BREAKING THE "DISTANCE DUALITY RELATION" TO EXPLAIN THE HUBBLE TENSION

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Based on work with:
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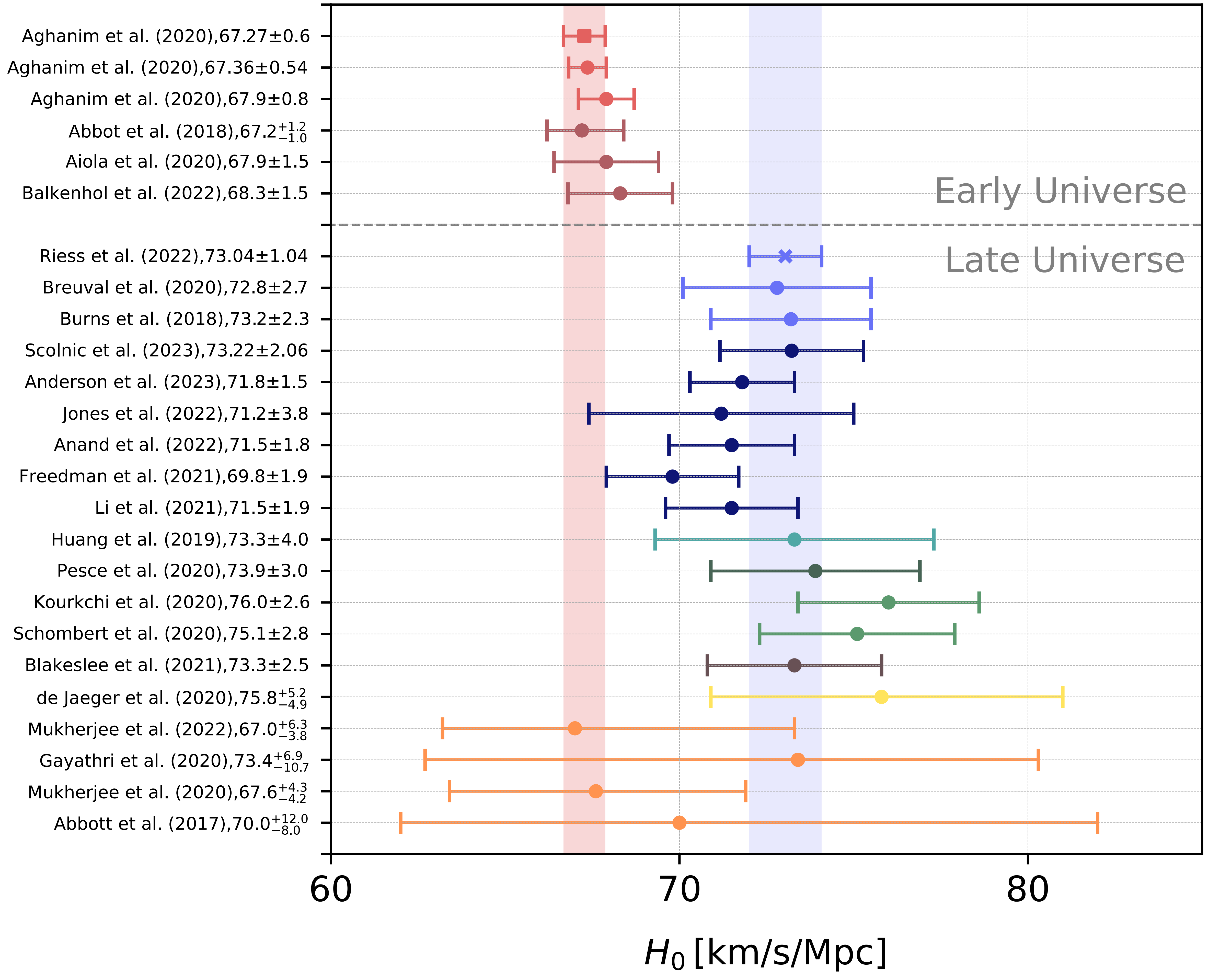
Illustrations: Inês Viegas Oliveira (ivoliveira.com)

The "Hubble Tension"

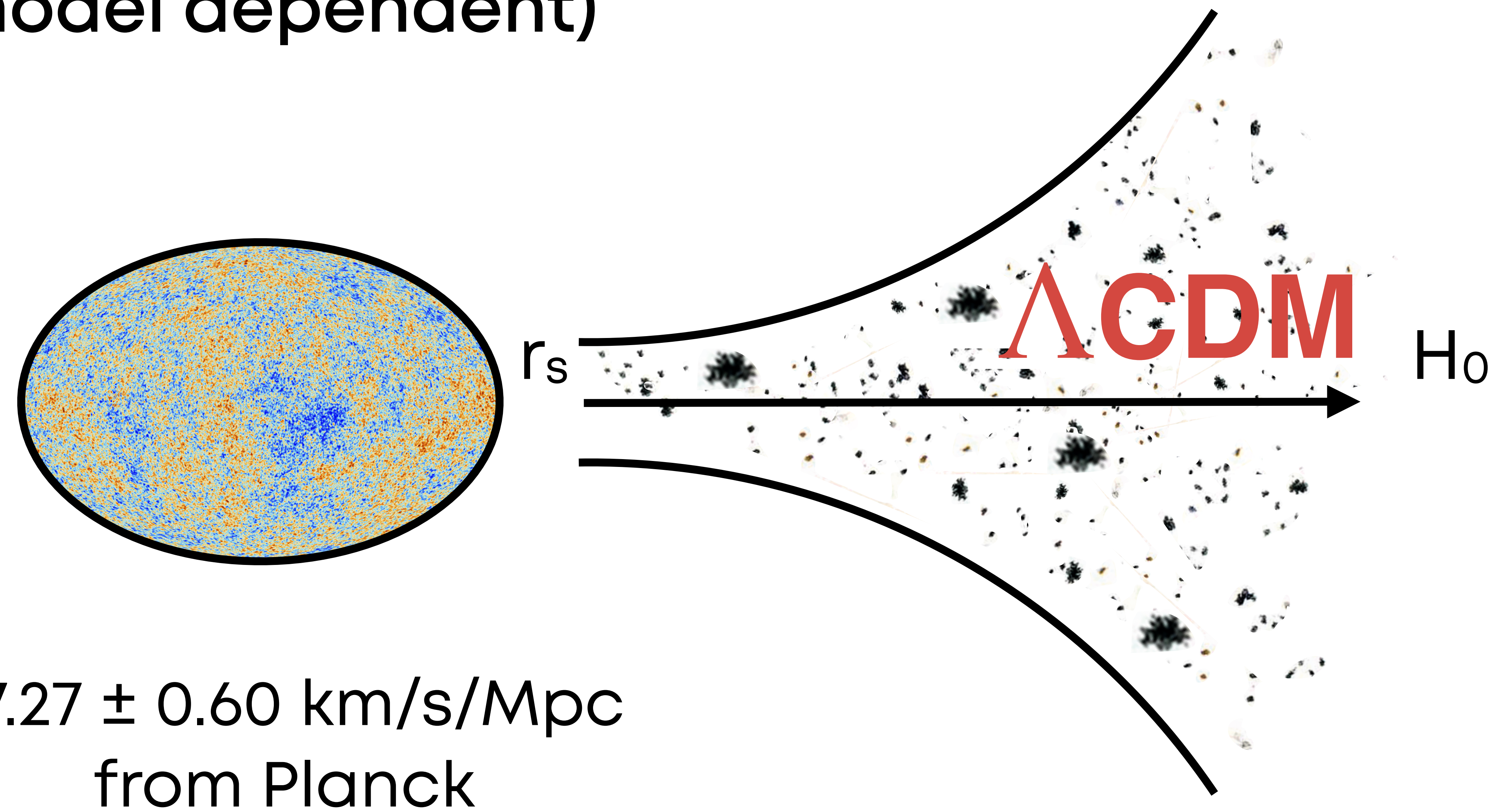
Unreconcilable values for H_0 from the CMB and from direct local distance ladder measurements

- 4.4σ tension between Planck 2018 and SH0ES:
  - CMB (Planck): $H_0 = 67.27 \pm 0.60$ km/s/Mpc
  - SNe (R22): $H_0 = 73.04 \pm 1.04$ km/s/Mpc
- The CMB data assumes the ΛCDM model
- DESI BAO (+BBN+CMB): $H_0 = 68.52 \pm 0.62$ km/s/Mpc [DESI Collaboration 2024]
- Compilation of early vs late time data that disagree
- But how do we measure H_0 in each case?

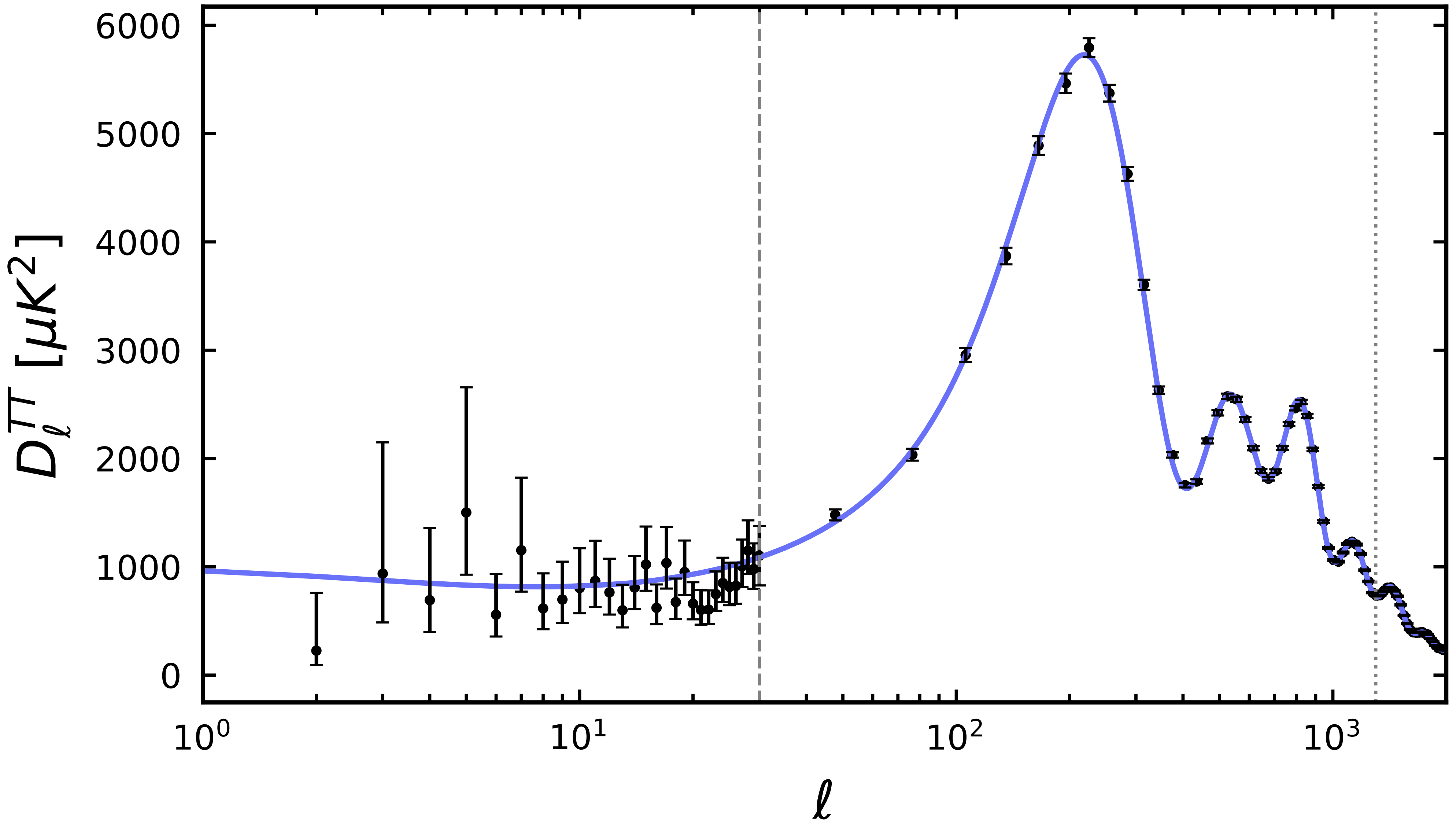


The "Hubble Tension"

CMB
(model dependent)



67.27 ± 0.60 km/s/Mpc
from Planck



[Aghanim et al.: Astron.Astrophys. 641 (2020) A6]

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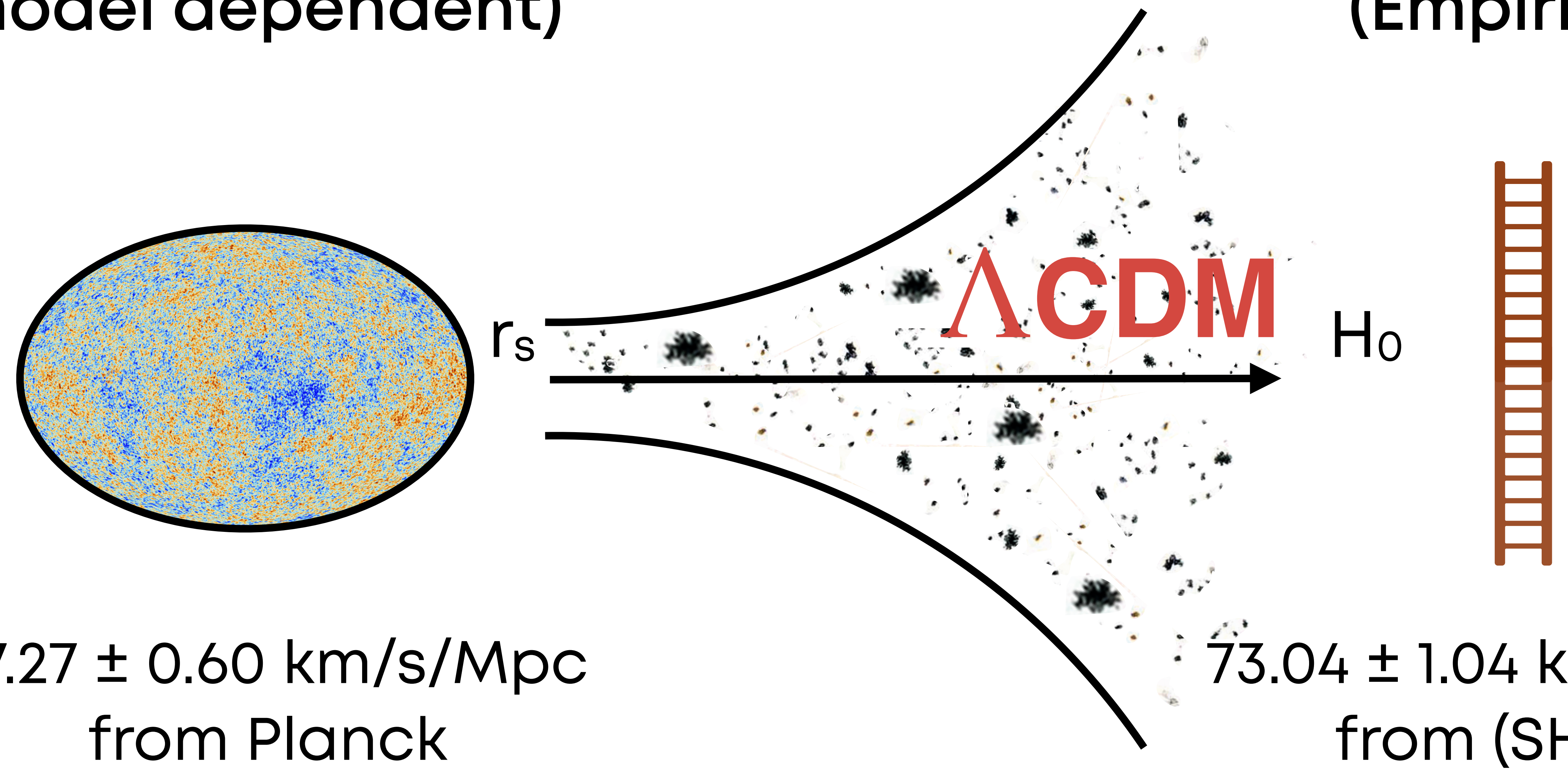
The “Hubble Tension”

