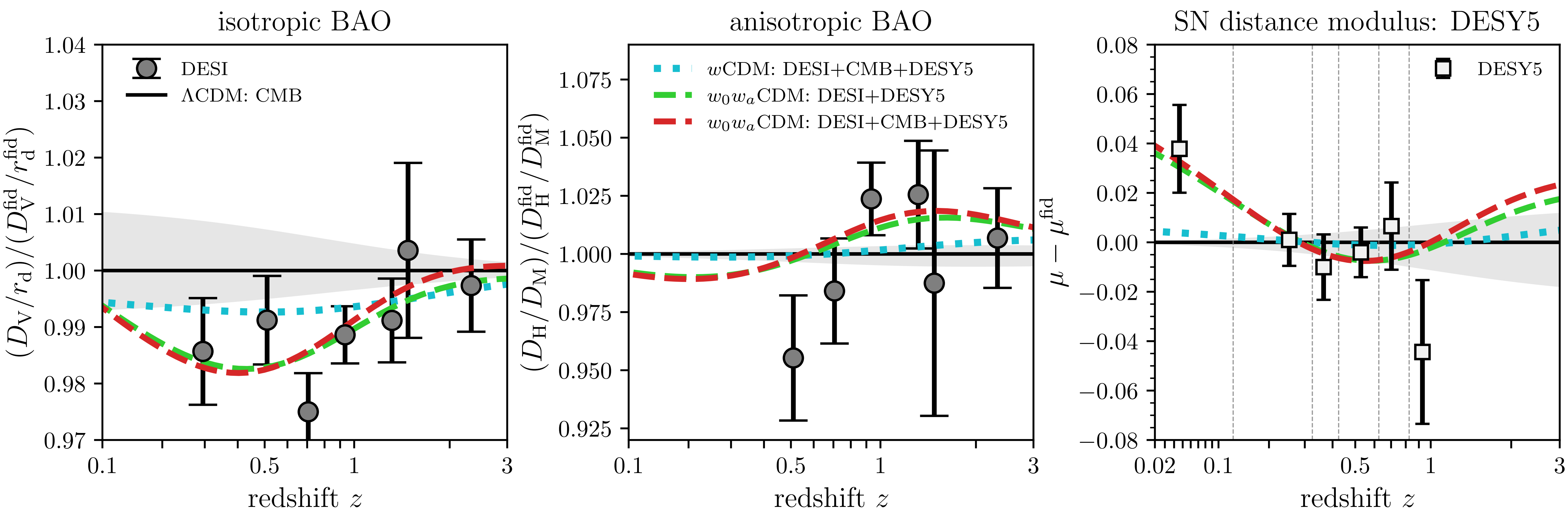

CMB can be encapsulated in 3 parameters: $(\theta_*, \omega_{\rm bc}, \omega_{\rm b})$

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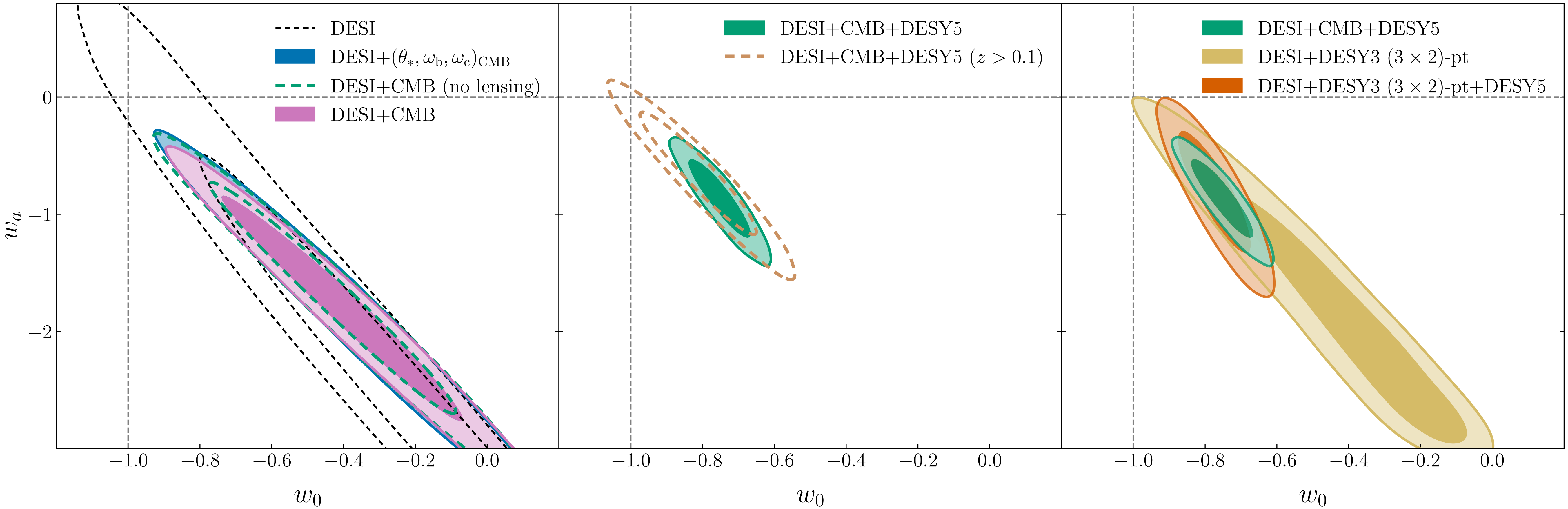
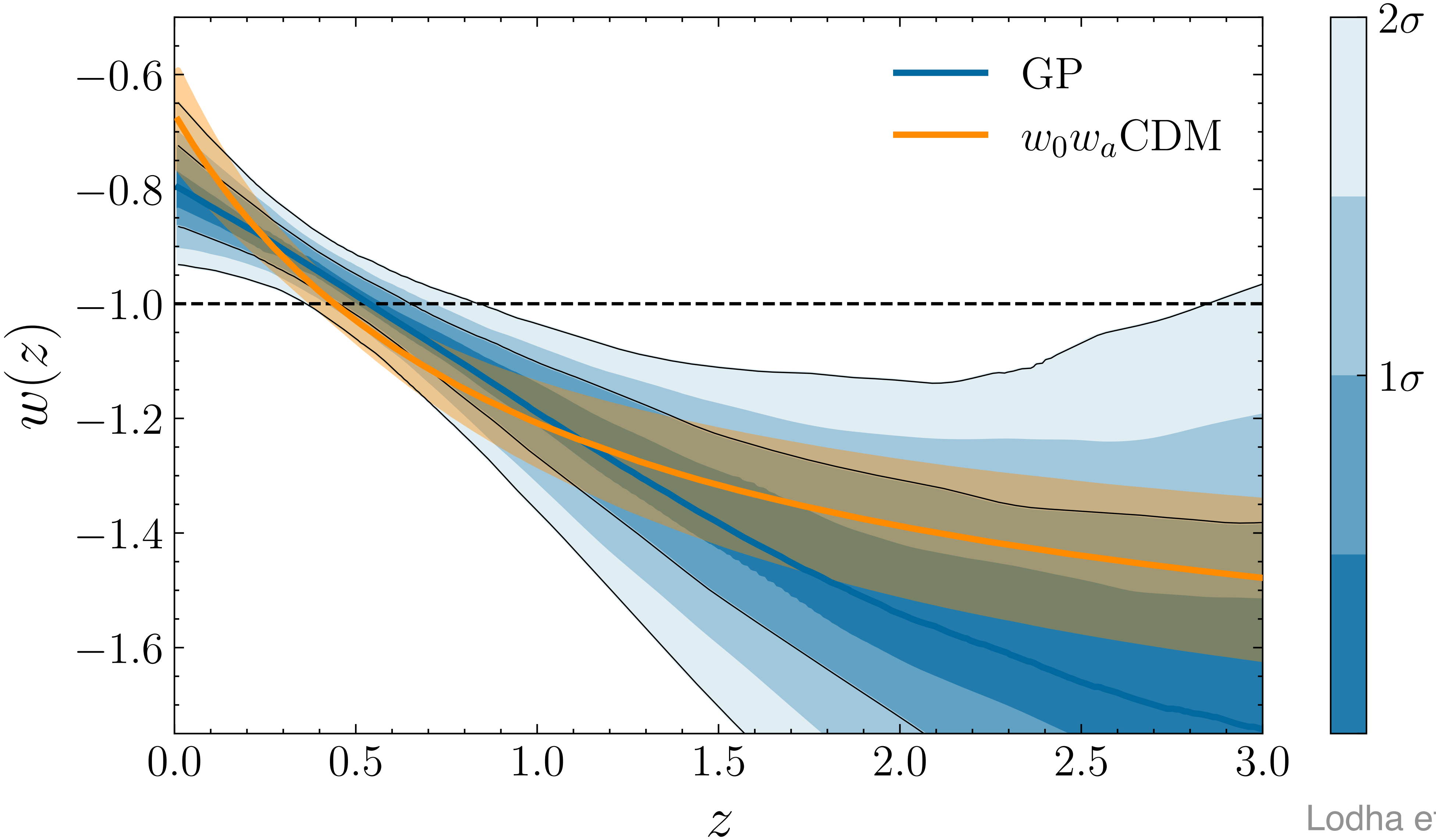
How robust is this result?