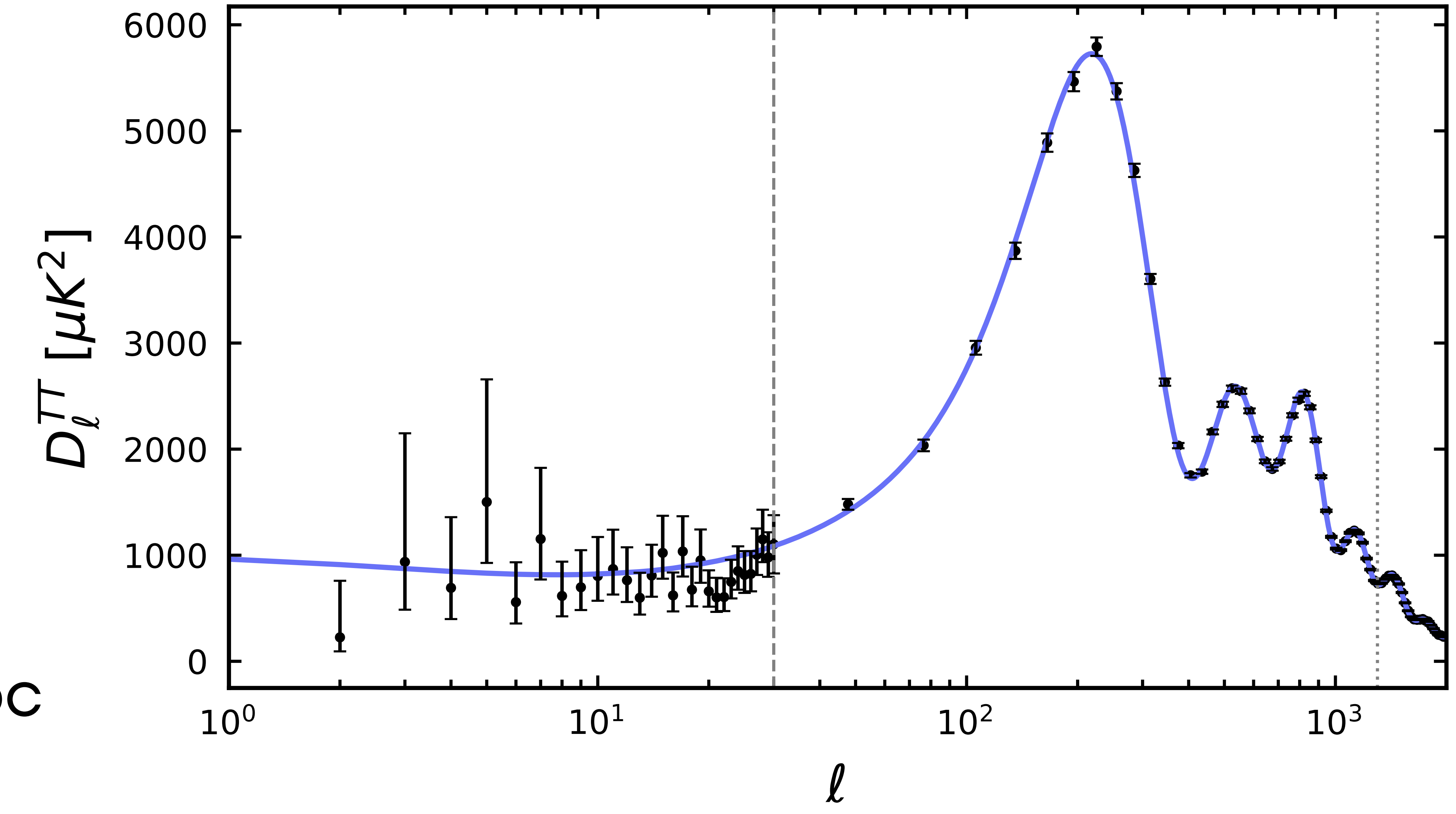
CMB
(model dependent)

Local
(Empirical)



67.27 ± 0.60 km/s/Mpc
from Planck

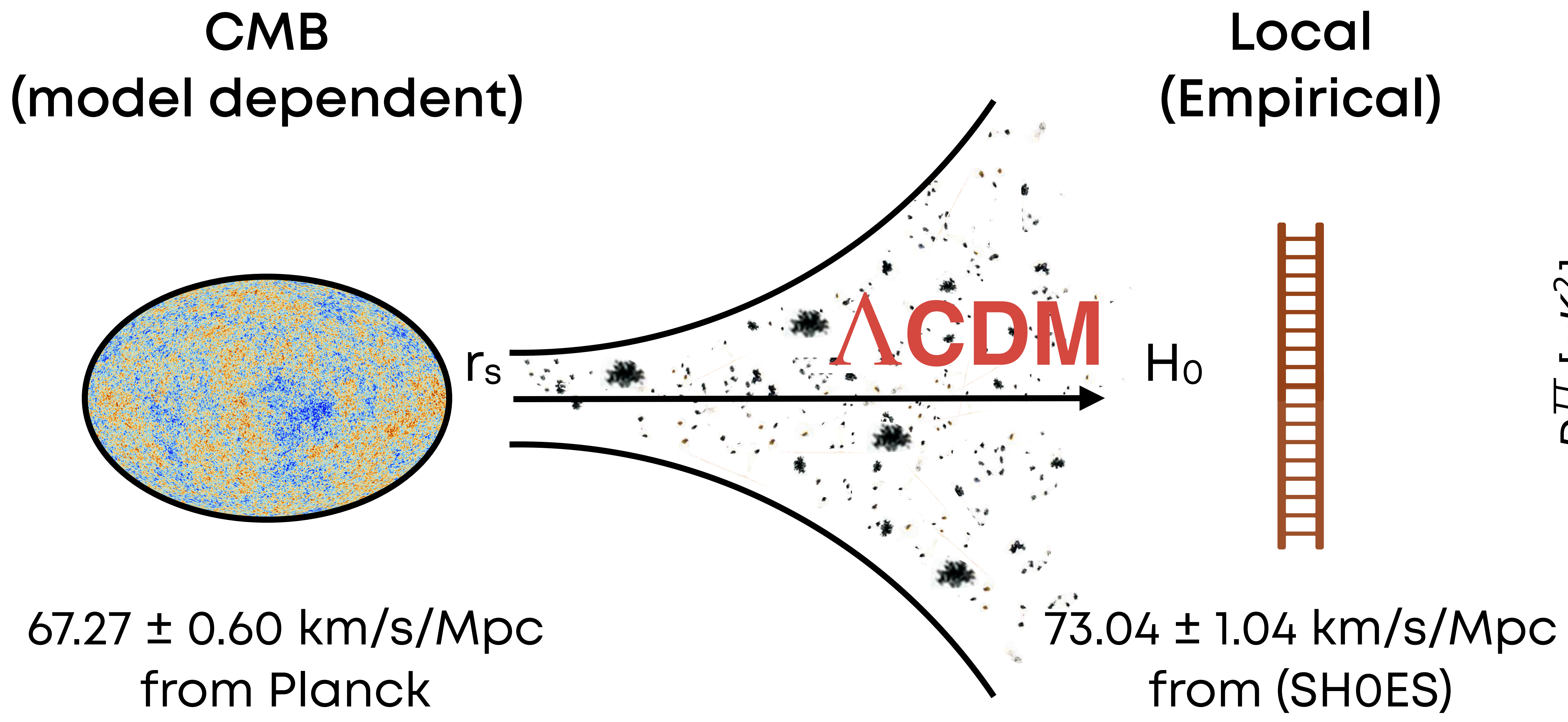
73.04 ± 1.04 km/s/Mpc
from (SH0ES)

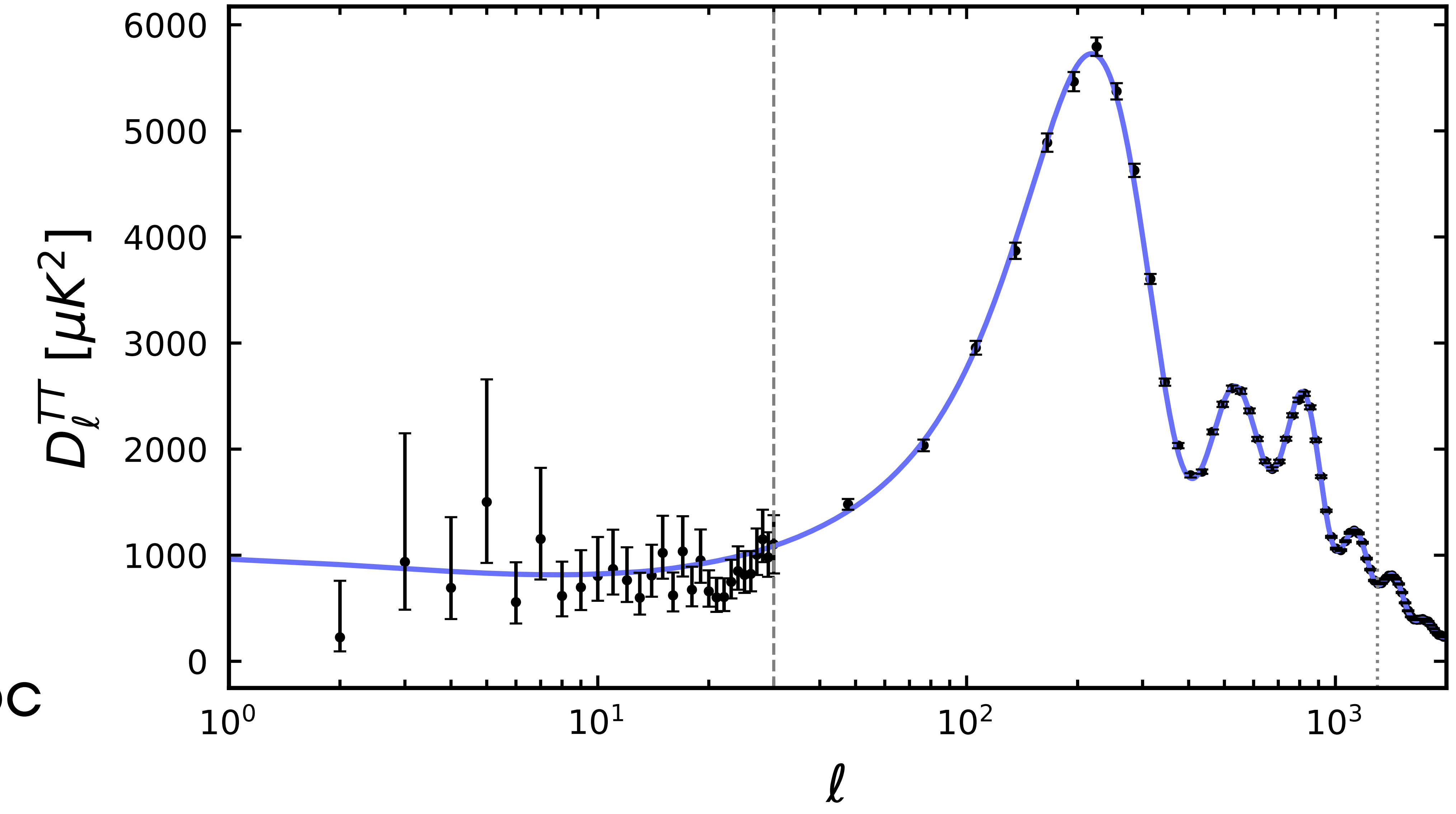


[Aghanim et al.: Astron.Astrophys. 641 (2020) A6]

- Infer H_0 from the cosmological distance ladder
- Based on local distance measurements and astrophysical observables/calibrations

The "Hubble Tension"

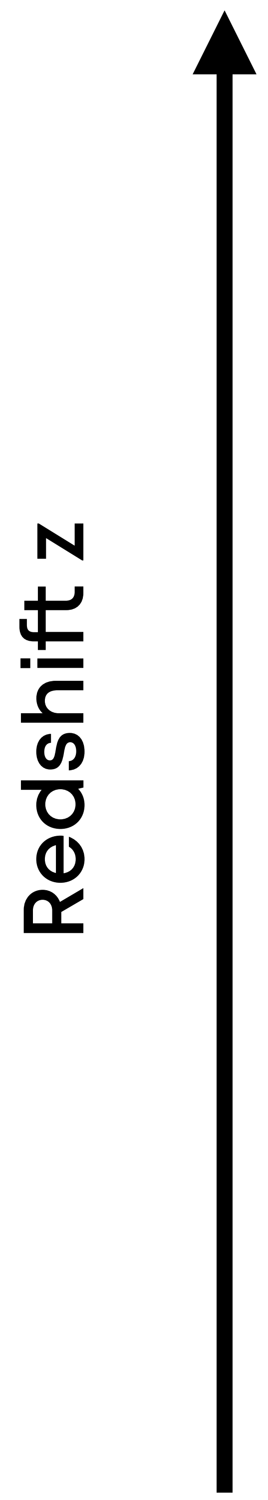




- Infer H_0 from the cosmological distance ladder
- Based on local distance measurements and astrophysical observables/calibrations

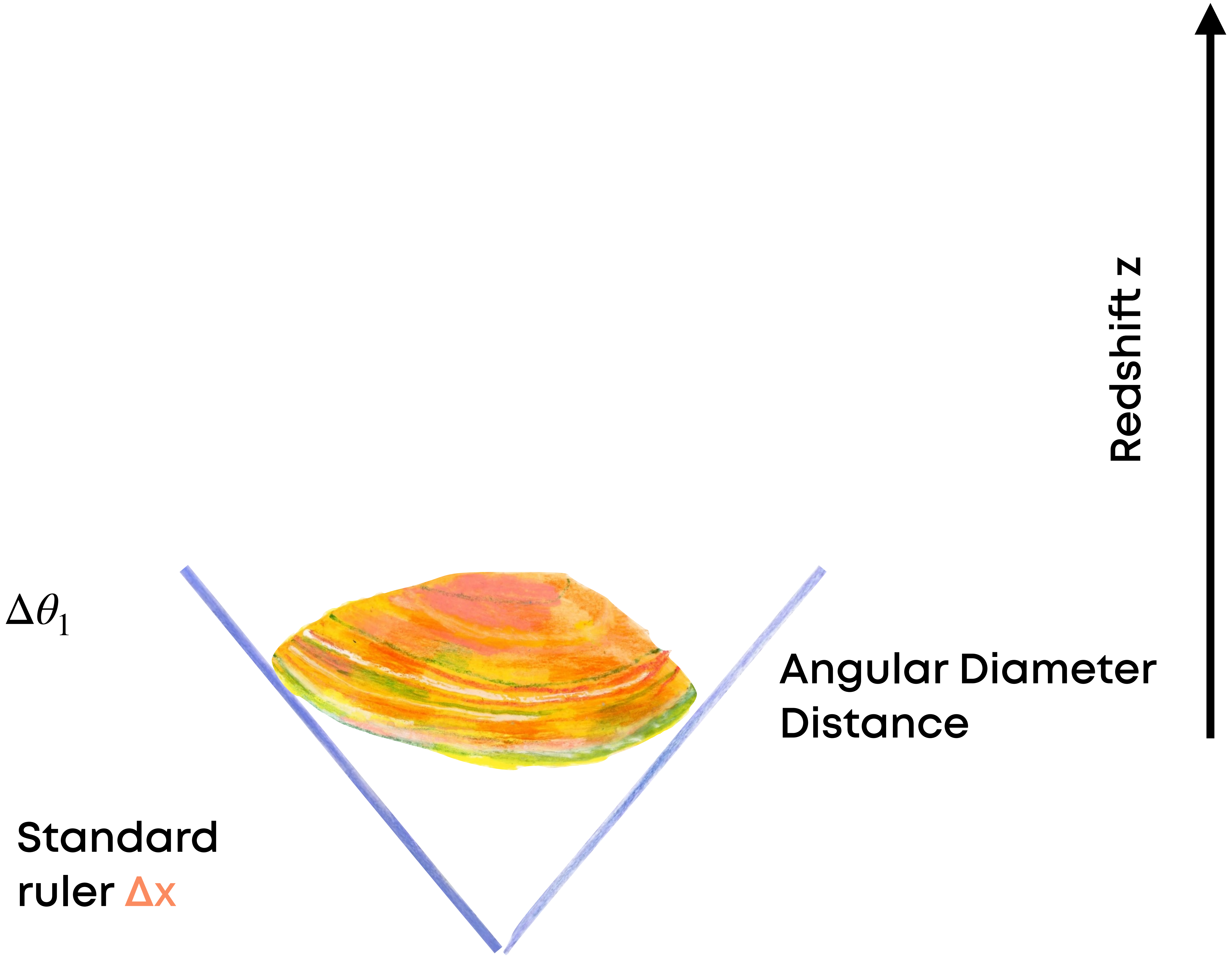
D_A from BAO

D_L from SN1a



D_A from BAO

D_L from SN1a



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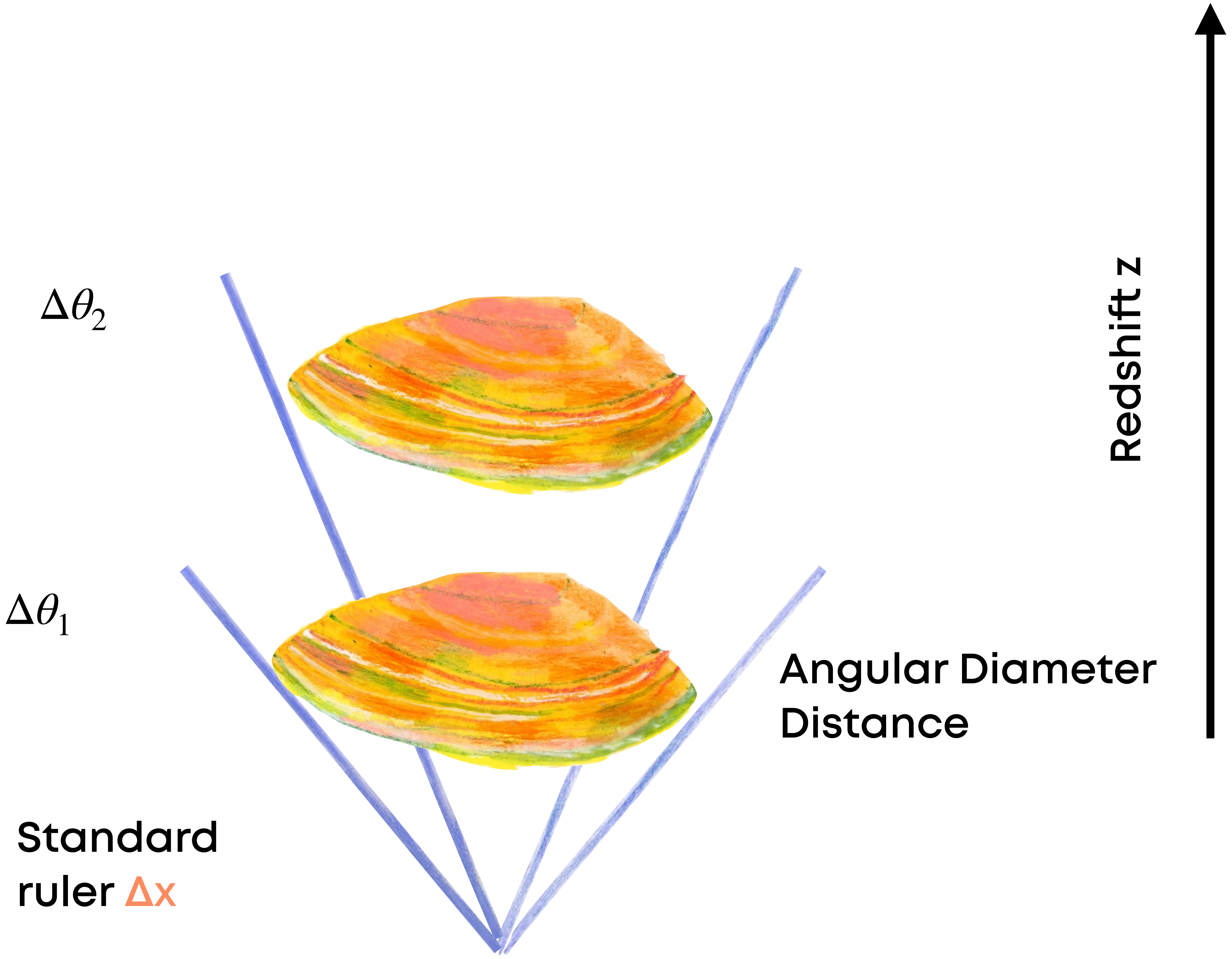

D_A from BAO

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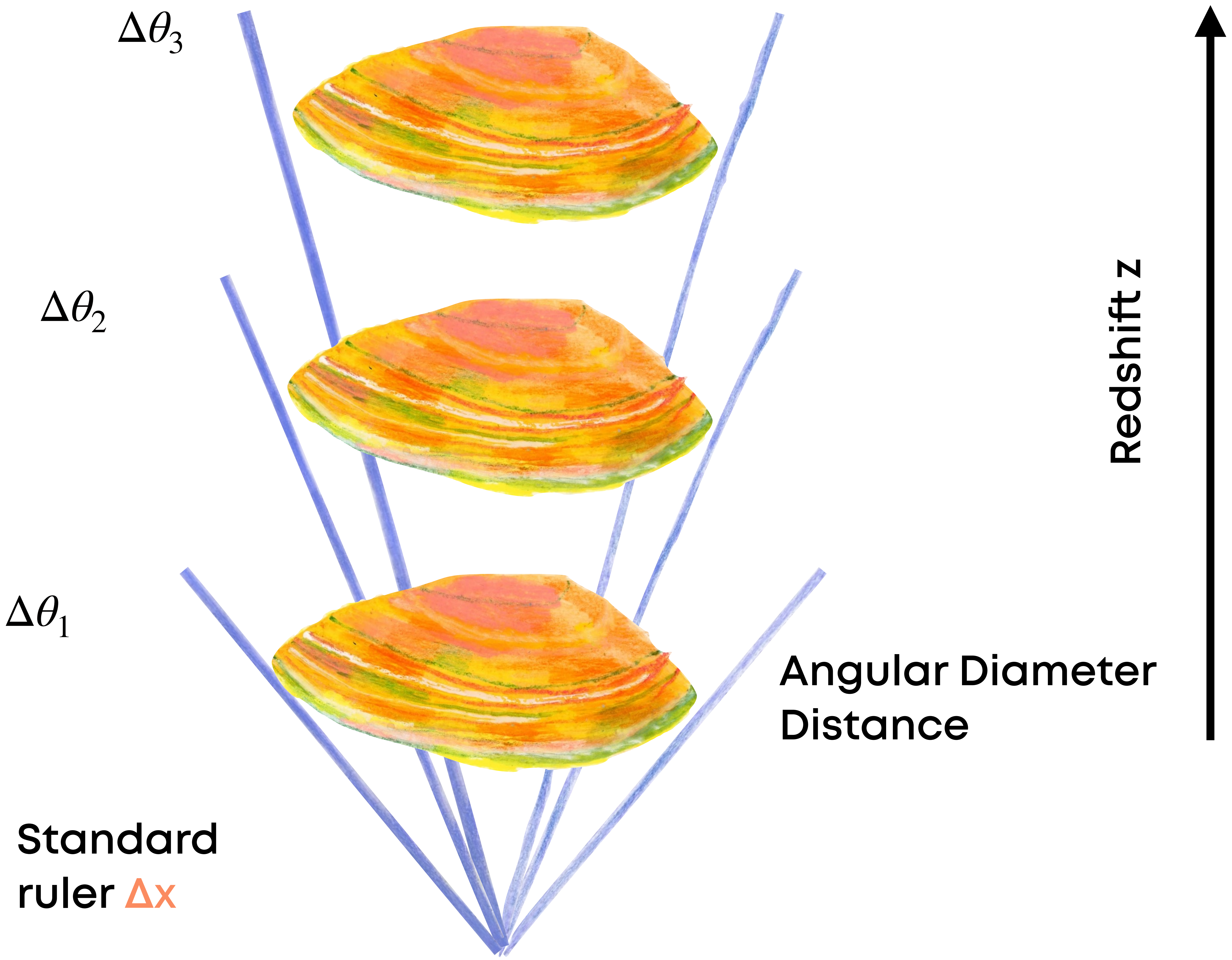