Swapping out different datasets changes the significance, but *the results stay in the same part of parameter space*

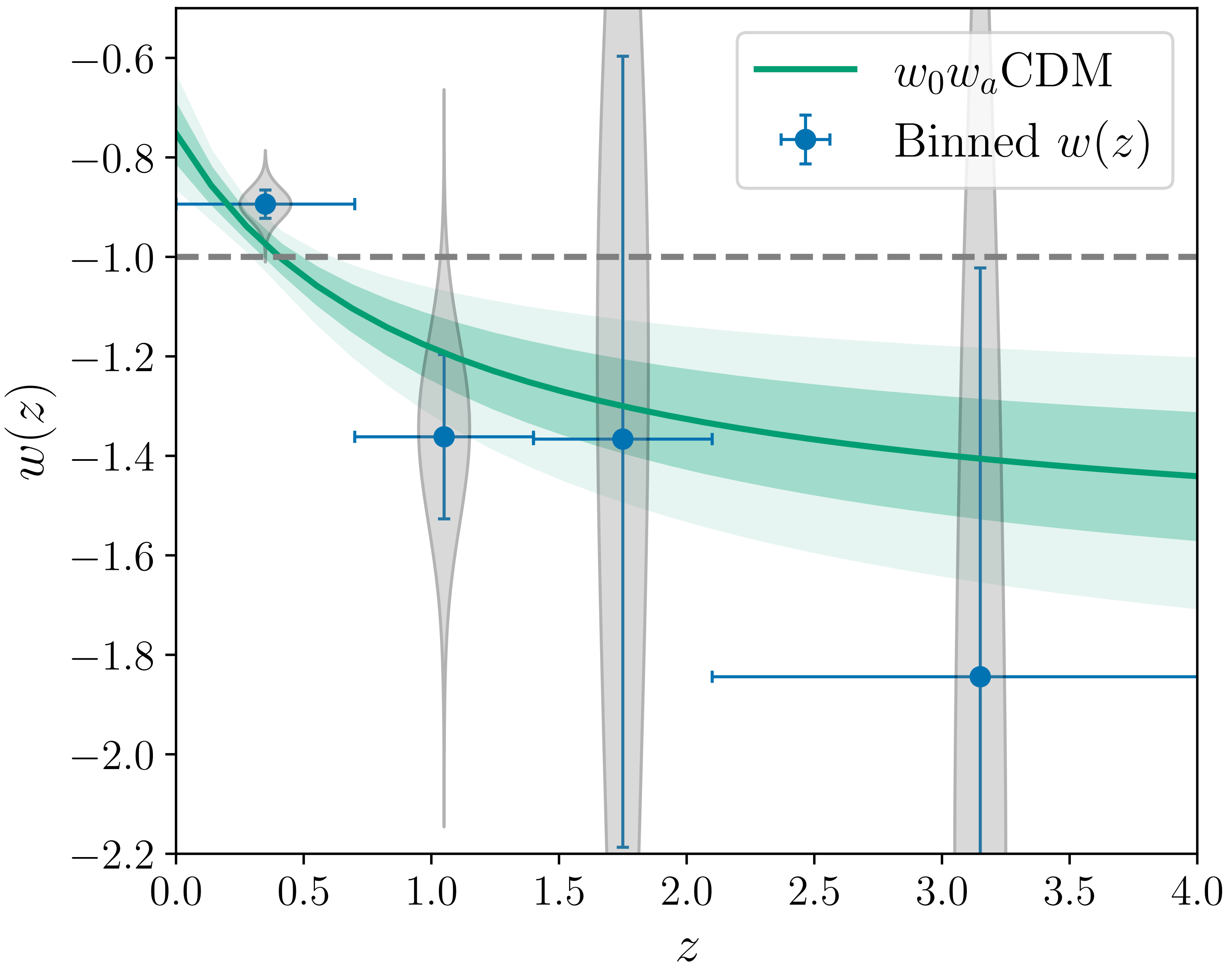
How robust is this result?



Lodha et al (2025)

It is not specific to the CPL parametrisation

How robust is this result?



It is not specific to the CPL parametrisation

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Can we avoid DE evolution?

- Hard to see any effects that could shift DESI BAO results
- CMB $\Omega_{\mathrm{m}}h^2$: ACT and SPT recently confirmed Planck results, hard to see much room for shifts
- SN data certainly could have some offsets (especially calibration across surveys and historical low-z samples)
  - big new SN data efforts on the horizon, esp. Rubin/LSST

- Perhaps some room for non-flat curvature? Dinda & Maartens (2025), Chen & Zaldarriaga
- Shift in optical depth to reionization, τ, could help ΛCDM? Sailer et al (2025)
- Modification of recombination history? Mirpoorian et al (2025)
- Interaction between DE and DM components? Khoury et al (2025)
- Non-minimal DE coupling to gravity? Wolf et al (2025)

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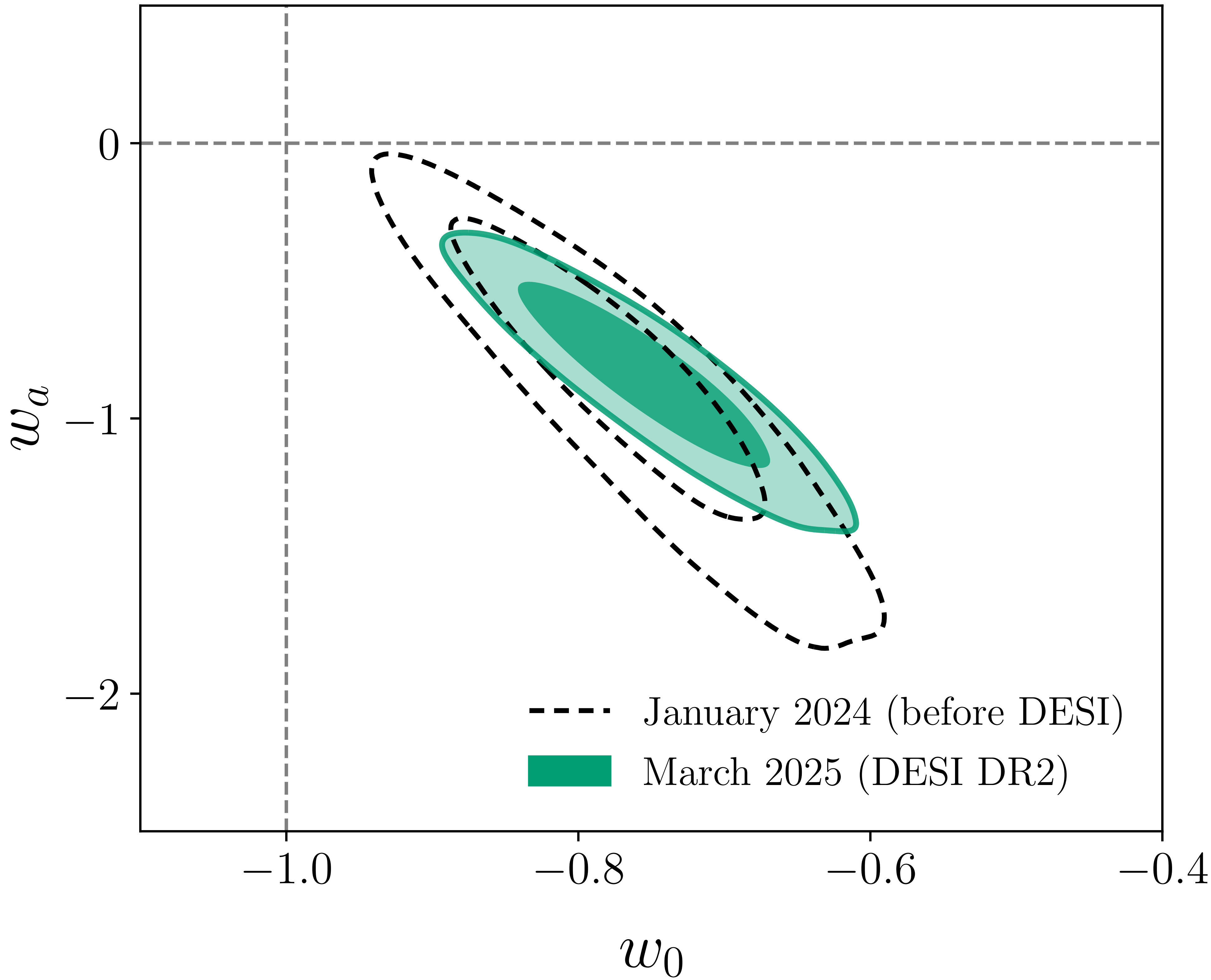
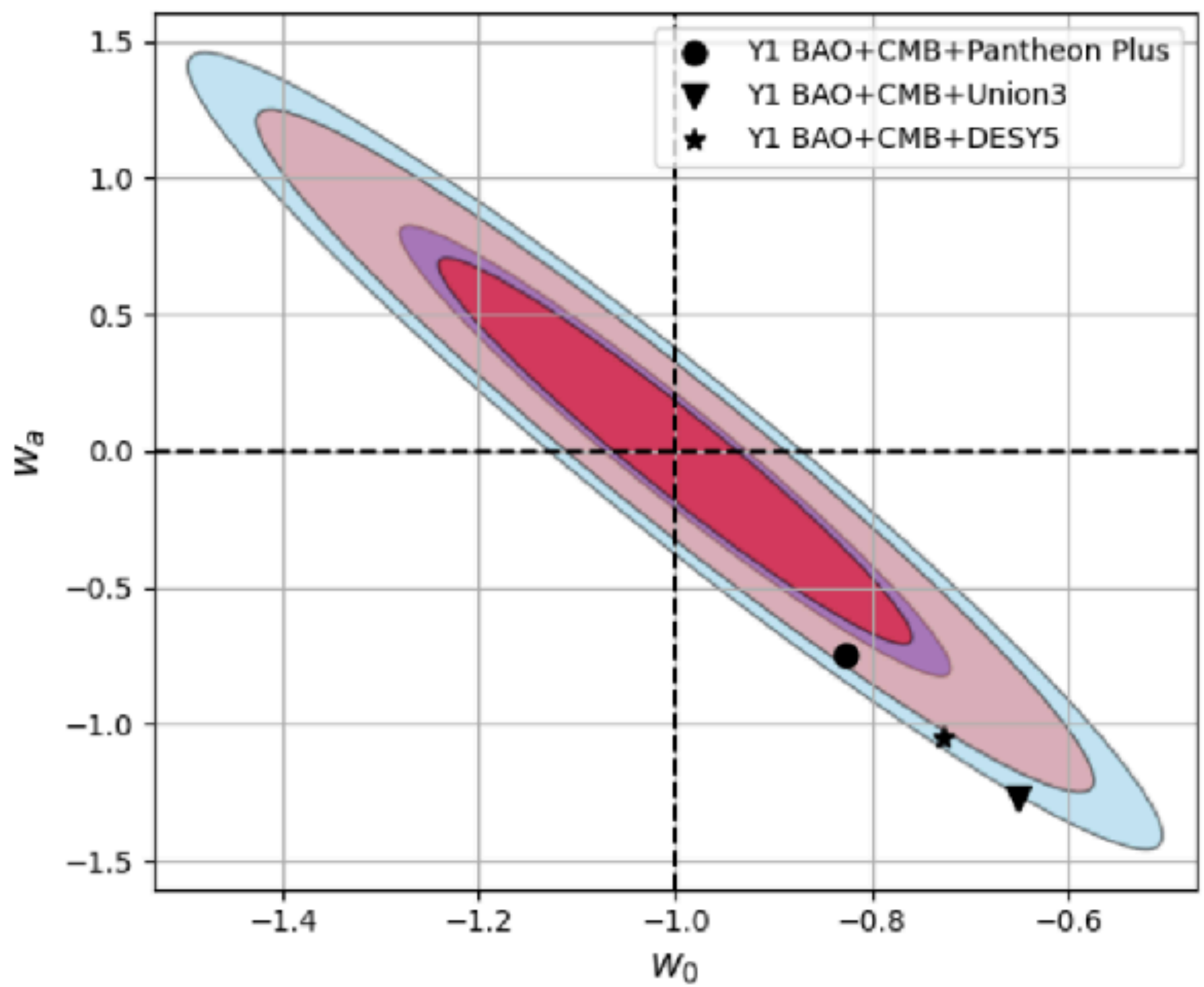
What information has DESI added?