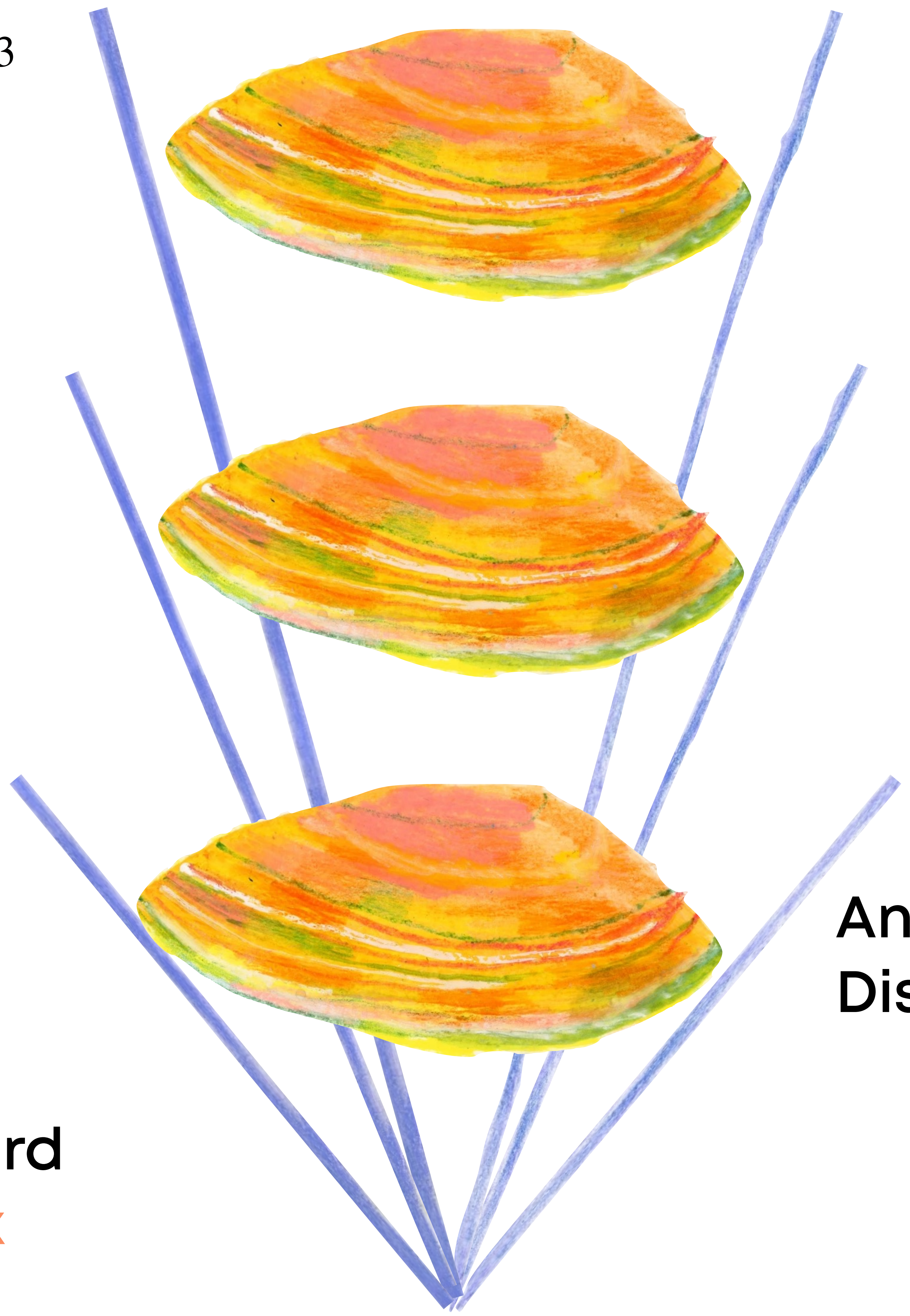
D_A from BAO

D_L from SN1a

$\Delta\theta_3$

$\Delta\theta_2$

$\Delta\theta_1$



Standard ruler Δx

Angular Diameter Distance

Redshift z

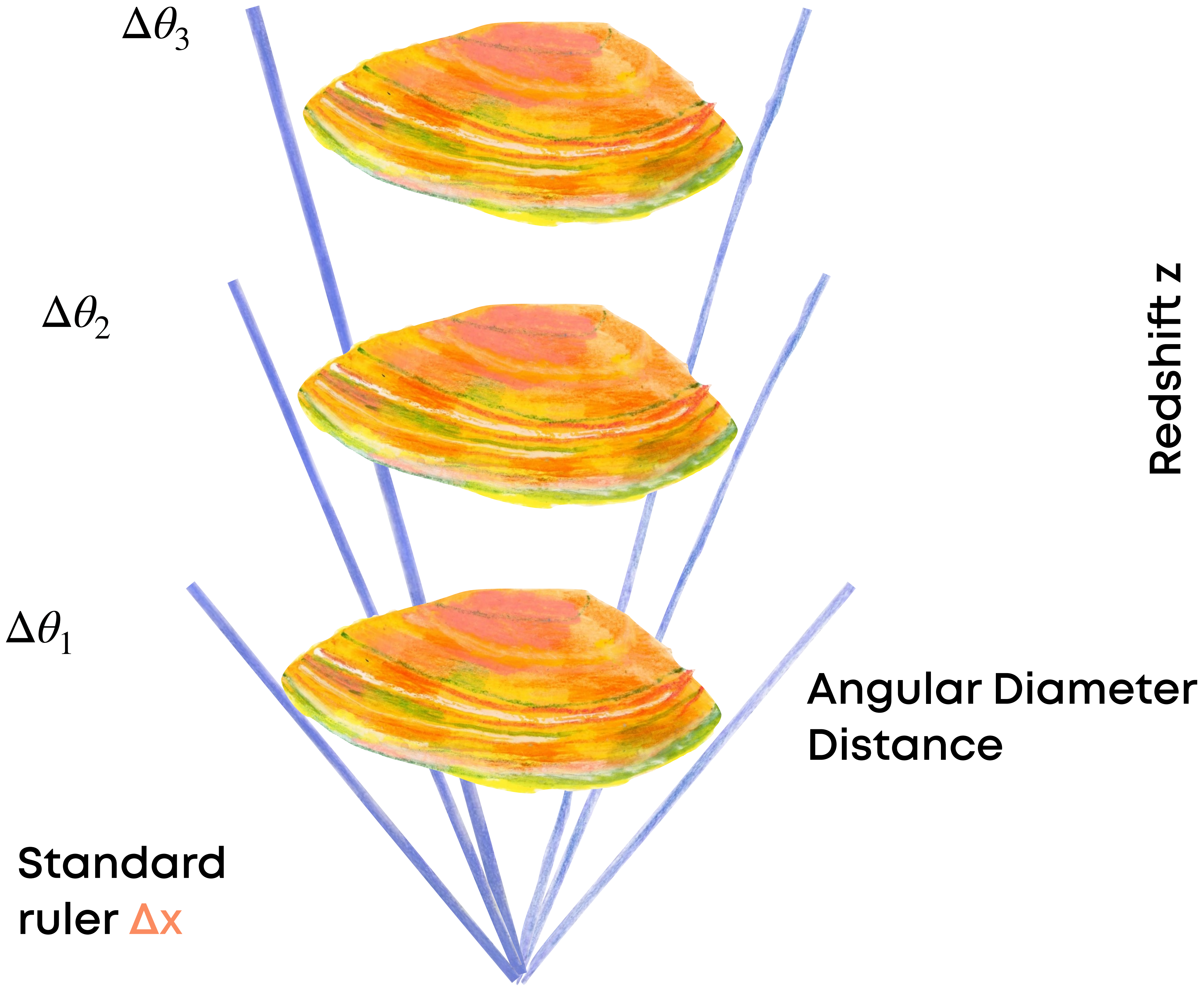
Luminosity Distance

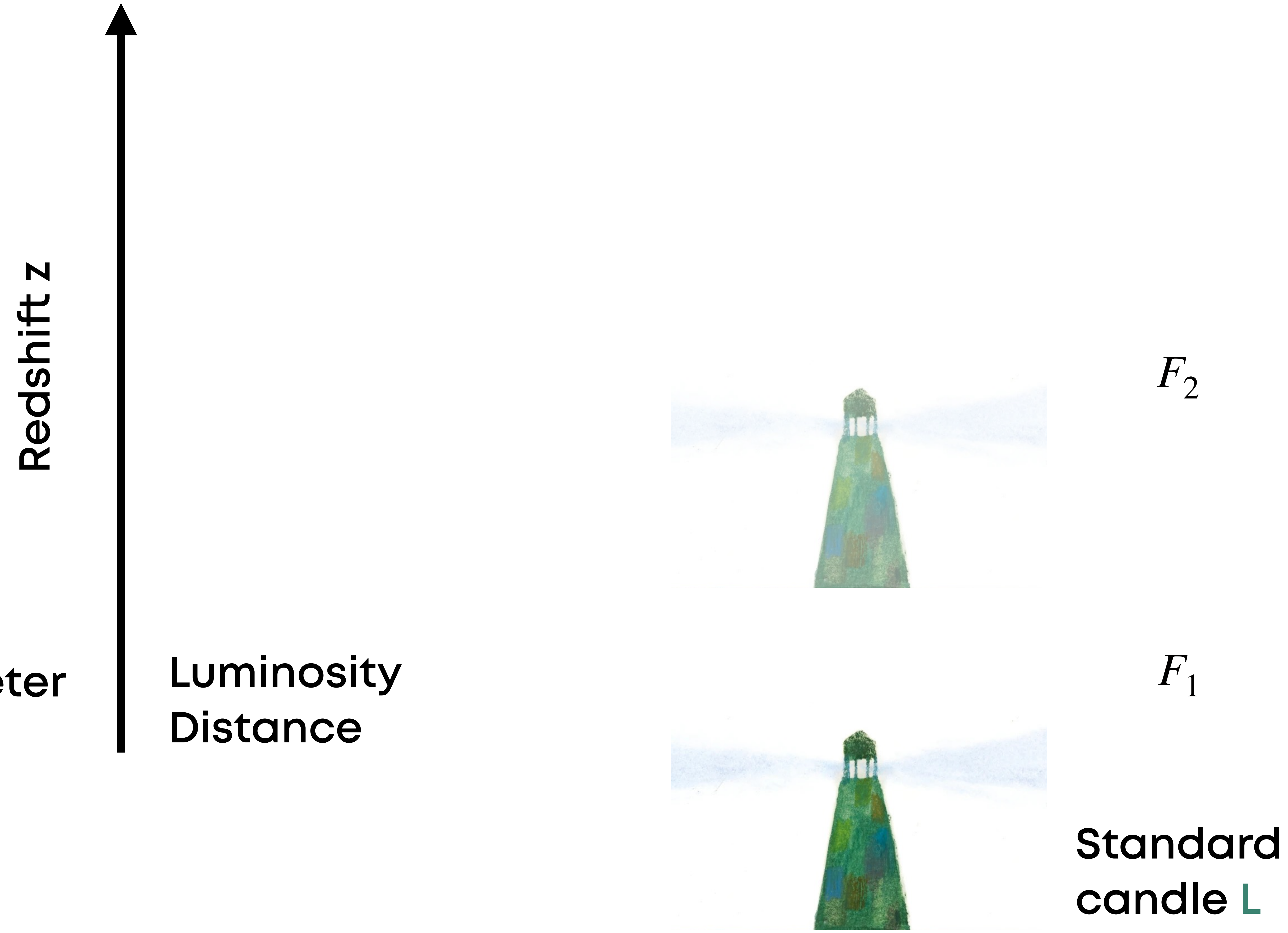
F_1

Standard candle L

D_A from BAO

D_L from SN1a





D_A from BAO

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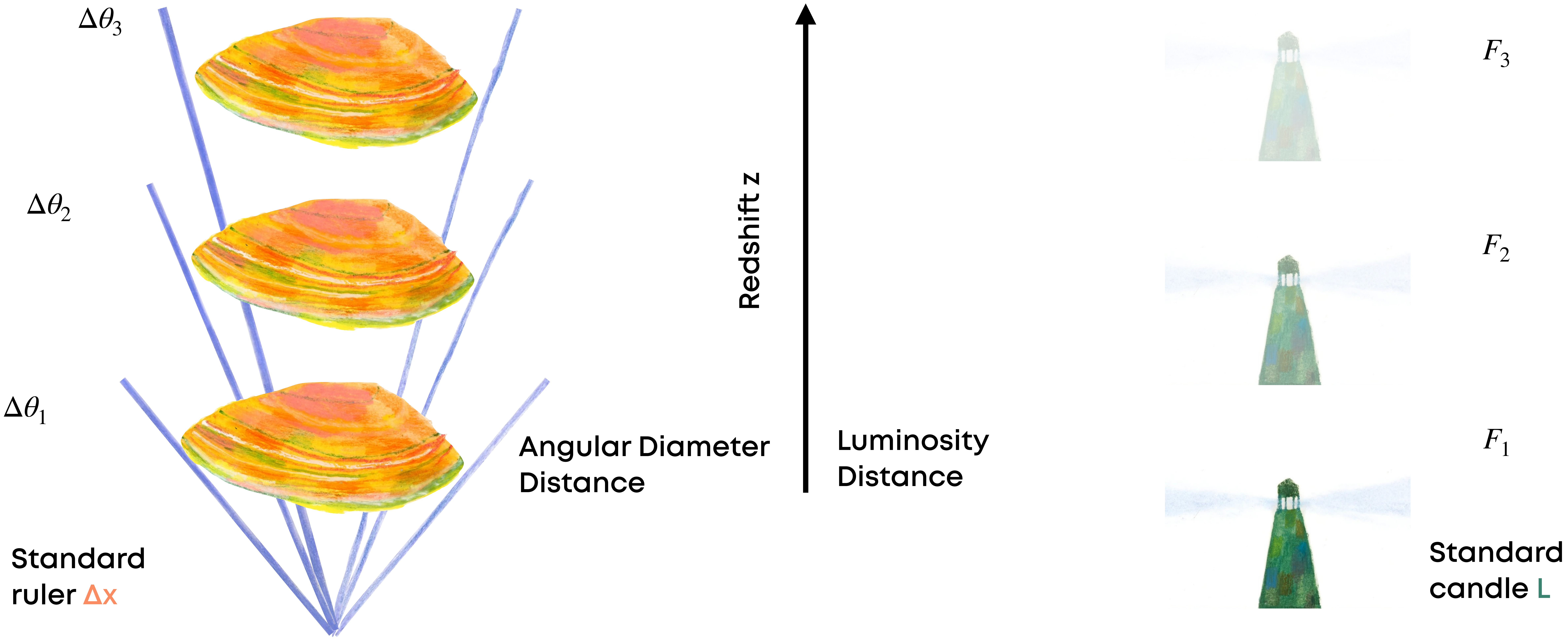
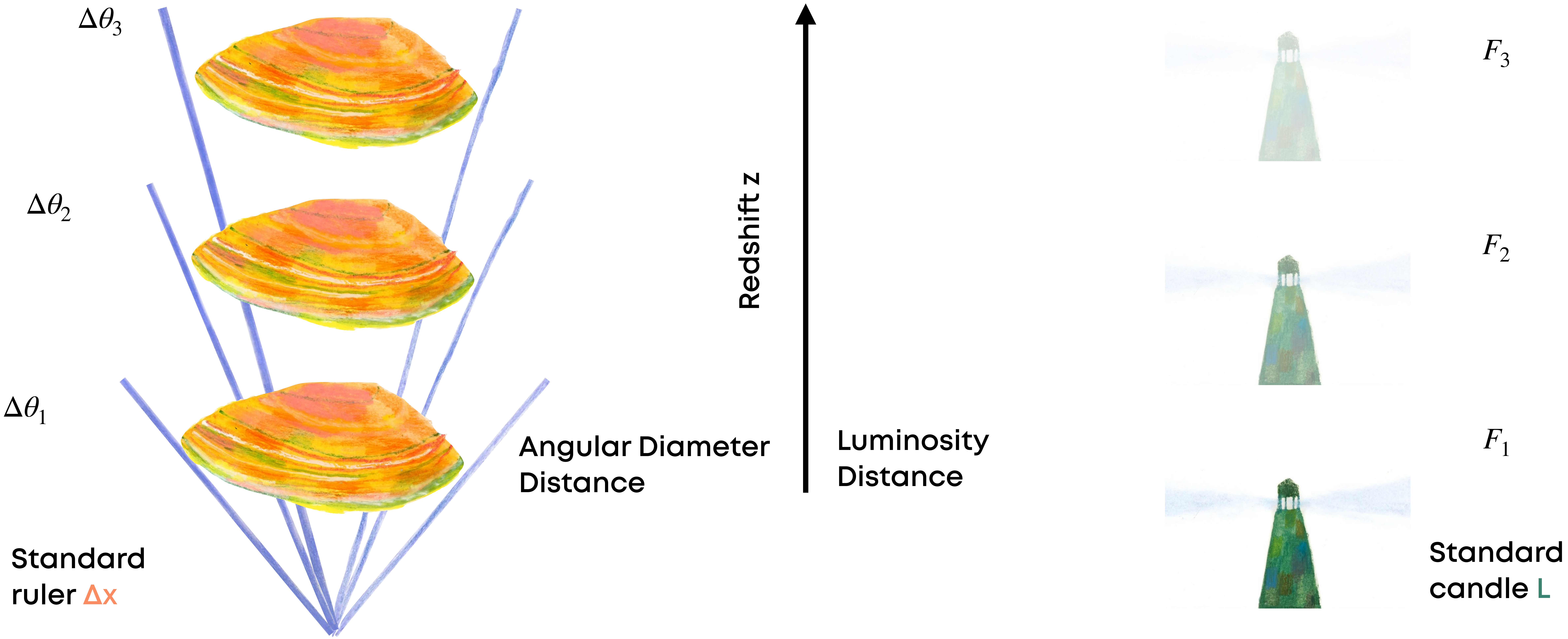


Distance Duality Relation (1933)

D_A from BAO

D_L from SN1a

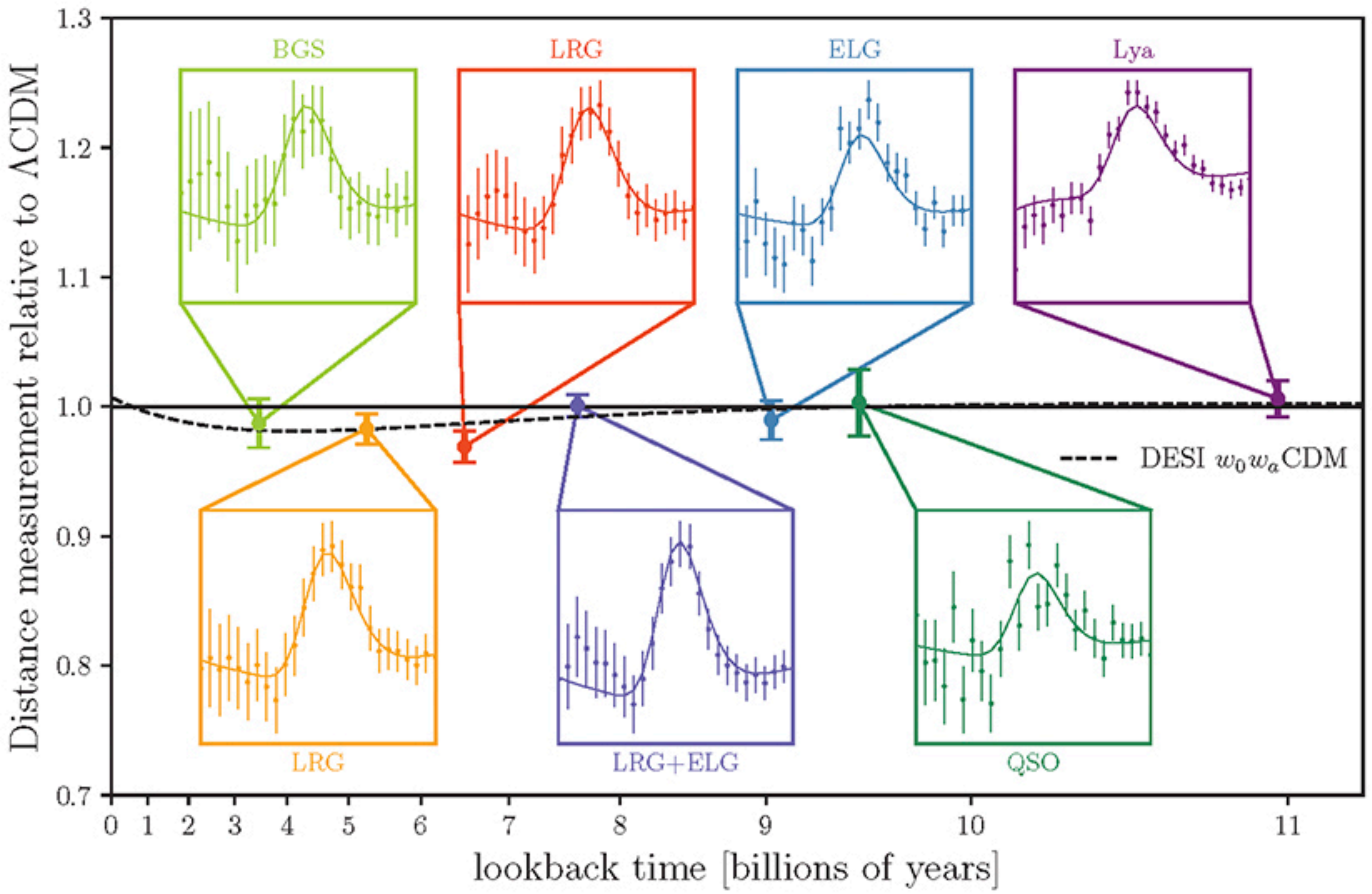


Distance Duality Relation (DDR)

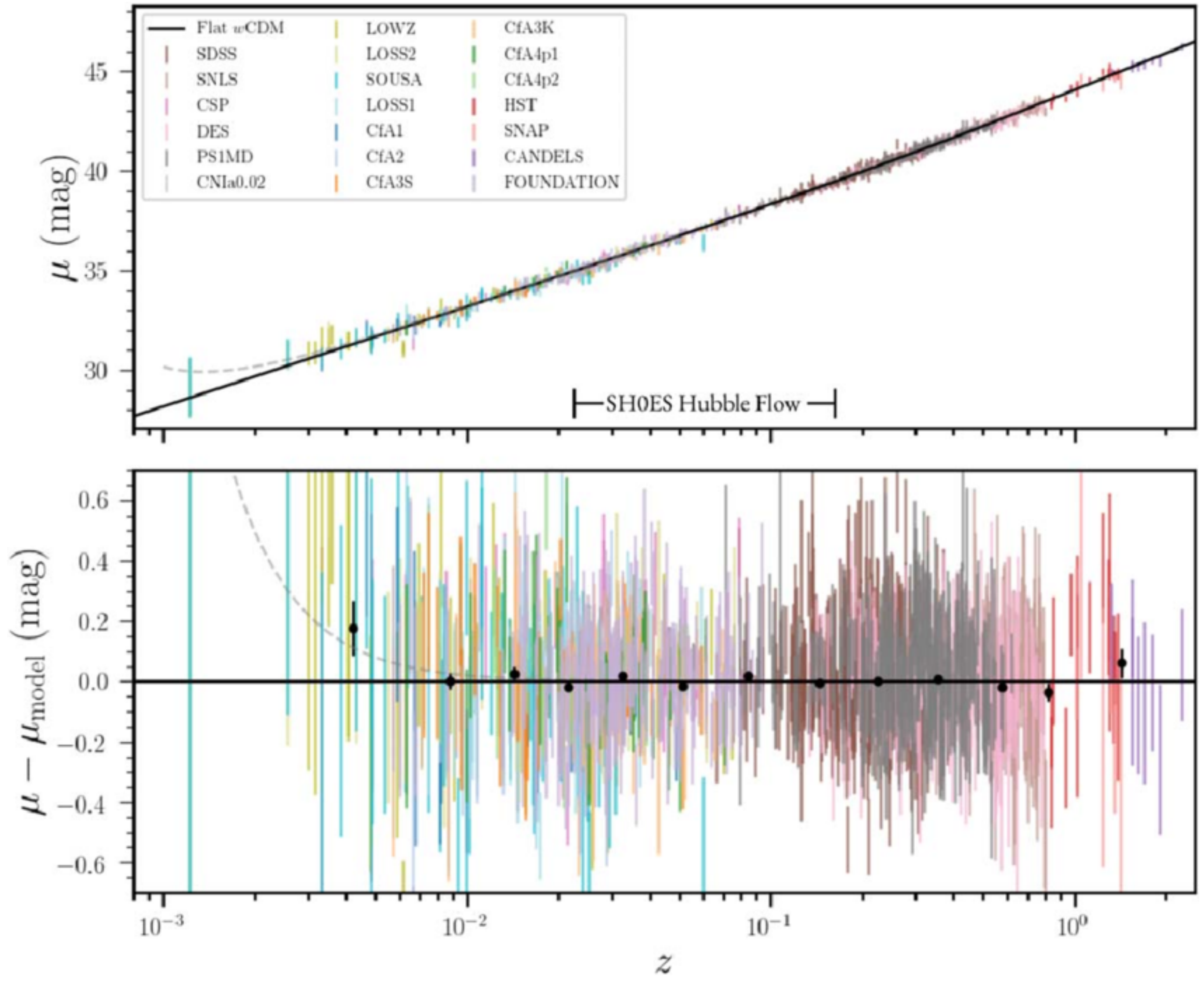
D_A from BAO

D_L from SN1a

[I. M. H. Etherington (1933)]

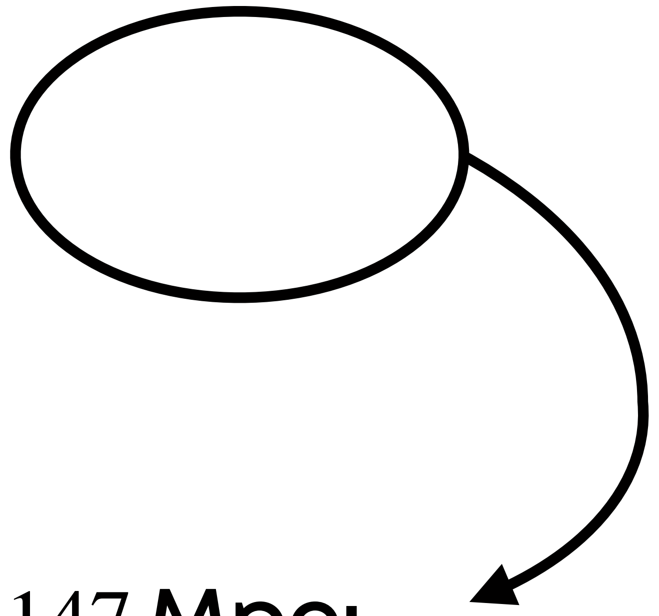


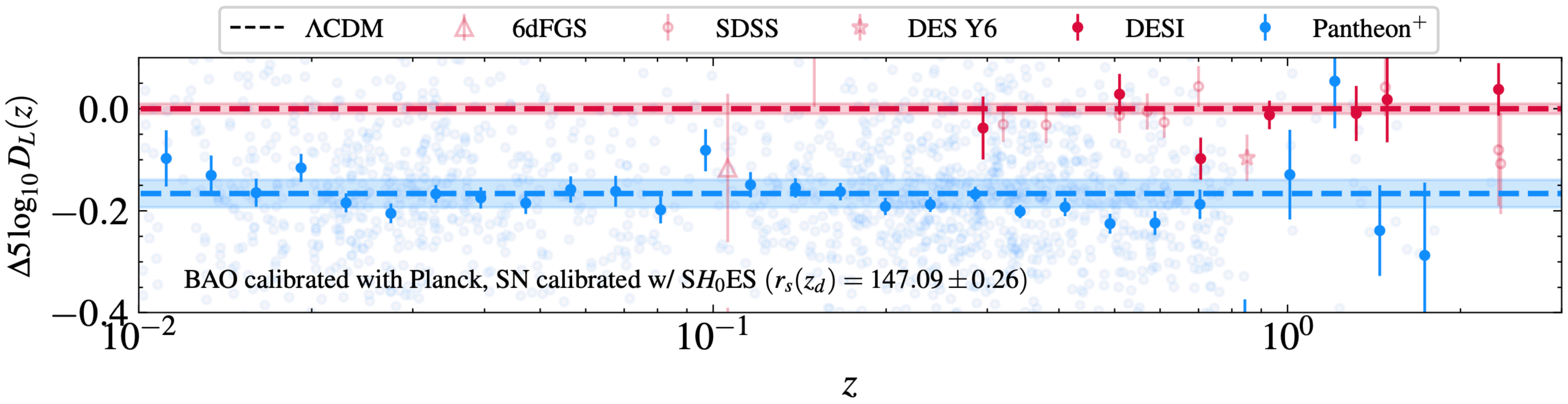
[DESI Collaboration 2024, arxiv:2404.03002]



[The Pantheon+ Analysis 2022, arxiv:2202.04077]

Hubble Tension or Distance Tension?