What comes next?

What’s next? – full DESI data

Dark energy **without** SNe uncertainties:



What's next? – other analyses

From DESI:

- Adding full-shape information to BAO (for DR2 and beyond)
- Higher-order clustering statistics (3-pt, 4-pt, …)
- Simulation-based / emulator approaches
- Lensing and cross-correlations
- …

From other surveys:

- Euclid – DR1 in late 2026, DR3 in 2031 (ask me about Euclid BAO)
- ZTF and LSST SNe
- LSST and Euclid weak lensing (and DES Y6 soon)
- Roman, SO, SphereX, …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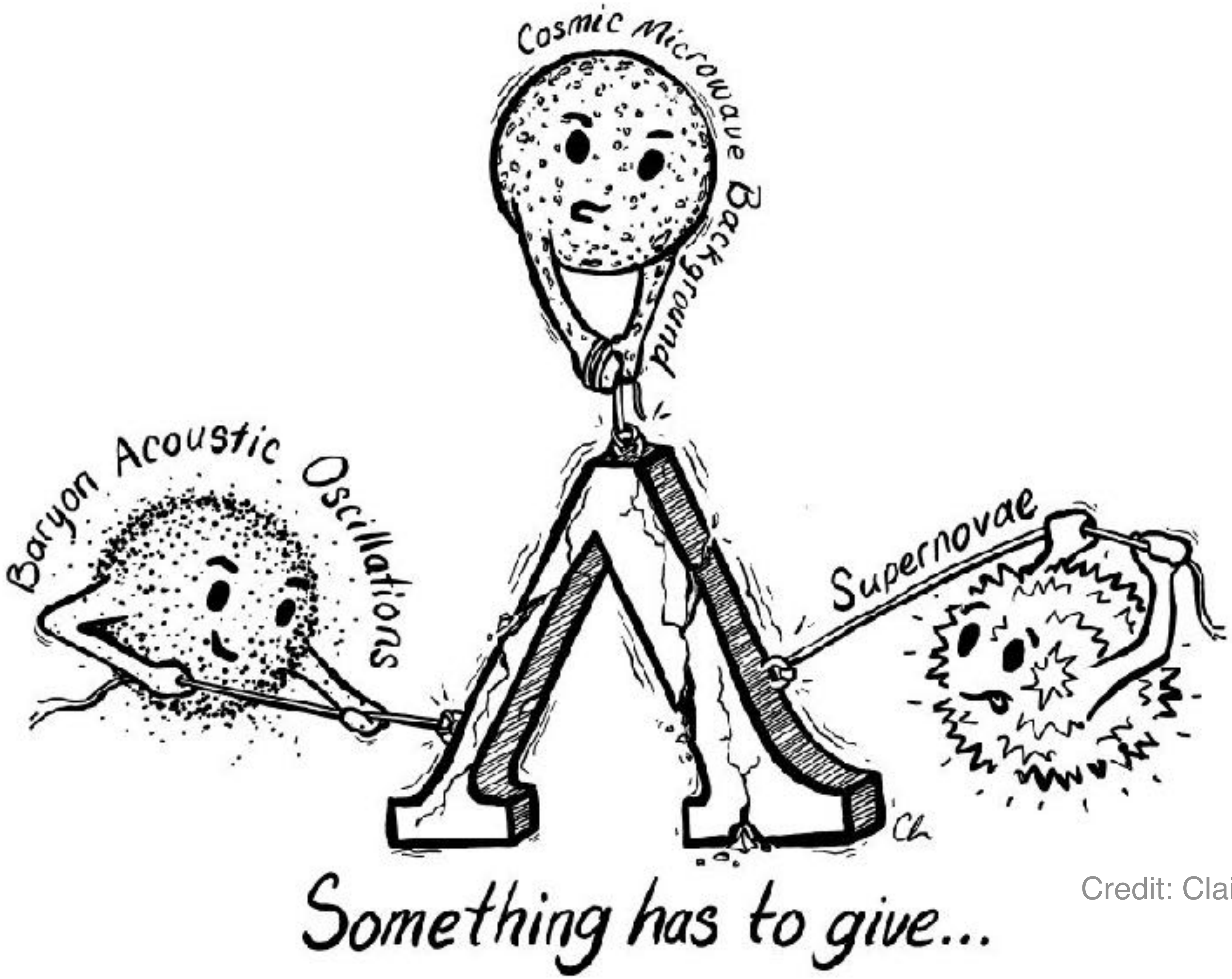
What's next?



Credit: Claire Lamman

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Frequently Asked Questions for DR2

Frequently asked questions for DR2

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1. Are there any BAO outliers? / Tension between DESI and SDSS BAO?
2. Why do you use only a 1D BAO fit to BGS at $z = 0.3$?
3. I heard DESI DR2 is *more* consistent with Planck than DR1, is this true?
4. Are BAO and SN in conflict (either distances or inferred parameters)?
5. How much do DE results depend on low-z SN?
6. Why does the data give $w \simeq -1$ in fixed wCDM?
7. Does it matter which CMB likelihood you use?
8. Can systematic errors in CMB change the DE conclusions?
9. Is non-zero curvature an explanation?

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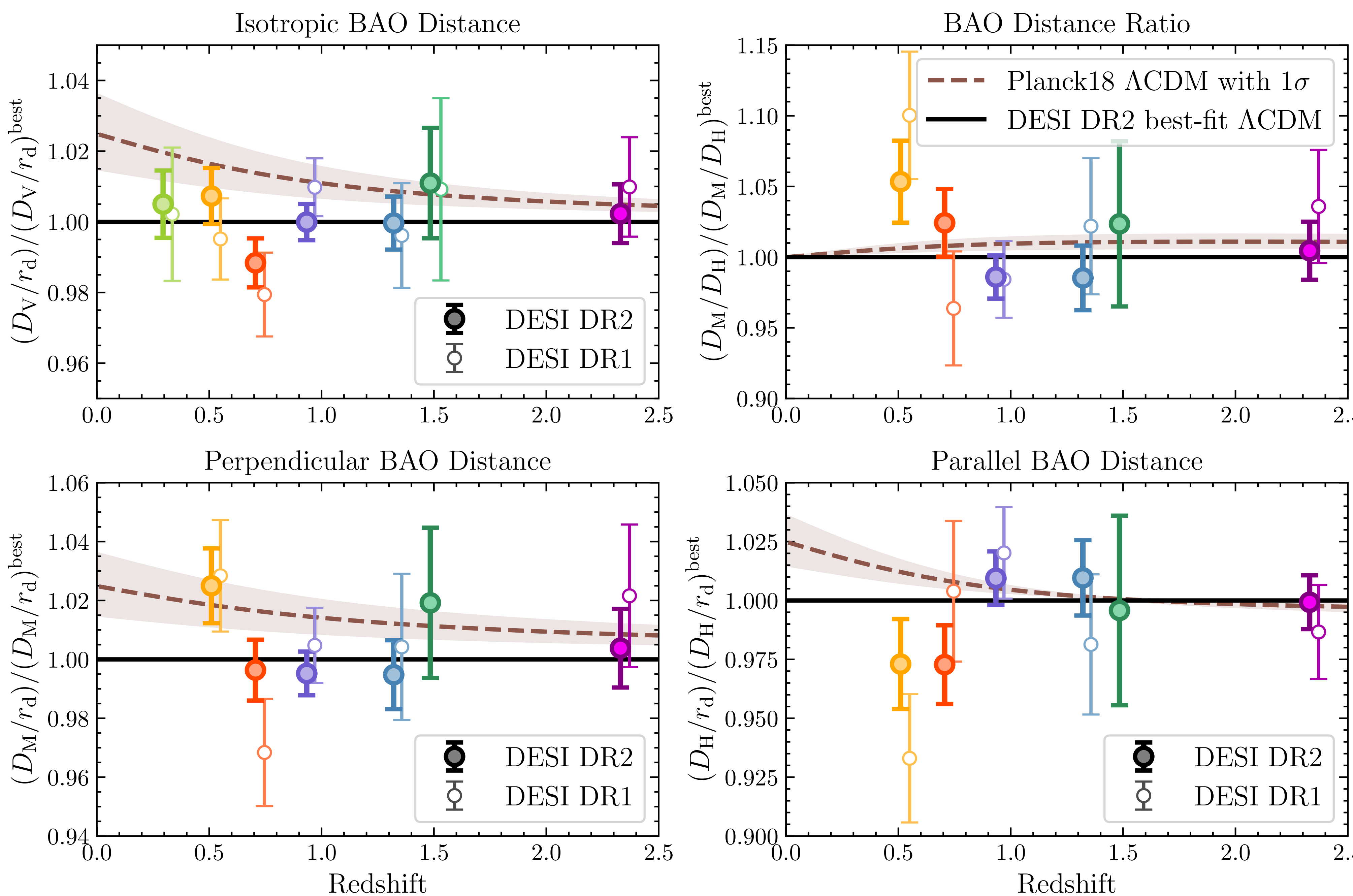
Q: BAO outliers/tensions with SDSS?

A: **No evidence** of unusual outliers; discrepancy between DESI and SDSS at $z = 0.71$ has **decreased** (~1.5 to 2.5σ) in DR2



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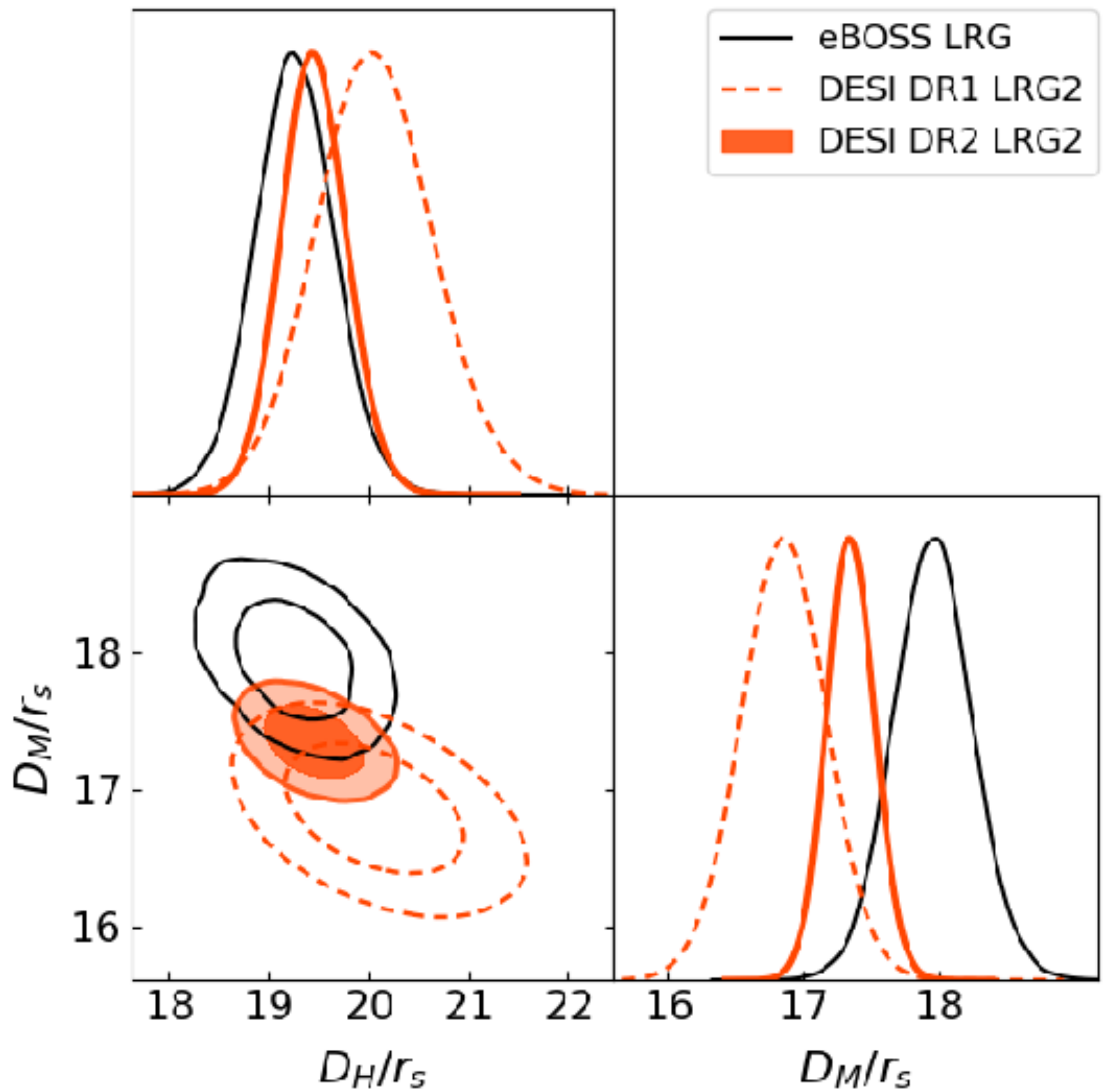

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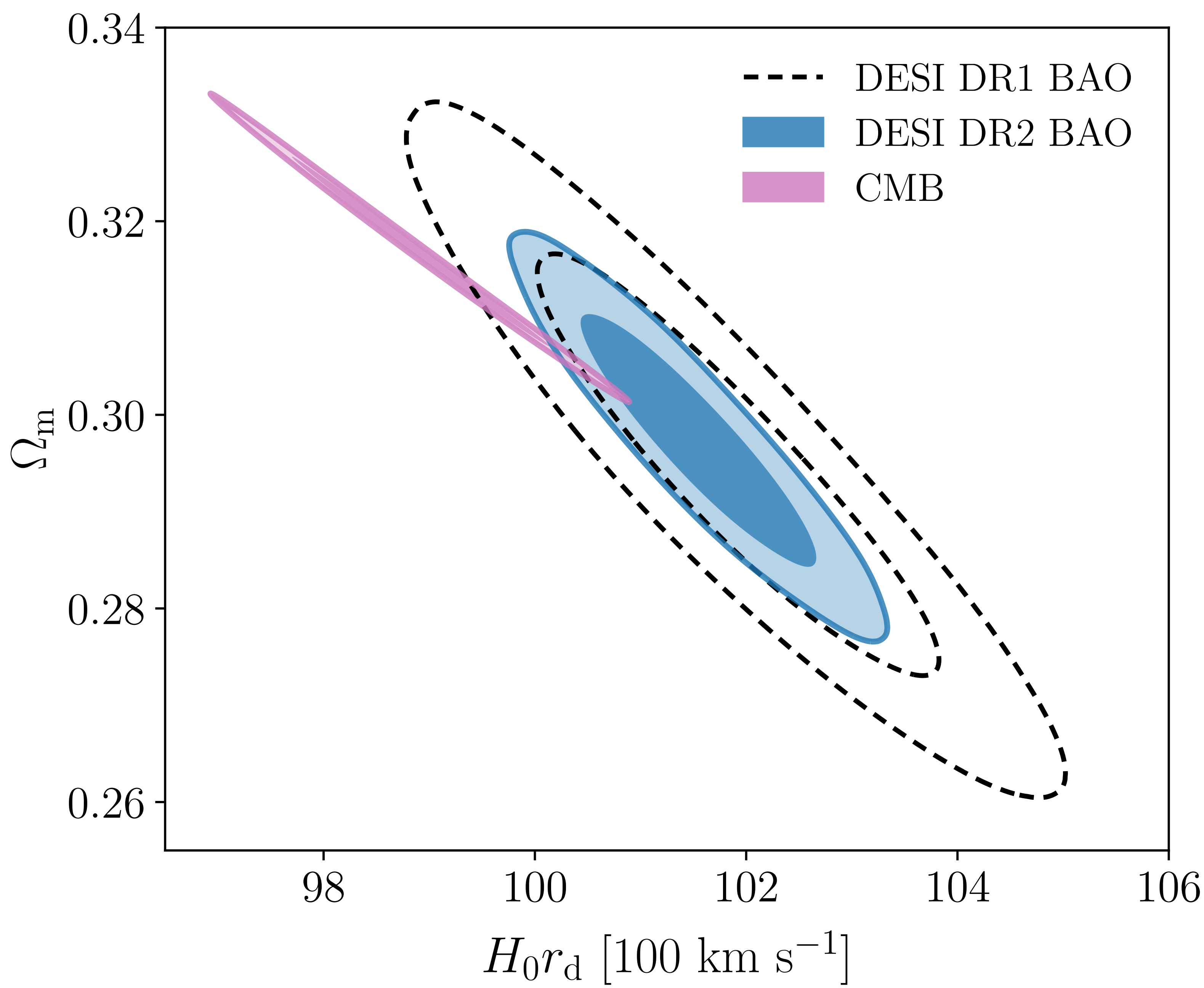
Q: Is DR2 closer to Planck than DR1??