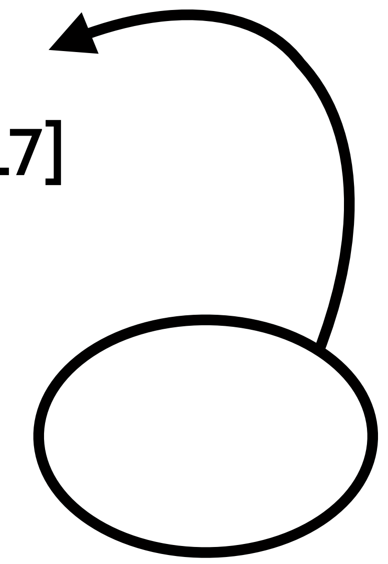


From *Planck*: $r_s \sim 147$ Mpc:

[Aghanim et al.: Astron.Astrophys. 641 (2020) A6]

From SH0ES: $M_b \sim -19.25$

[Riess et. al: Astrophys. J. Lett. 934 (2022) 1 L7]



[Poulin et al.: arXiv: 2407.18292]

[Camarena et al.: arXiv: 2101.08641]
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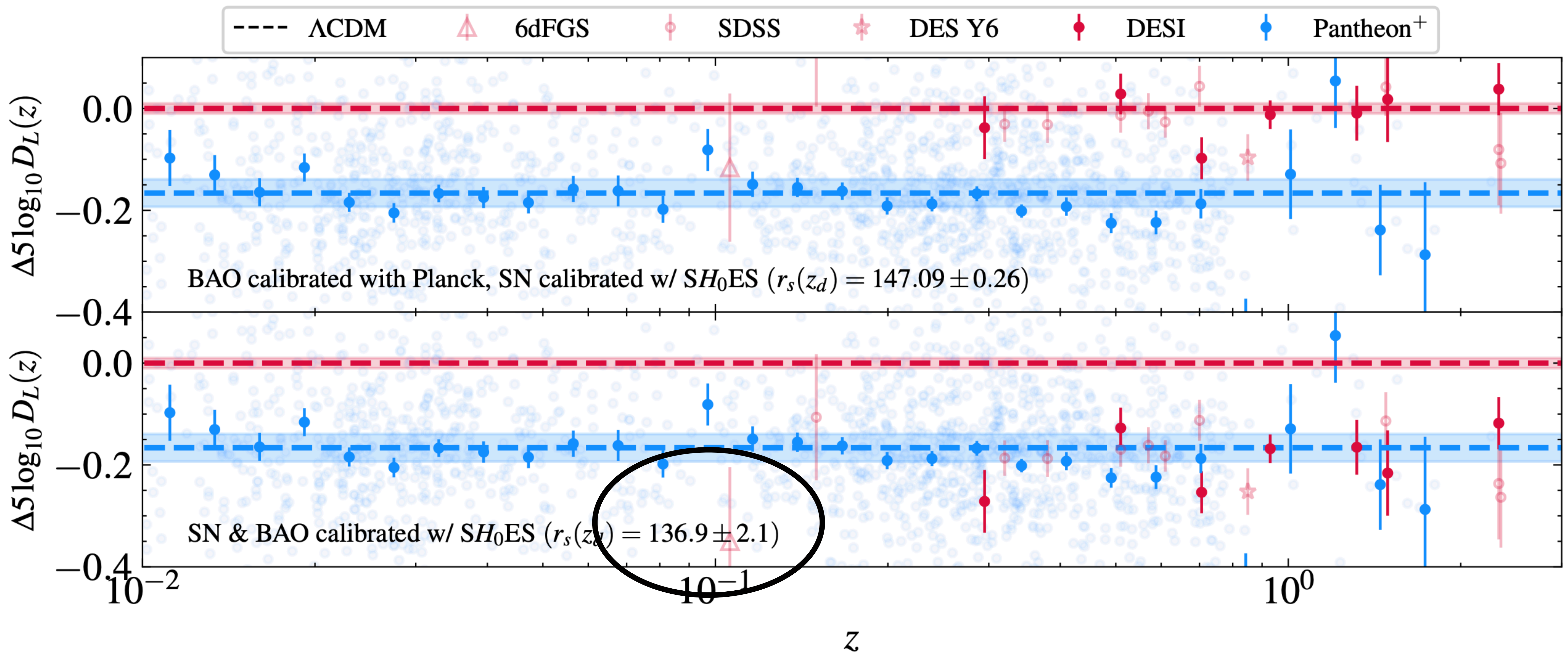

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Bring the data sets together:

- Change calibrators, e.g. change r_s (constant overall shift)

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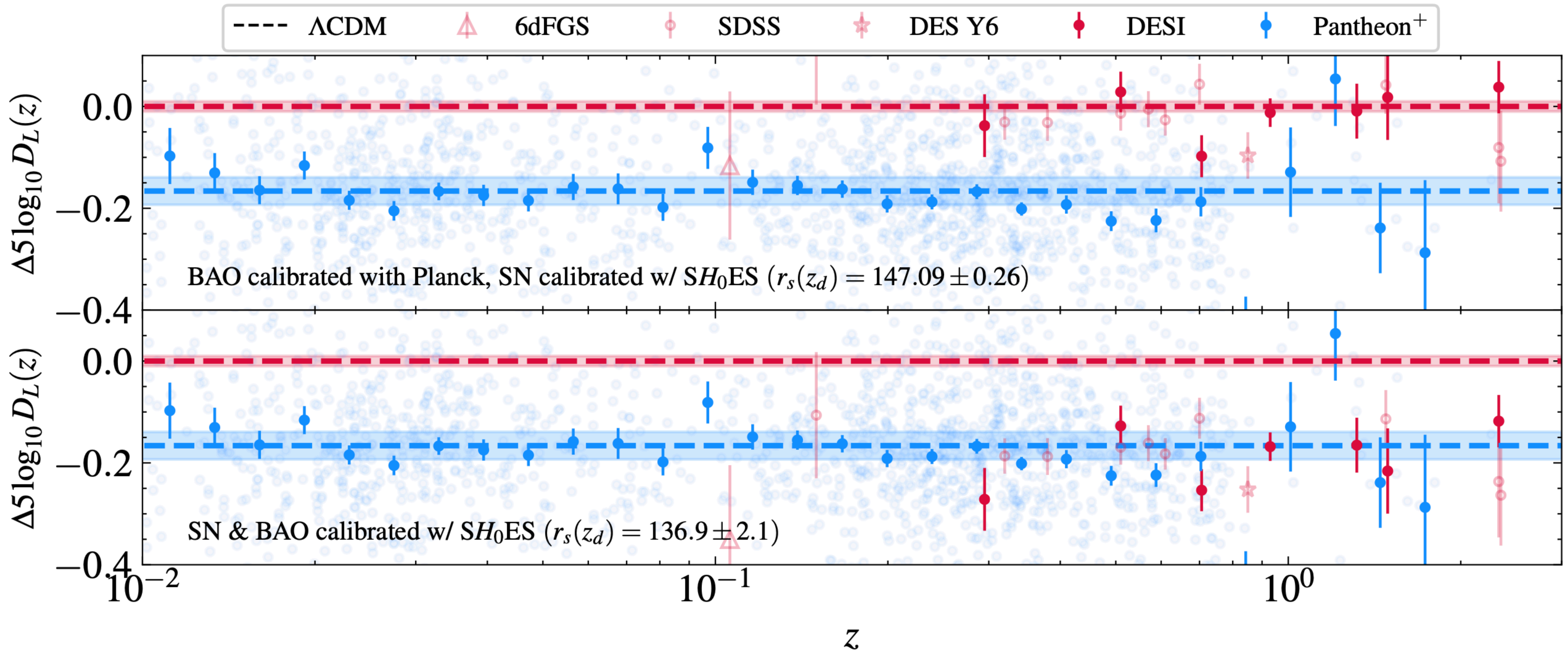

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Bring the data sets together:

- Change calibrators, e.g. change r_s (constant overall shift)
- Break the “distance duality relation” (possible redshift dependance)

[Poulin et al.: arXiv: 2407.18292]

[Camarena et al.: arXiv: 2101.08641]
[Efstathiou: arXiv: 2103.08723]
[Raveri: arXiv: 2309.06795]
[Tutusaus et al.: arXiv: 2311.16862]

But how?

Reconciling the cosmological distances between DESI BAO and Pantheon+ SN

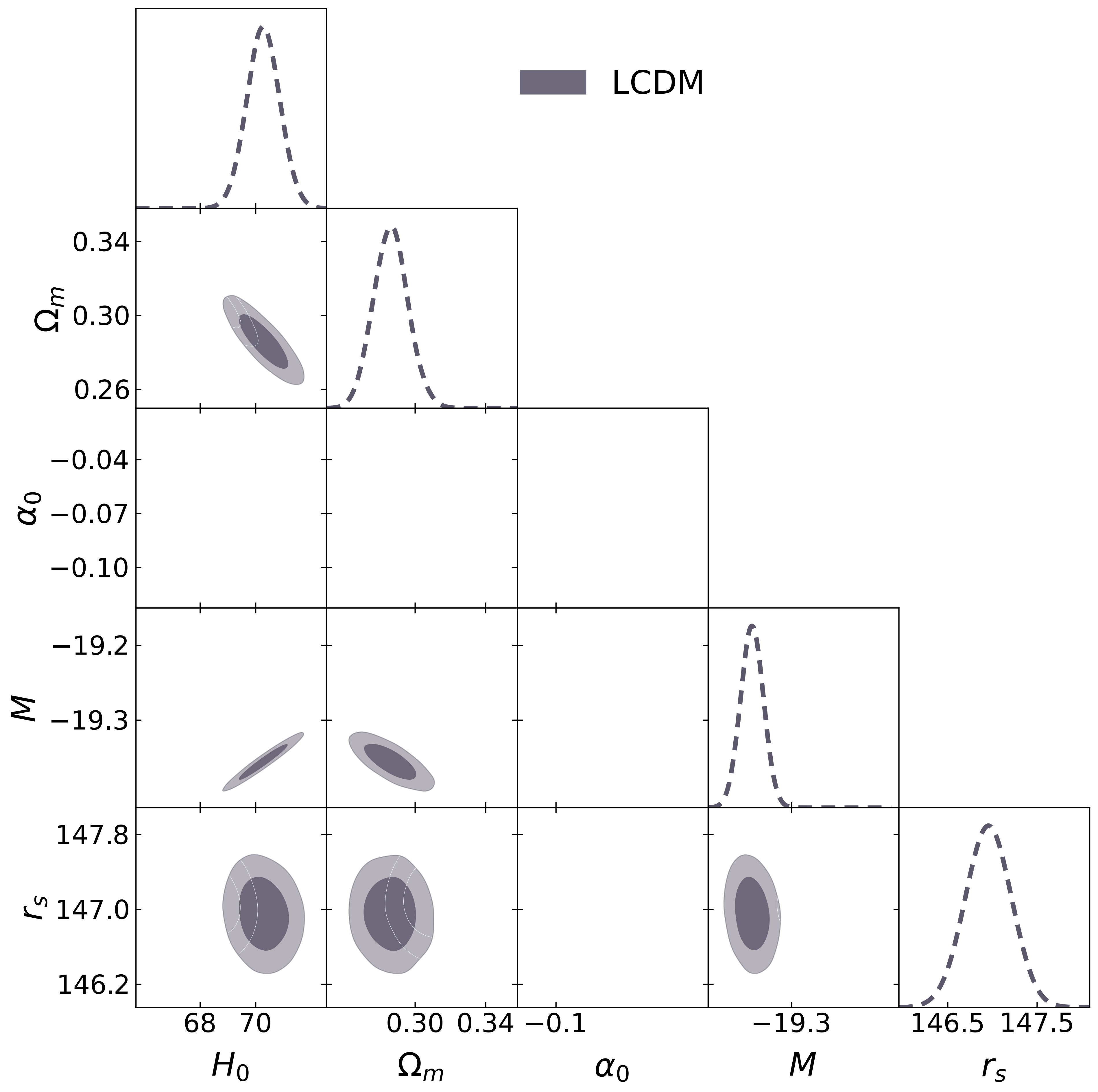
- DDR holds for metric theories of gravity assuming photon number conservation
- Violation in e.g. models in which photons interact with BSM particles or astrophysical absorption/opacity
- First approximation: look at effect of breaking DDR for distances in SN and BAO only
- If $\eta(z)$ is just a constant then we are probably dealing with calibration issues [Poulin et al.: arXiv: 2407.18292]
- If there is evidence for more than 1 dof and/or redshift dependence then study possible mechanisms and the physical implications in the whole expansion history

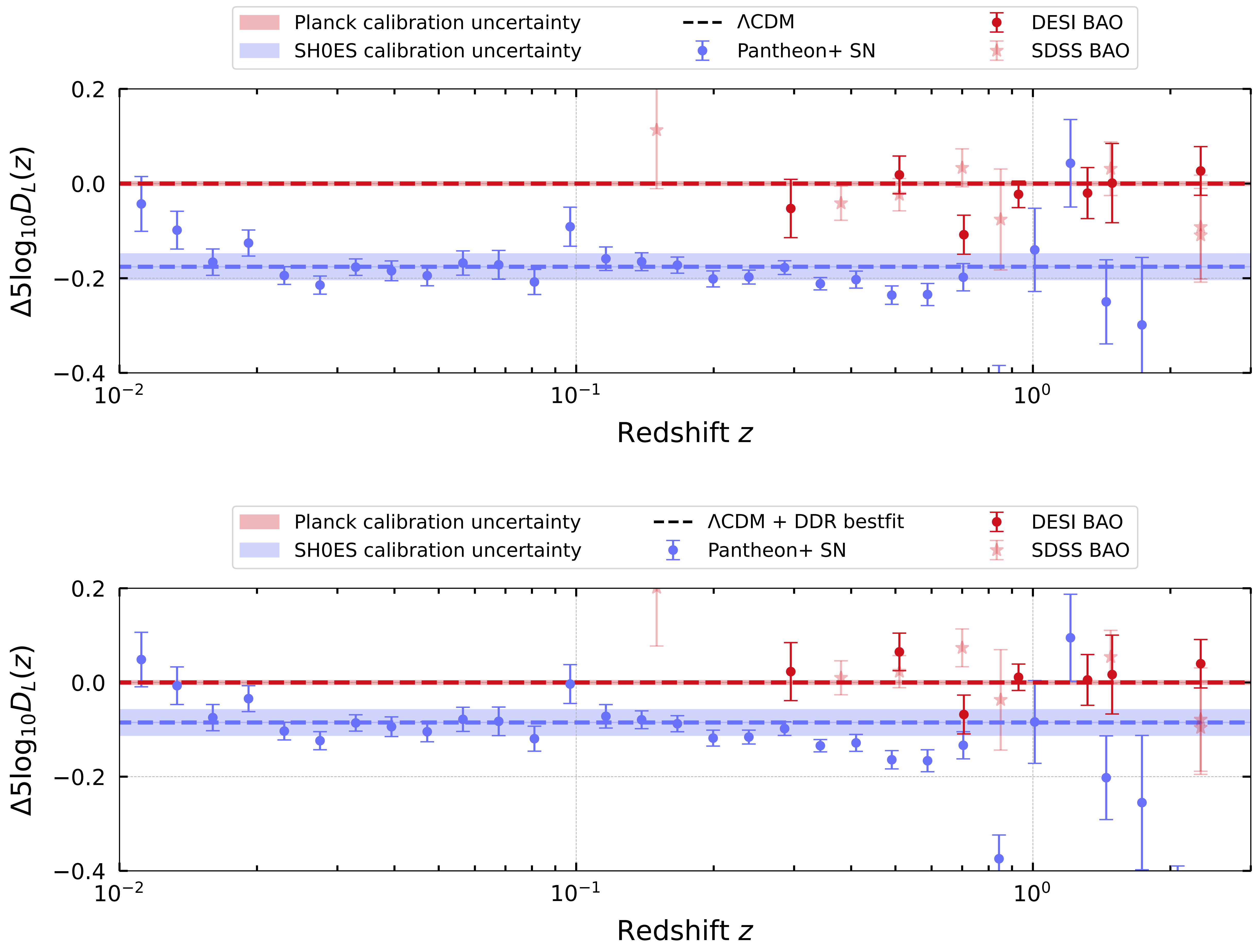
Breaking the DDR

Reconciling the cosmological distances between DESI BAO and Pantheon+ SN

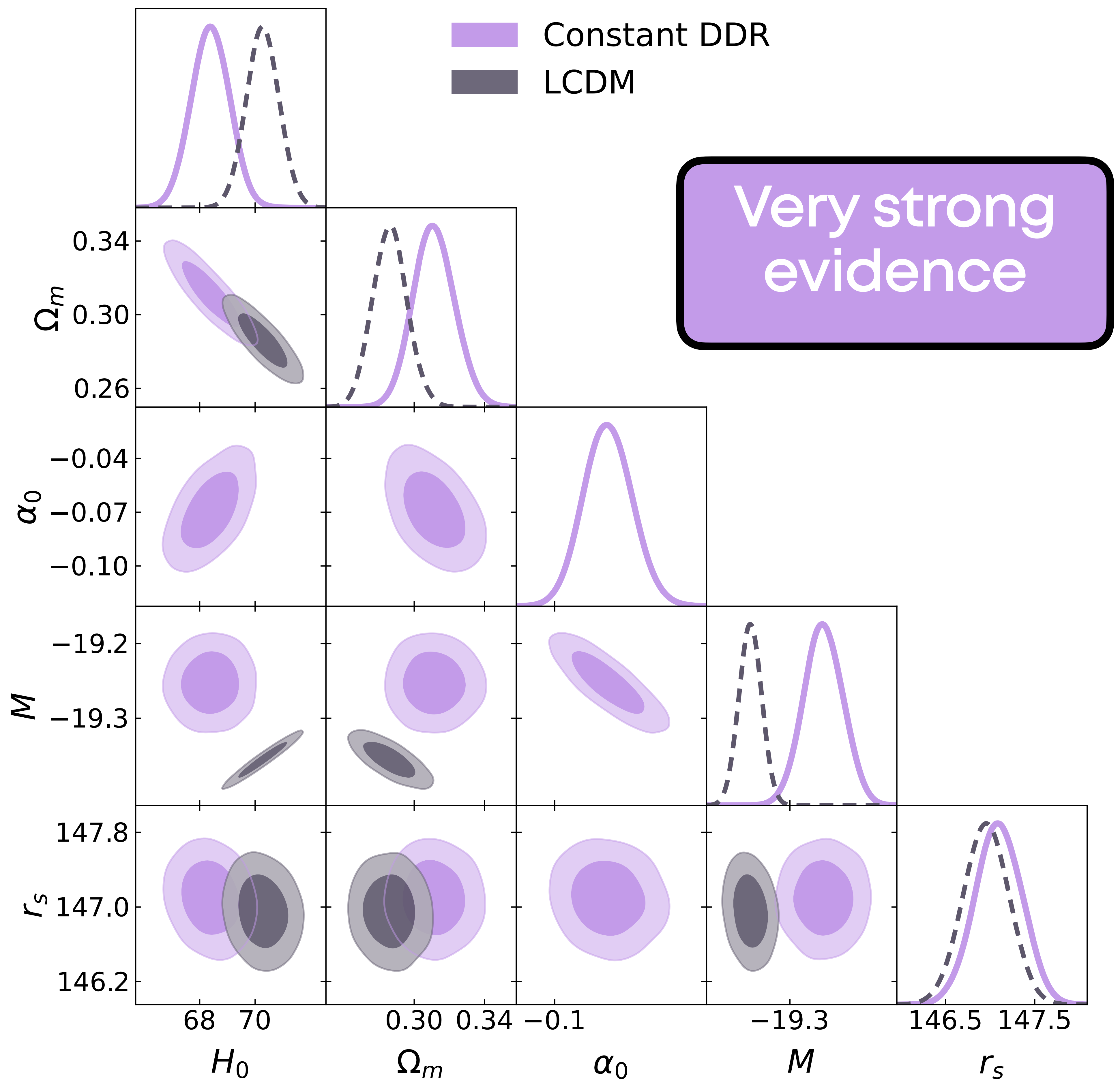
- Apply gaussian priors to keep consistency with calibrators: preserve the CMB under ΛCDM and SH0ES
- The SN high value of H_0 spoils the expansion history and CMB - need early time physics to restore ΛCDM
- Assume BAO distances are correct and give the right cosmology (keep D_A from BAO and change D_L from SN)
- Having a lower H_0 will ensure that we live in ΛCDM
- Then need to bring H_0 from SN down from ~73 to ~68
- Can the DDR breaking reconcile the SN distances for ΛCDM in agreement with CMB?