A: Judge for yourself!

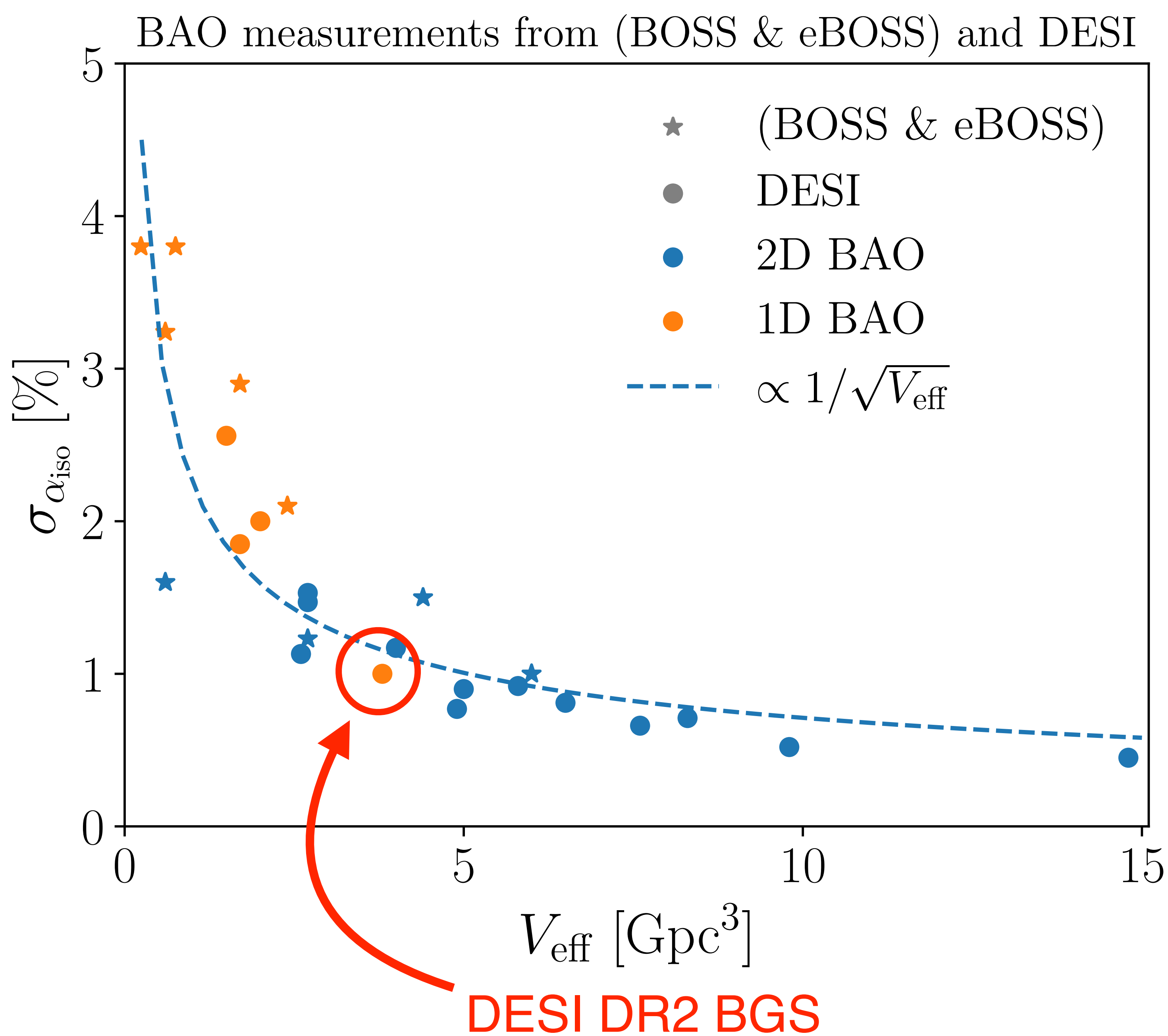


Q: Why only 1D BAO for BGS?

A: We made a **conservative** decision before unblinding

Factors considered:

- Blinded posterior for $\alpha_{\rm AP}$ suggested possible non-Gaussianity
- $\sim 5\,\%$ precision on $\alpha_{\rm AP}$ at BGS redshift adds very little cosmological information anyway
- Wanted to avoid any changes after unblinding



Q: Are BAO and SN in conflict?

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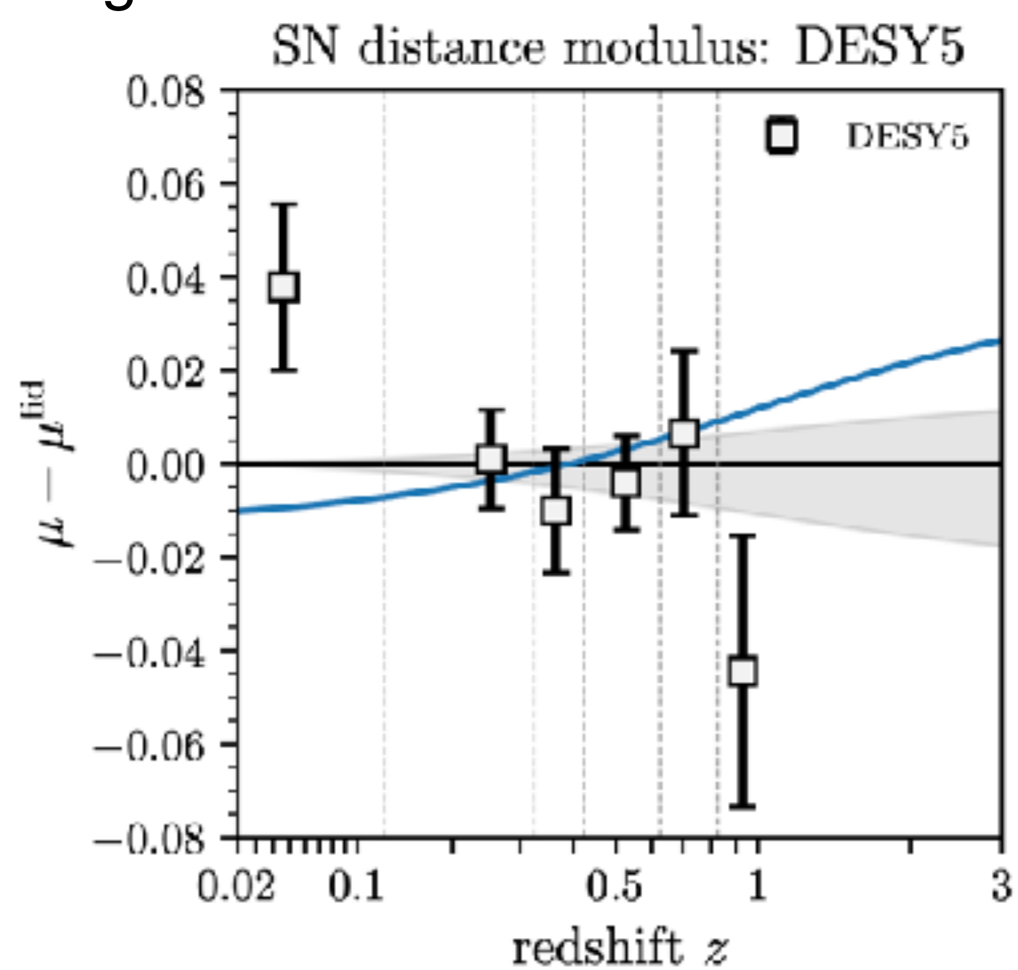
A: **No**, in the overlapping redshift range they are very consistent!

From the paper:

pernovae. For supernovae at $z > 0.1$, which partially overlap the redshift range of DESI, the ΛCDM model that best fits the DESI data is also a good fit to the SNe data. Relative to models that best fit each of the DESY5, Union3 and Pantheon+ SNe samples alone, over the full redshift range, the DESI best-fit model gives only small shifts in the quality of the fit to the SNe data, with $\Delta\chi^2 = -1.2$, 1.5 and 2.3 respectively. Unfortunately, no