Combine the data

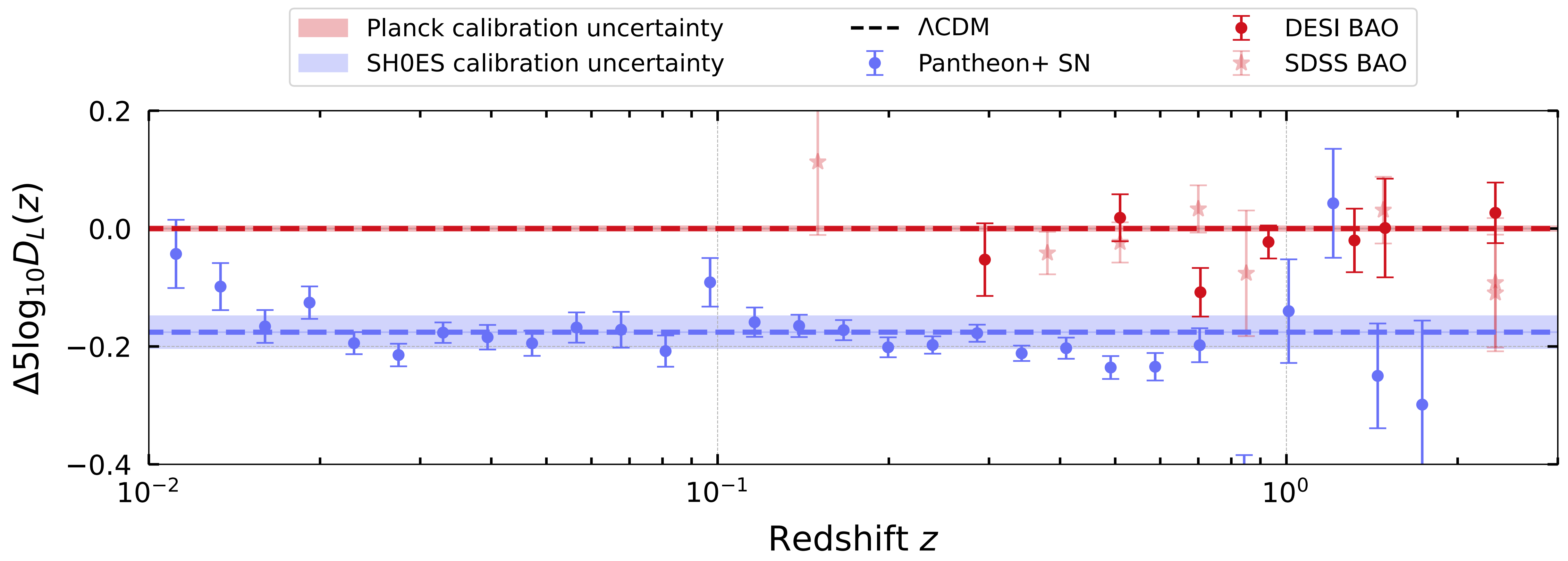


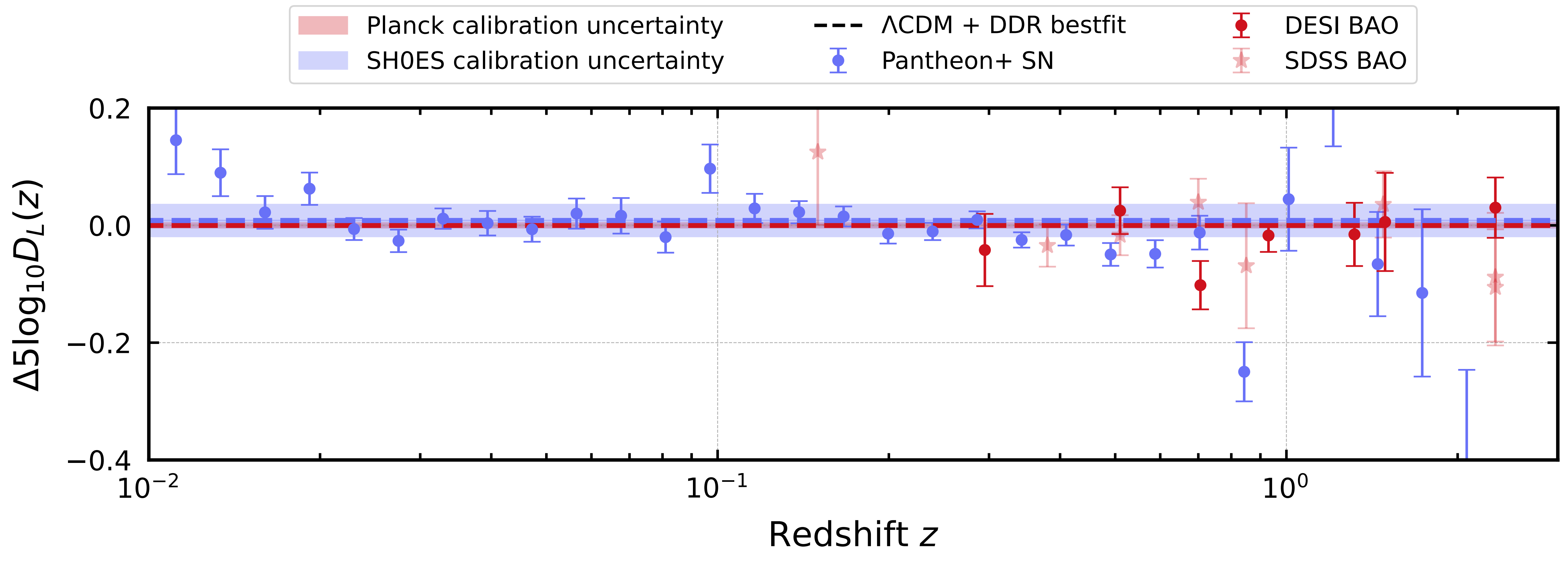


Constant DDR

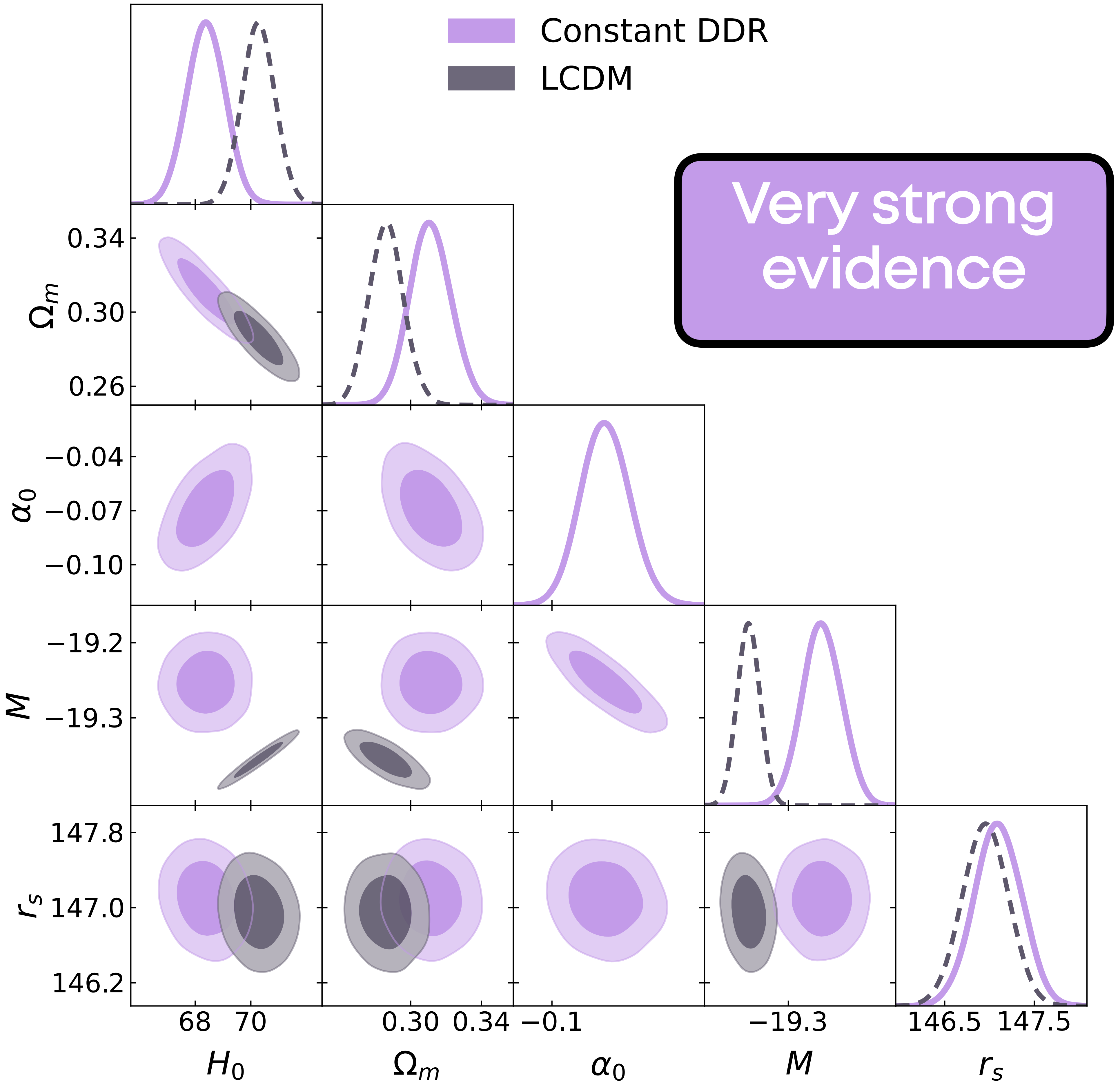


Very strong evidence



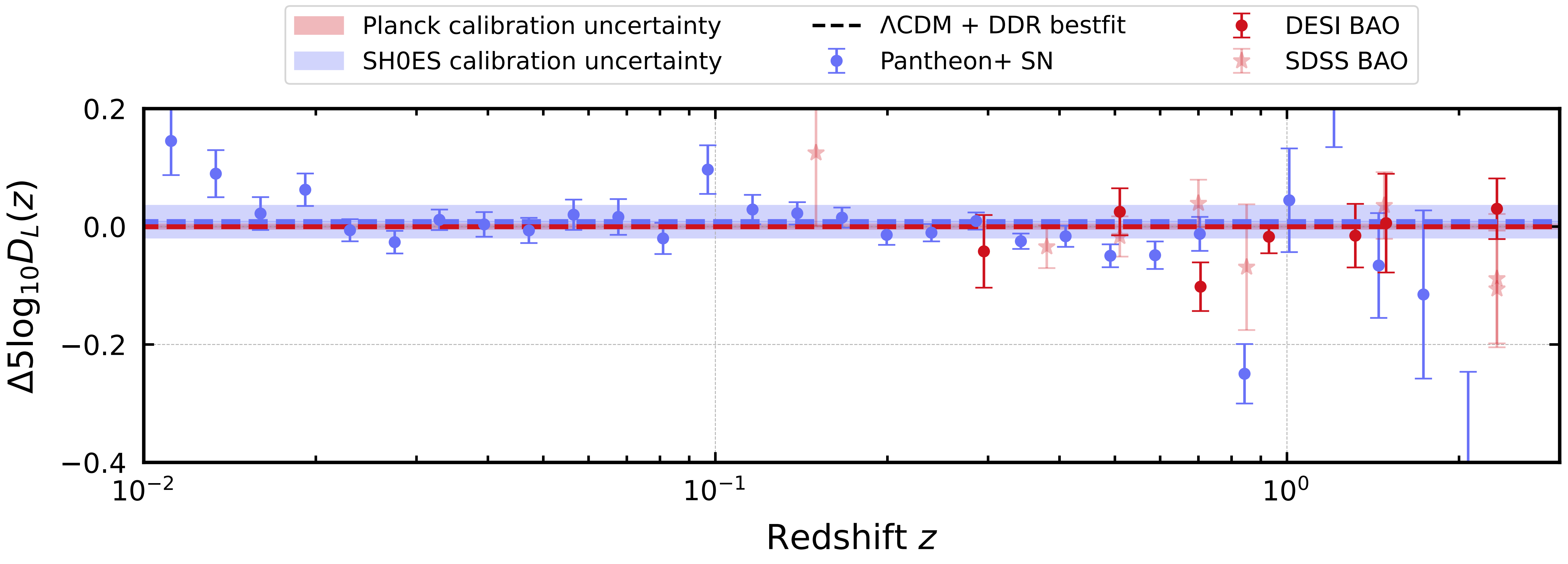


Constant DDR

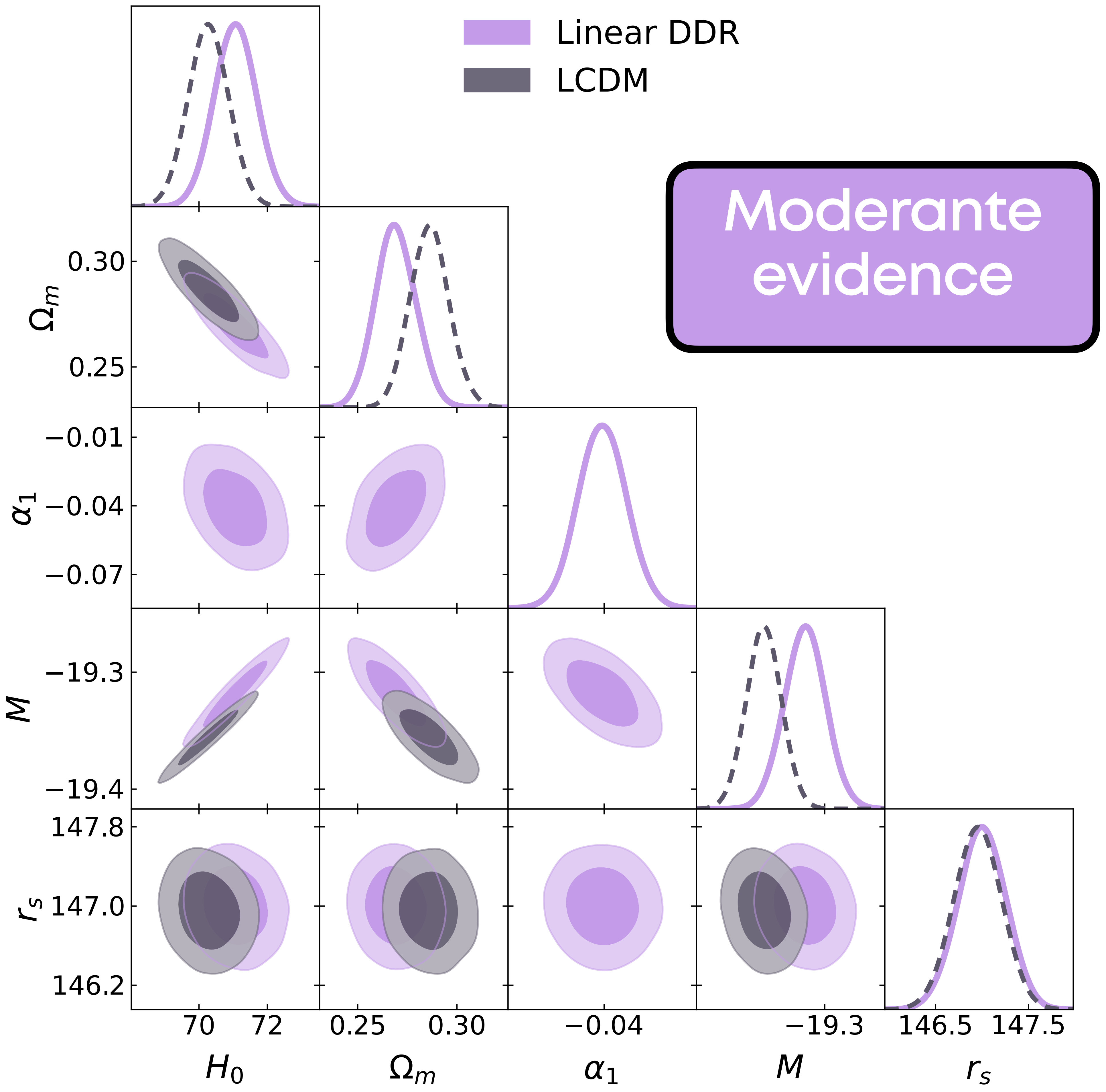


Very strong evidence

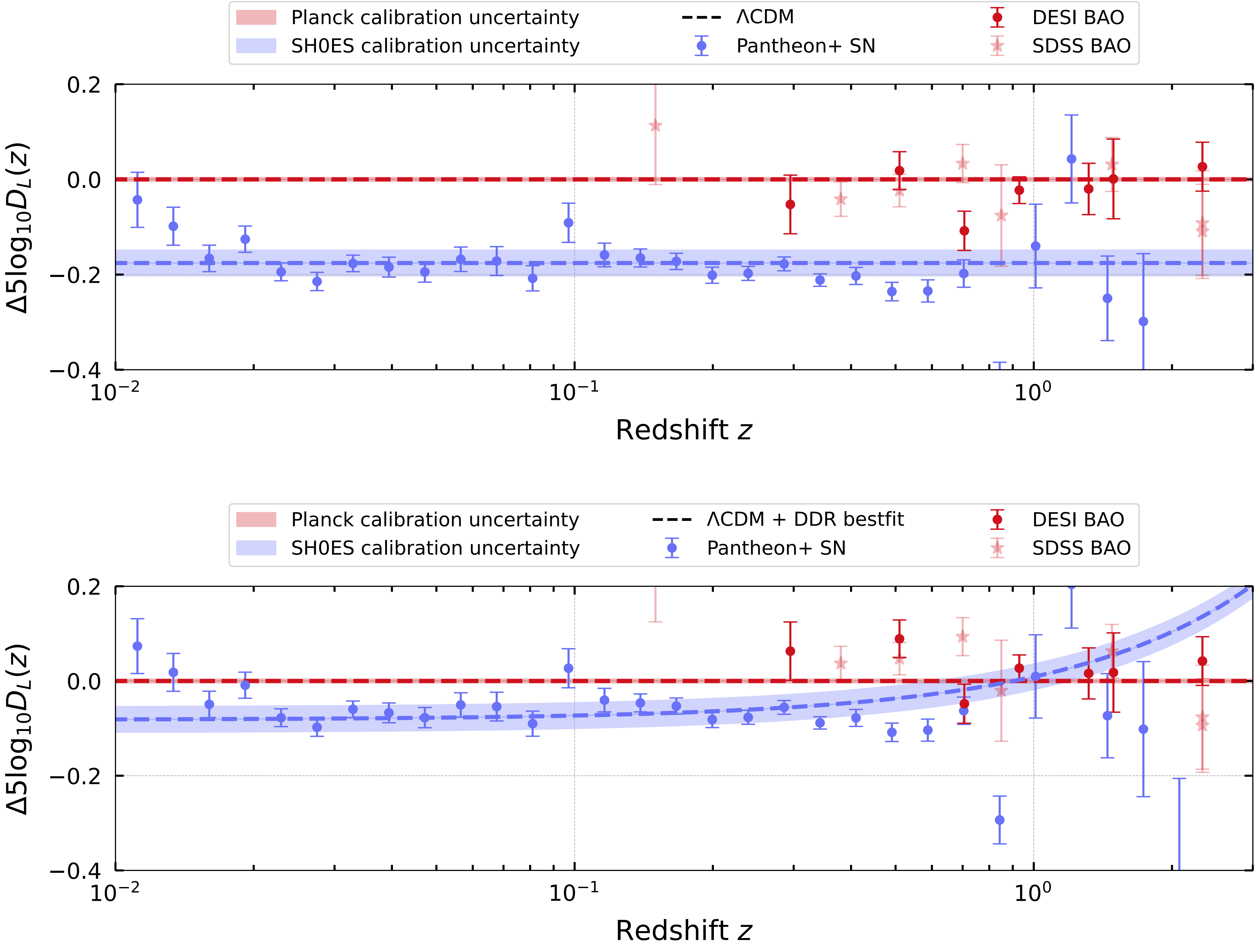
- Reconcile with low H_0 Universe from CMB
- Compatible with larger Ω_m to preserve ω_m
- Bestfit of DDR shift: $\alpha_0 = -0.069 \pm 0.014$
- Consistent with same shift in r_s and M from SH0ES ($r_s^{\rm CMB} = 147.09 \pm 0.26$ to $r_s^{\rm SH0ES} = 136.9 \pm 2.1$)