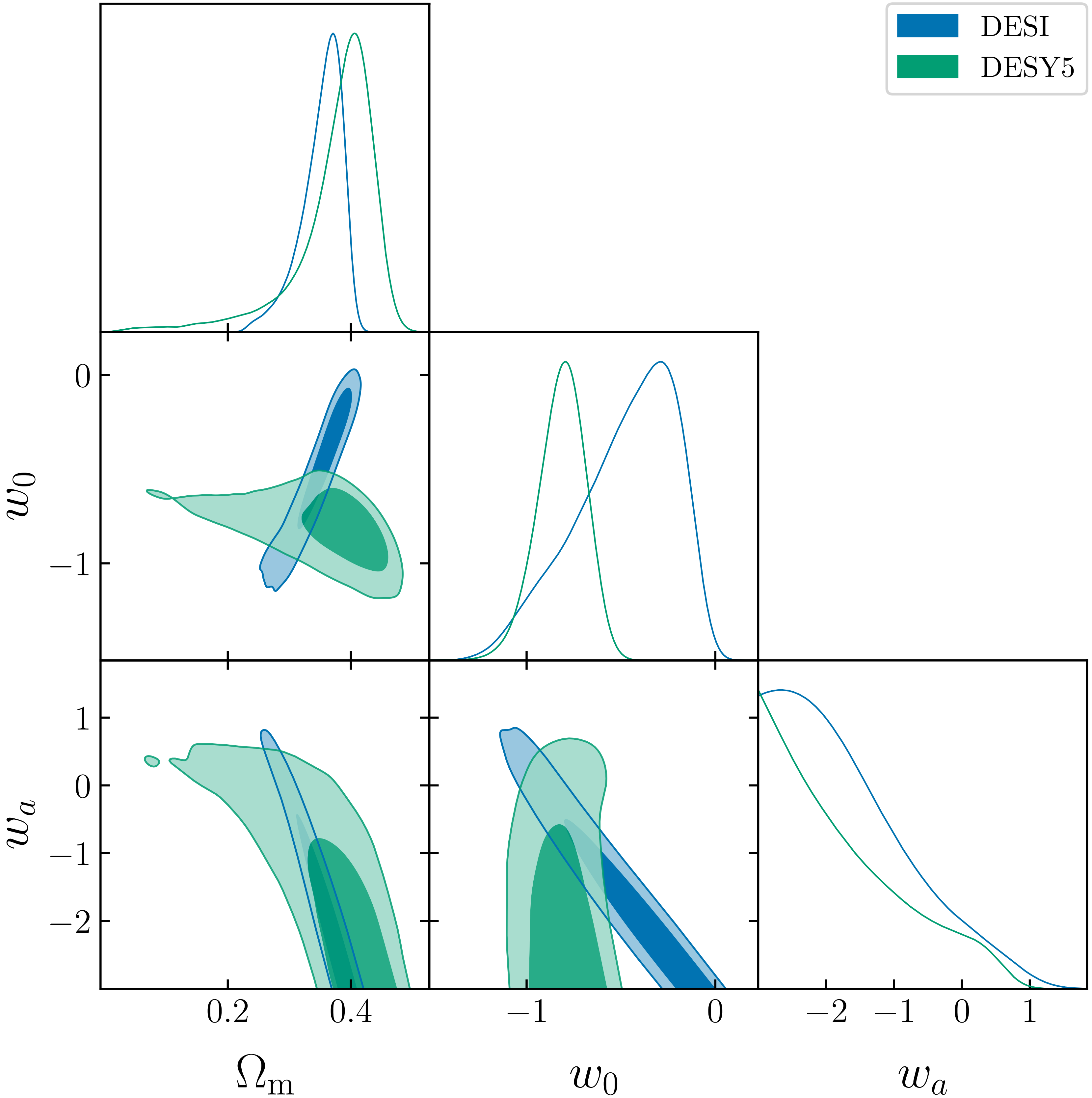
E.g.



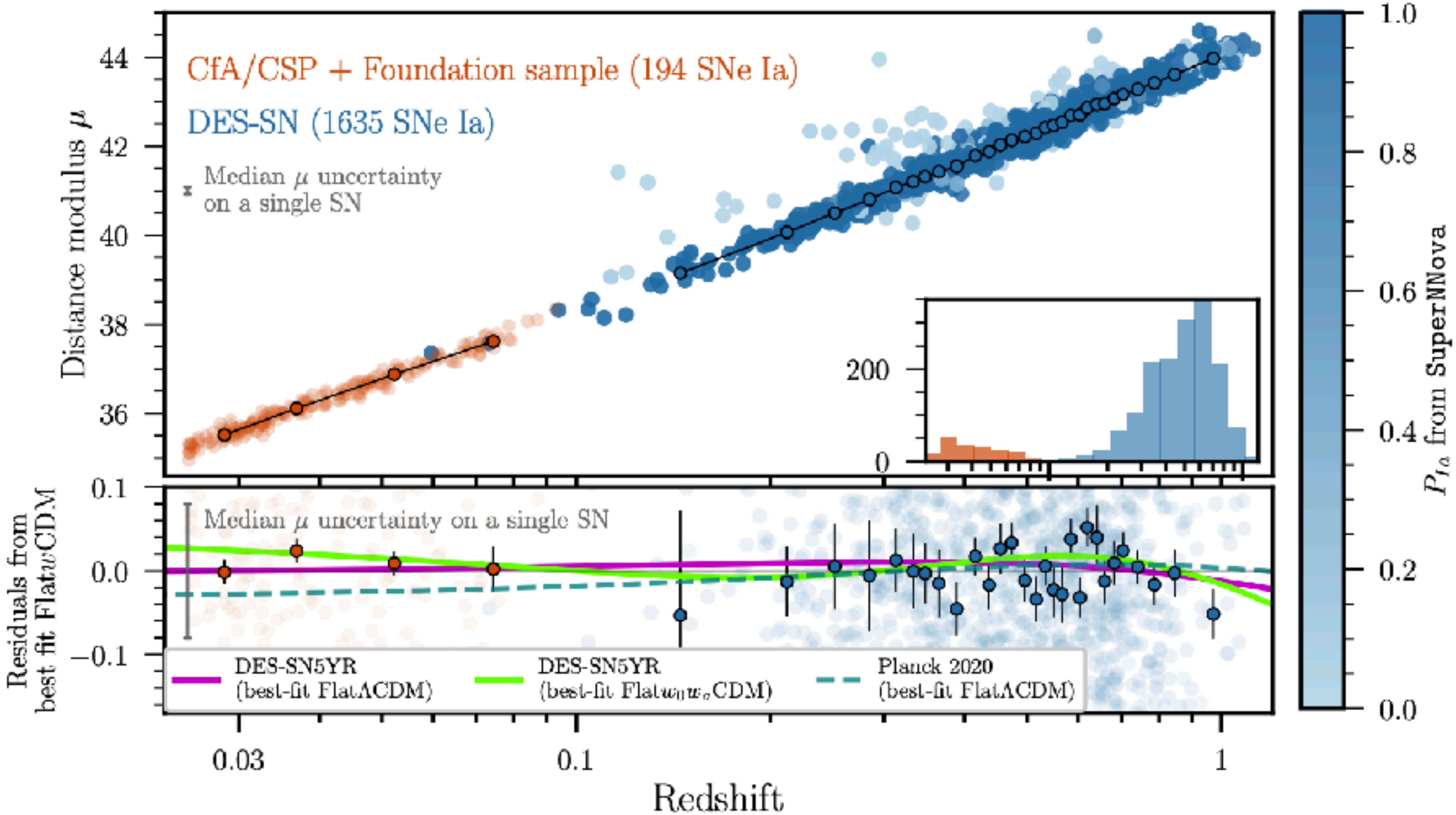
Note: Some mistaken claims in the literature come because they compare *calibrated* SN (using SH0ES H_0) to *calibrated* BAO (using Planck H_0) – this is just the Hubble tension again.

Q: Are BAO and SN in conflict?

A: In ΛCDM, parameter constraints (on Ω_m) from BAO and SN are in tension; but in $w_0 w_a$CDM they are **consistent with each other**



Q: How important are low-z SN?

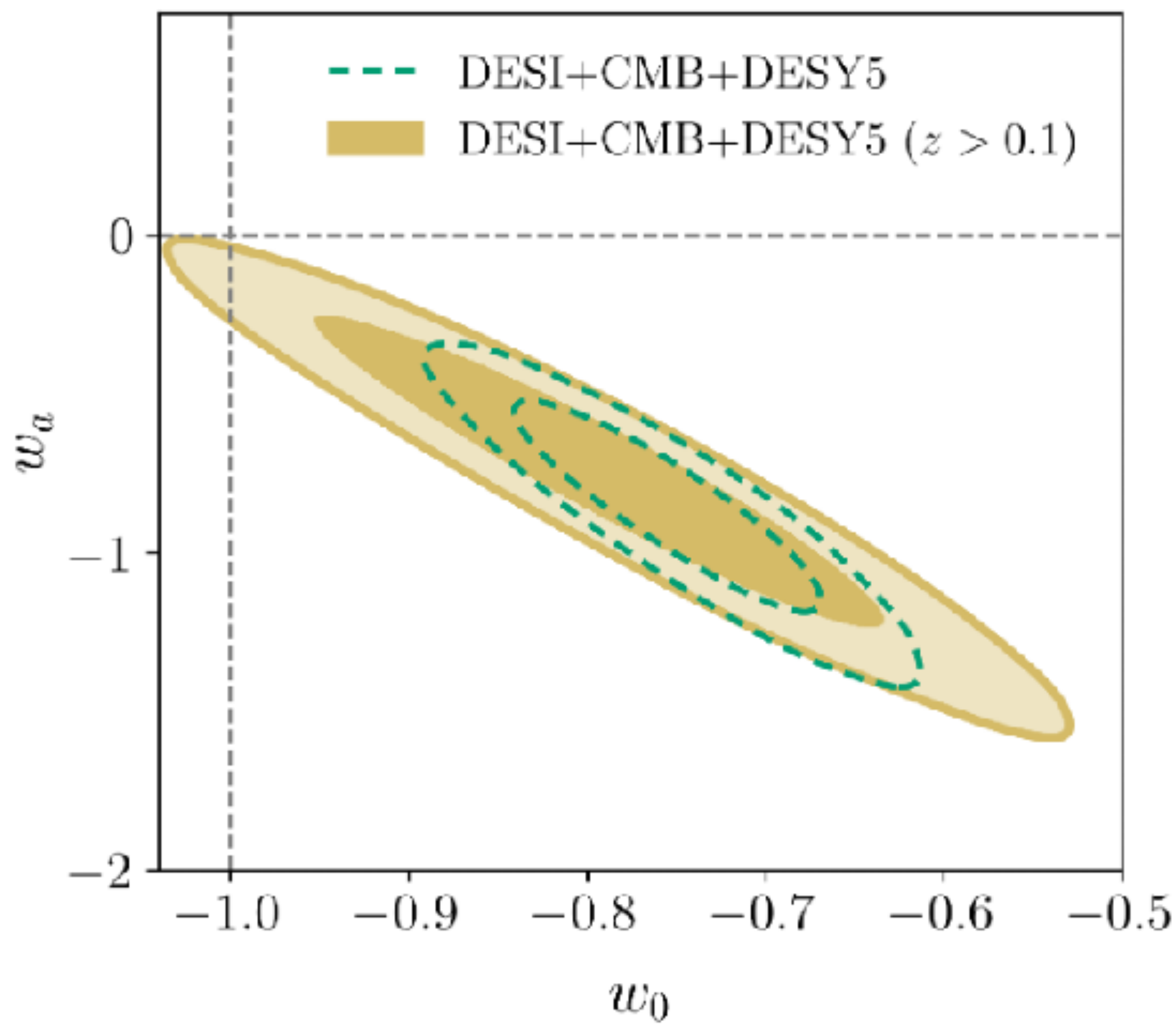


Q: How important are low-z SN?

Without the low-z SN, constraints are much weaker. But central value doesn't really shift.

Another view: DESY5 and Pantheon+ do differ in low-z treatment.

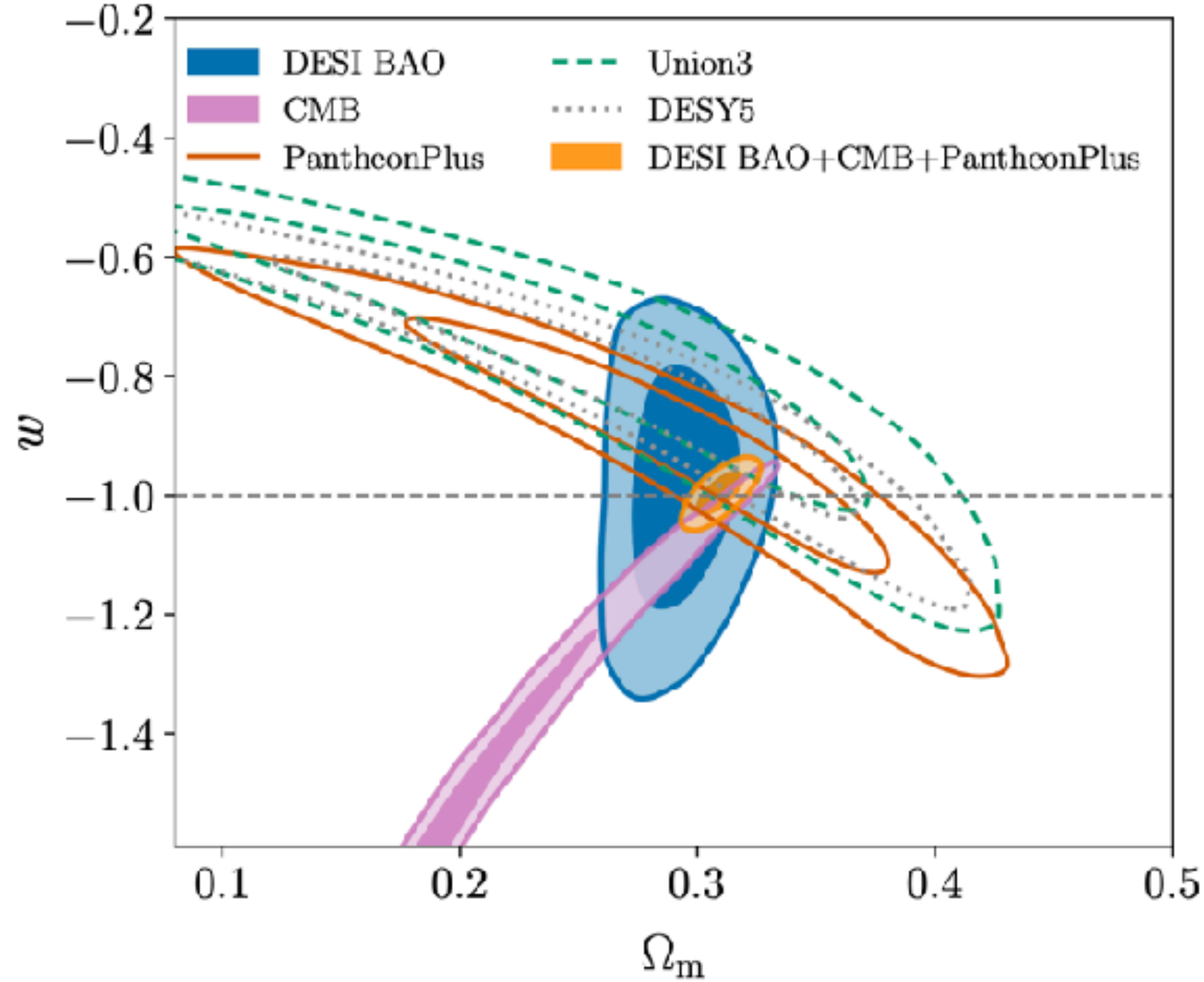
3rd view: DESI + CMB with no SN is $\sim 3.1\sigma$ away from ΛCDM



Q: Why $w = -1$ in fixed wCDM?

Related Q: Why is $w(z) \simeq -1$ at the pivot redshift?

A #1: wCDM gives a (poor) compromise b/w high-z CMB and low-z SNe



Q: Why $w = -1$ in fixed wCDM?

Related Q: Why do you find $w(z) \simeq -1$ at the pivot redshift?

https://arxiv.org/pdf/0708.0024.pdf

The Mirage of $w = -1$

Eric V. Linder
Berkeley Lab, University of California, Berkeley, CA 94720, USA

A #2: This was answered in 2007!

Thus a high redshift distance measurement consistent with LCDM virtually forces (within the picture so far) the value $w(z \approx 0.4) = -1$, irrespective of true time variation. However, low redshift measurements insufficiently sensitive to time variation measure only an averaged EOS that corresponds strongly to the value at a sweet spot or "pivot" redshift with the pivot near $z \approx 0.4$. That is,

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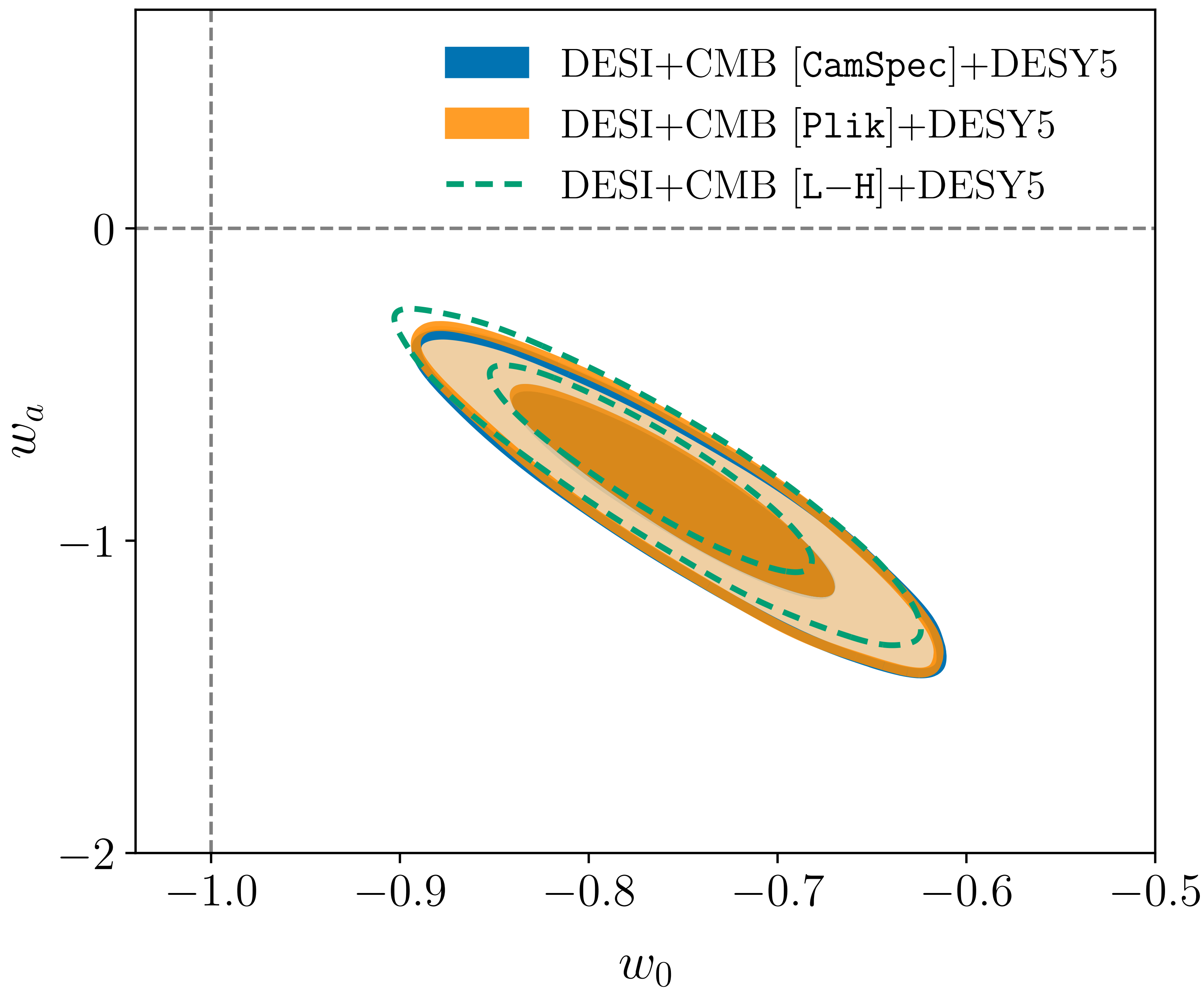
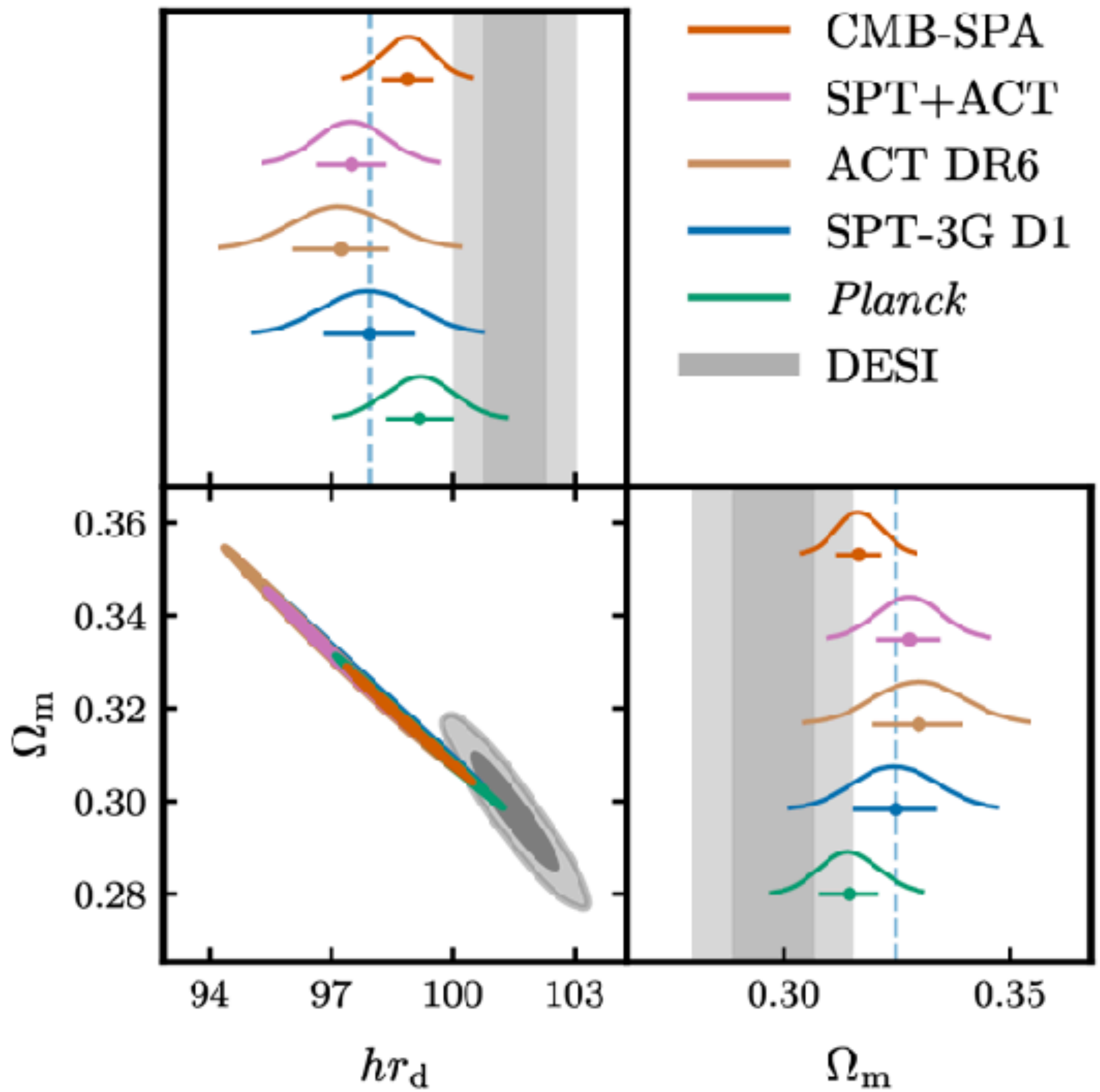
Q: Does it matter which CMB likelihood?

A: **Not important for DE:**



Q: Possible systematic errors in CMB?



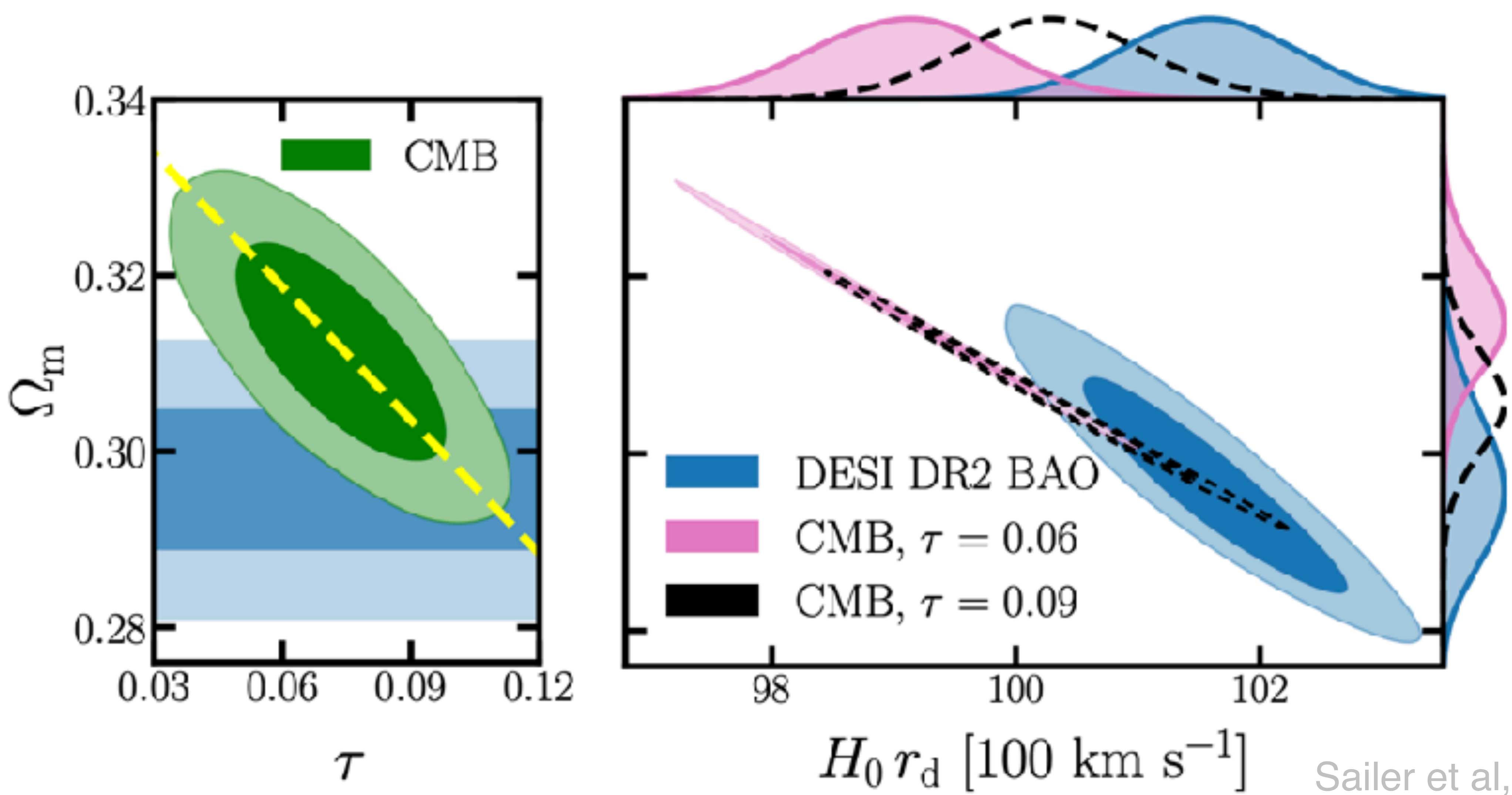
Perhaps the Planck value of Ω_m (or $\Omega_m h^2$) is slightly off?

But recent ACT and SPT results confirm Planck and in fact *increase* the tension with DESI in ΛCDM (now $\sim 2.8\sigma$ for CMB-SPA)

Camphuis et al, 2506.20707

Q: Possible systematic errors in CMB?

Another possibility: perhaps the optical depth τ is much higher than believed? 0.09 vs 0.06 – this would need a $\sim$4-5σ shift, still doesn't work well with SN



Sailer et al, 2504.16932

Q: Is curvature a possible explanation?

Dinda & Maartens and Chen & Zaldarriaga suggest non-zero curvature can resolve BAO vs CMB tension instead of evolving DE

But not strongly favoured (only $\sim 2\sigma$ preference for curvature over ΛCDM from DESI+CMB alone) and in any case **cannot fit the SN data**