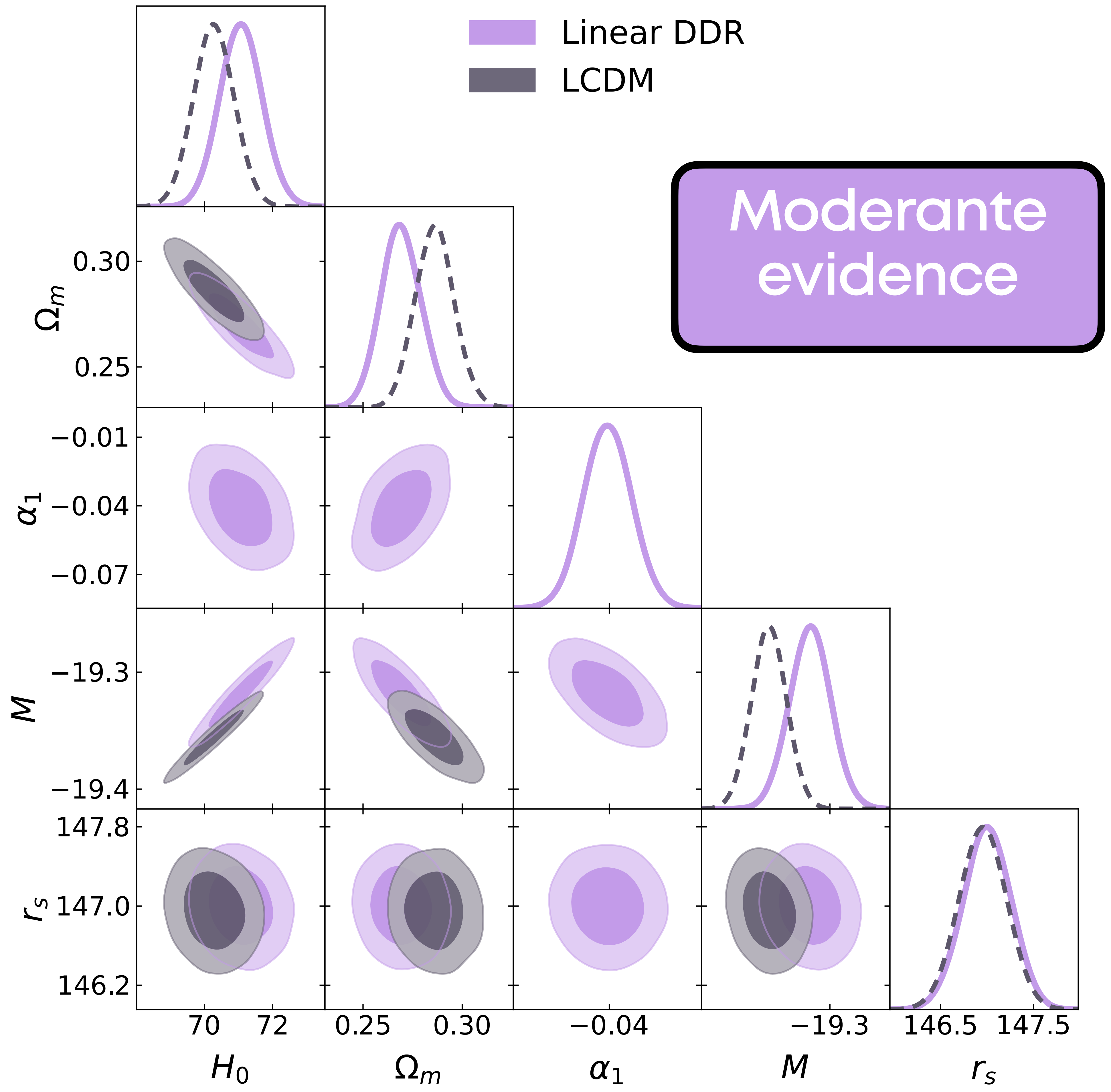
Linear DDR



Moderante evidence

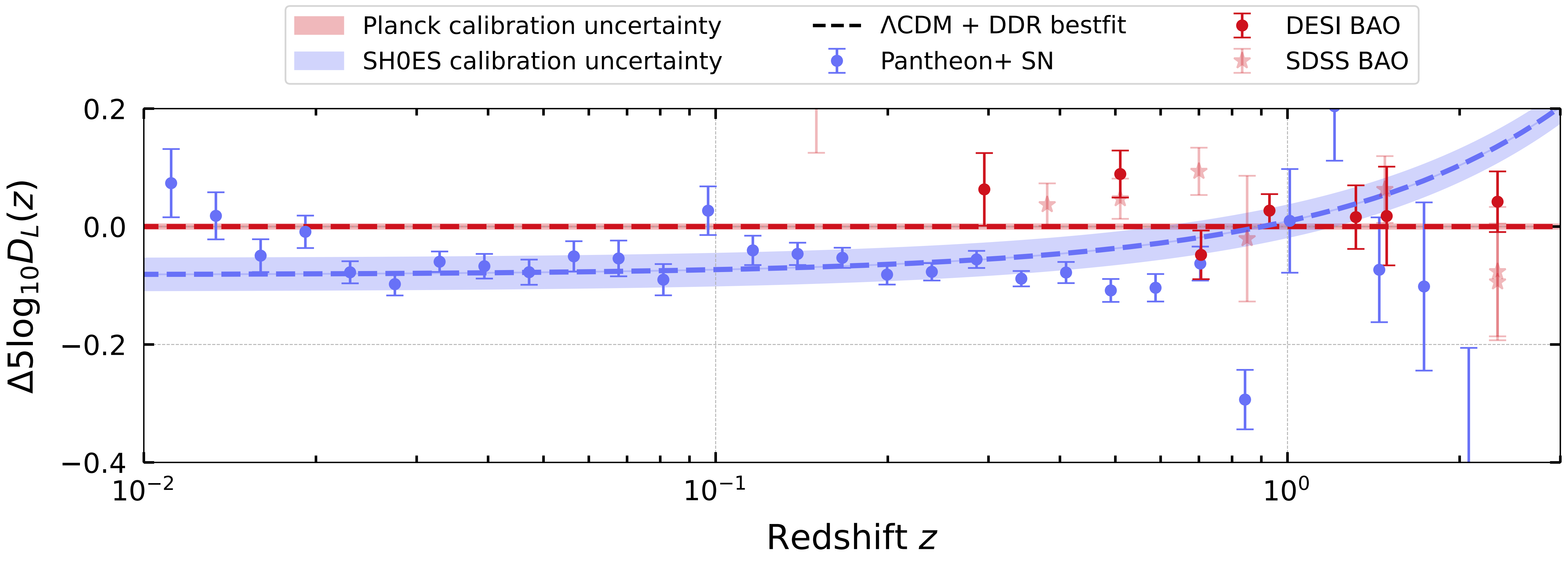


Linear DDR

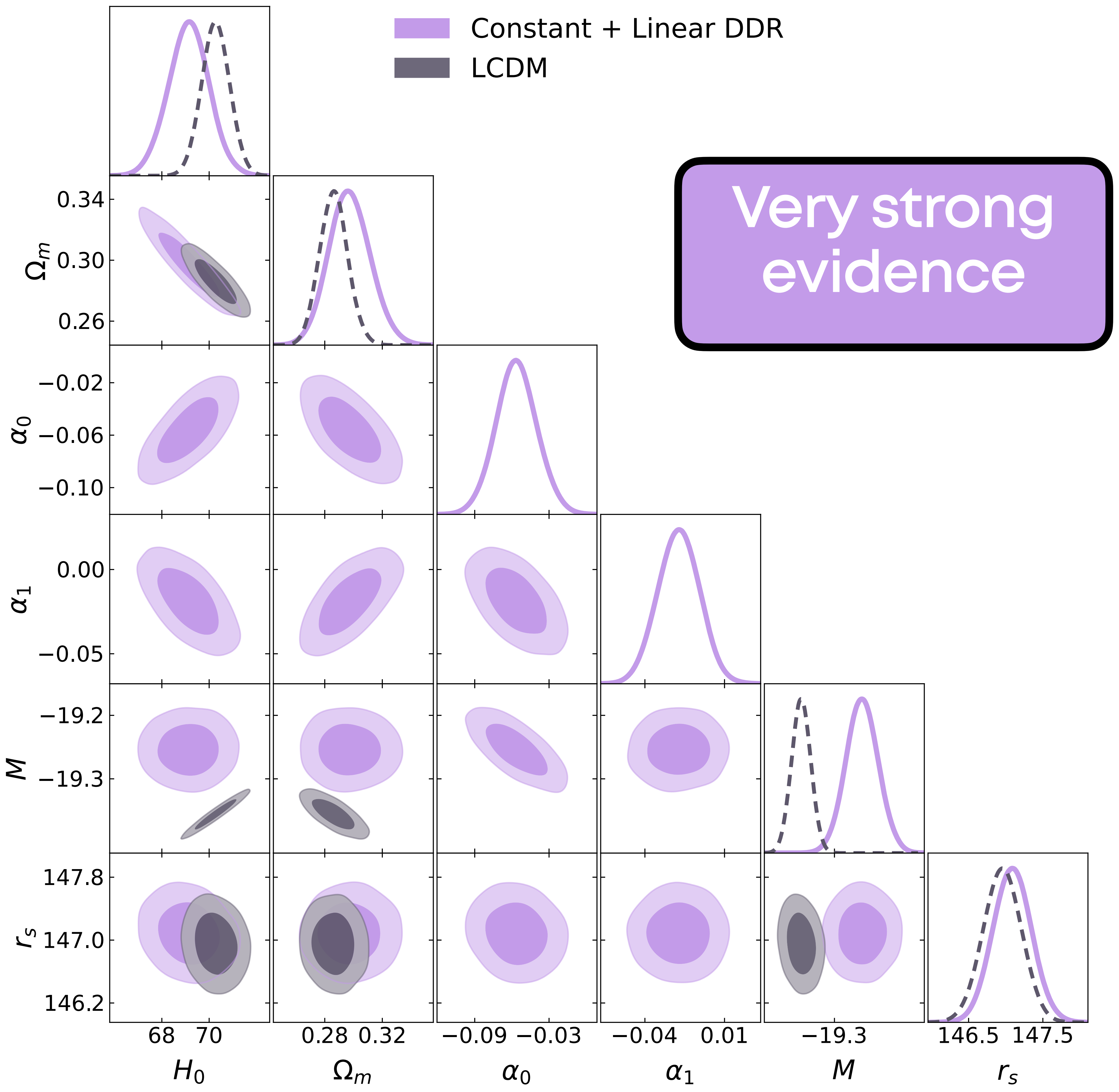


Moderante evidence

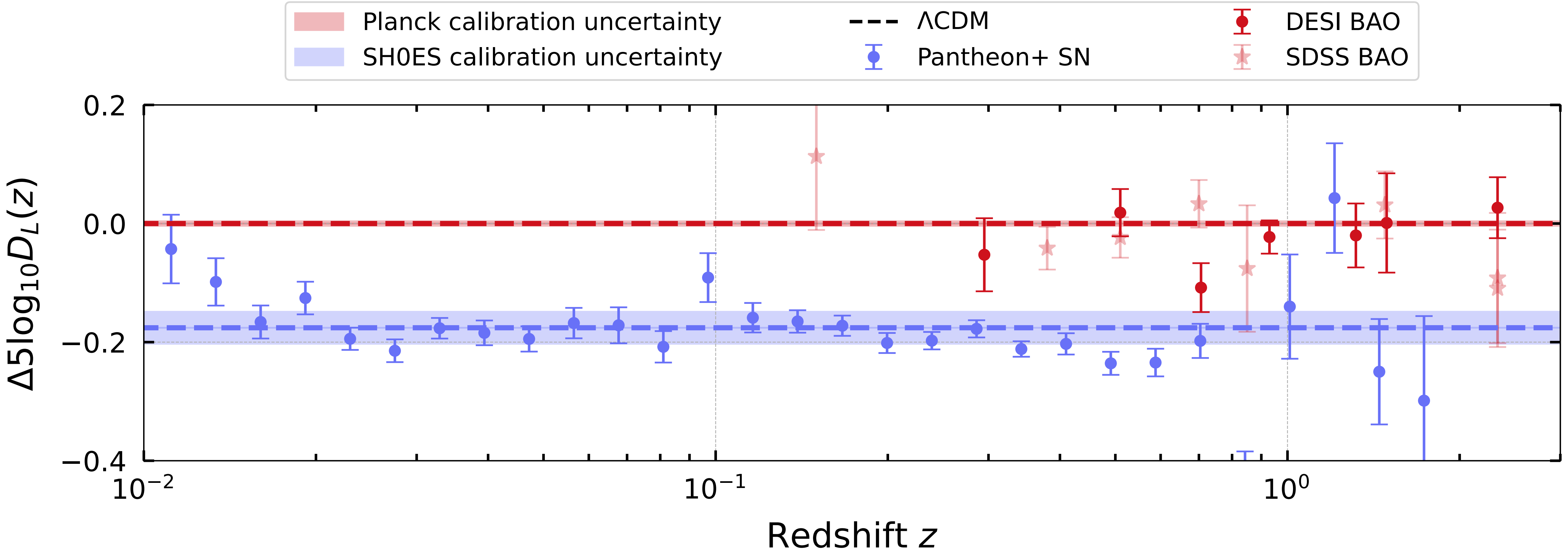
- The z-dependence is not enough to lower H_0 because of the low redshift SN
- Need smaller Ω_m to preserve ω_m
- Best-fit of DDR violation $\alpha_1 = -0.041 \pm 0.011$
- Compromise of M between SH0ES and CMB

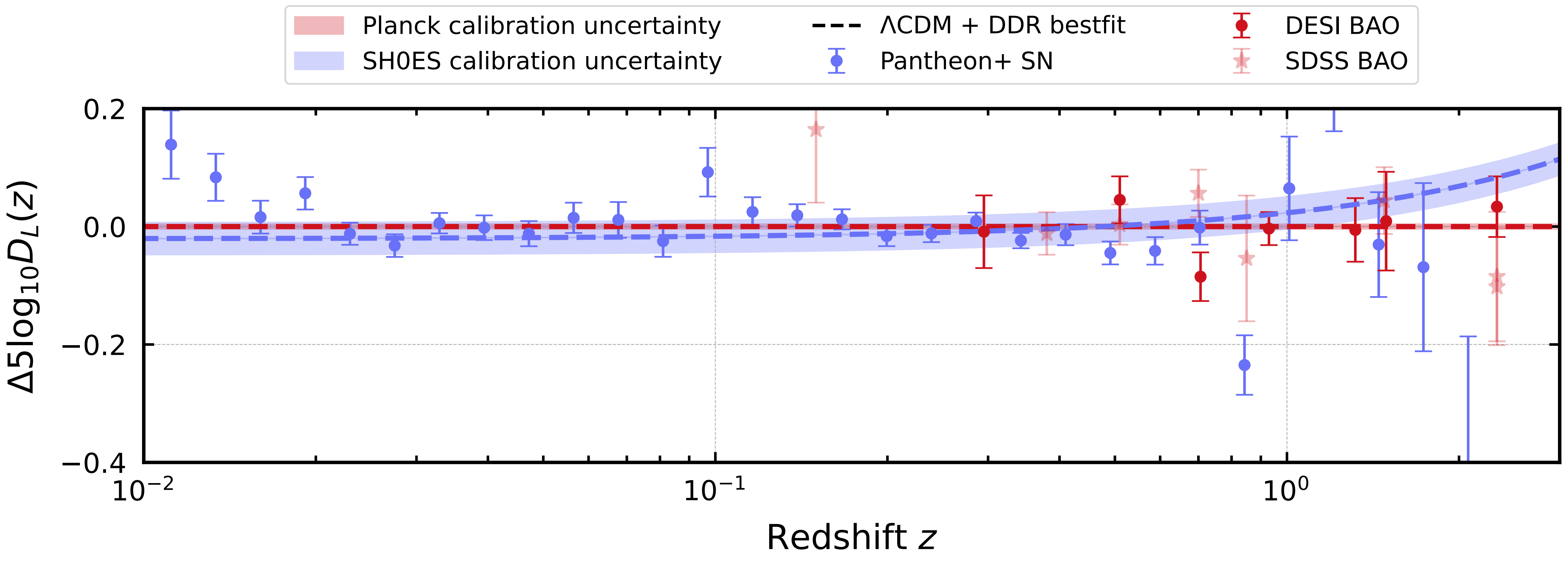


Linear DDR



Very strong evidence





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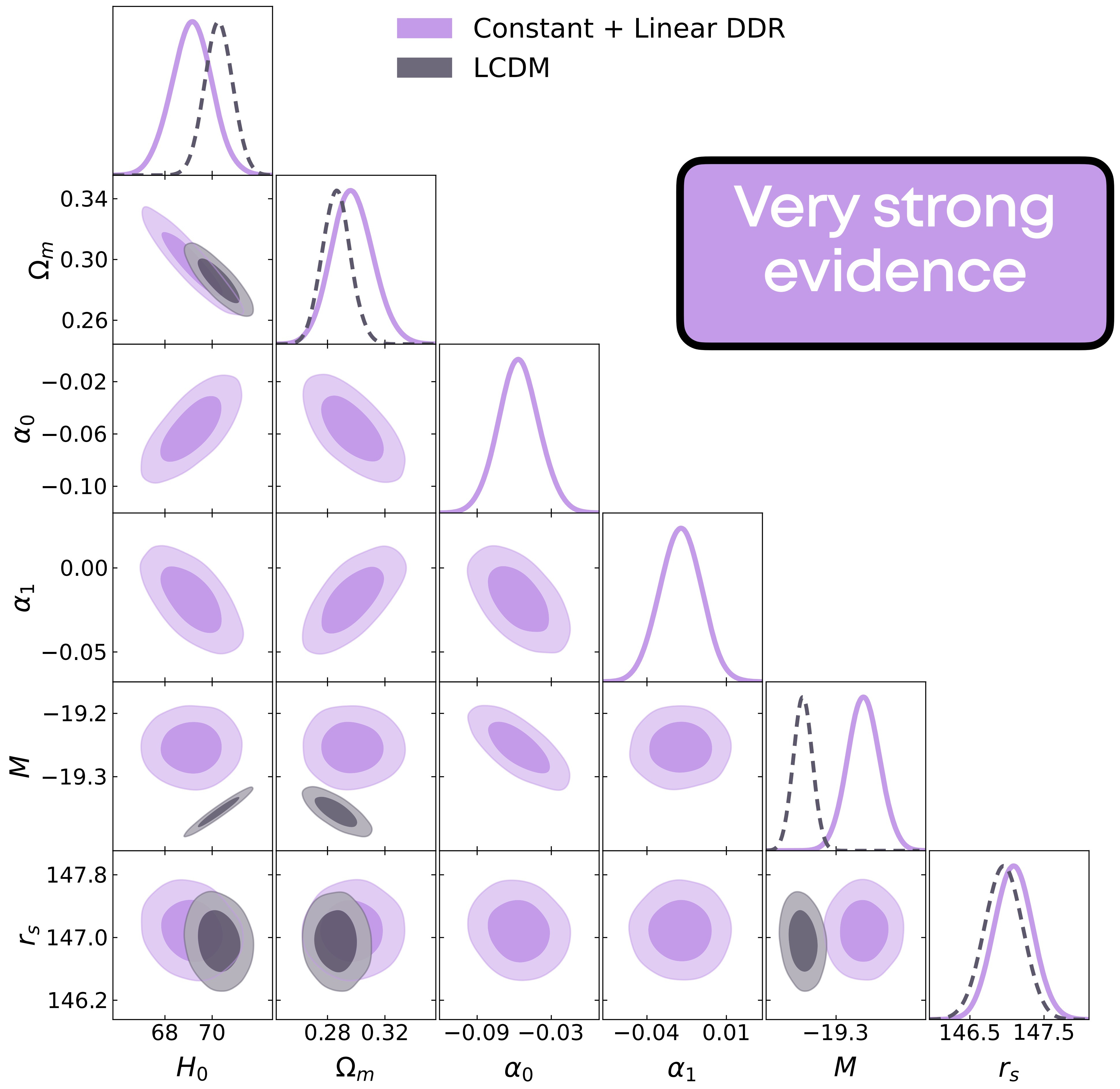
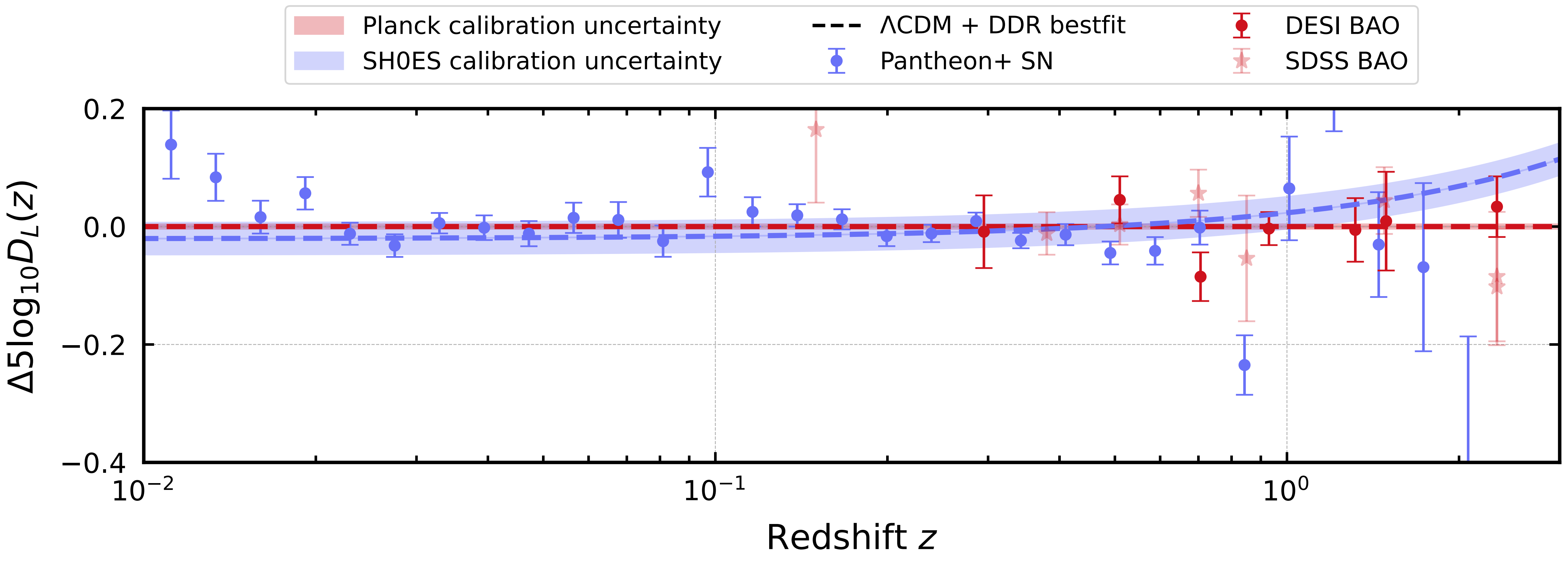
Linear DDR

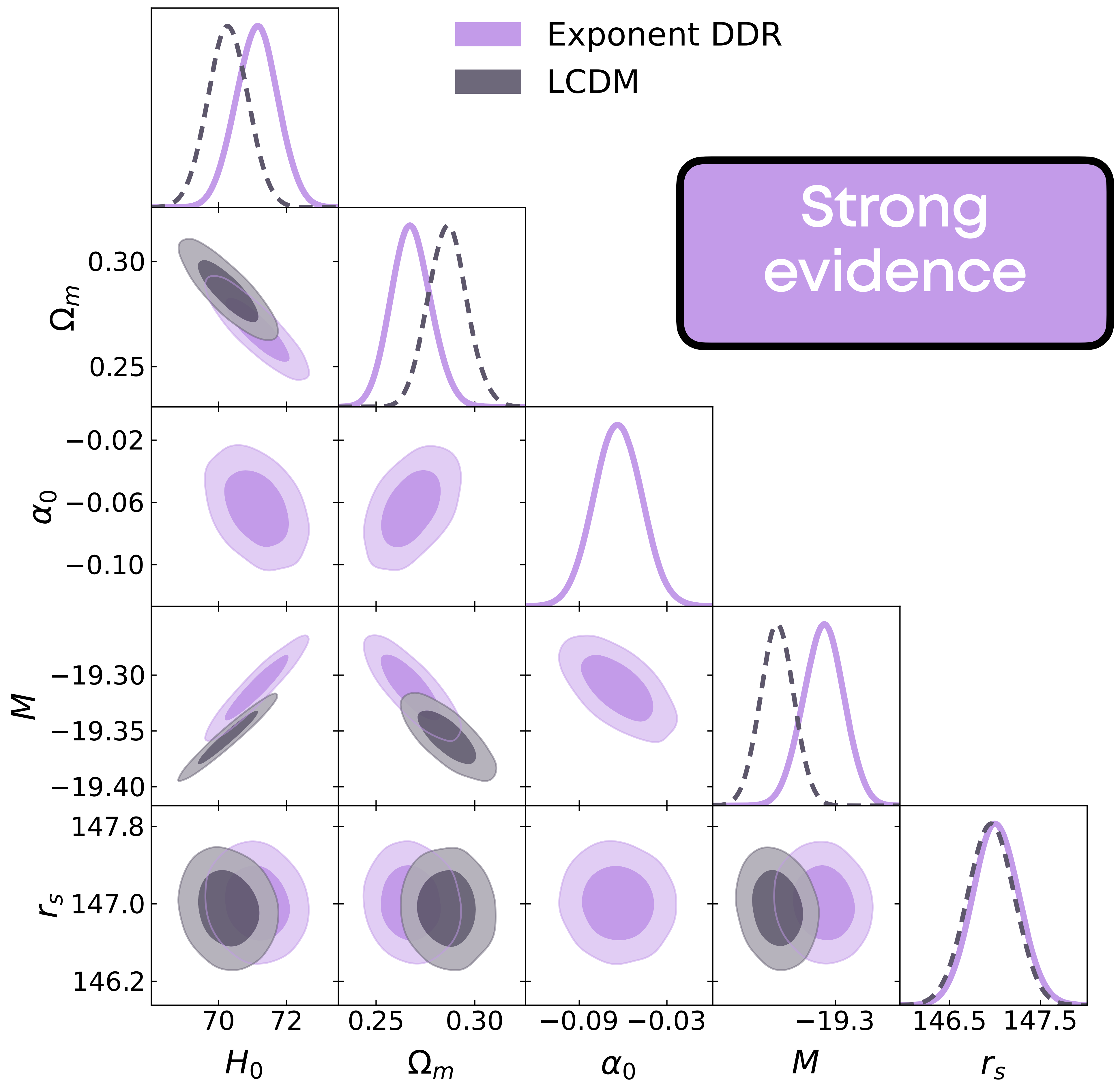


Very strong evidence

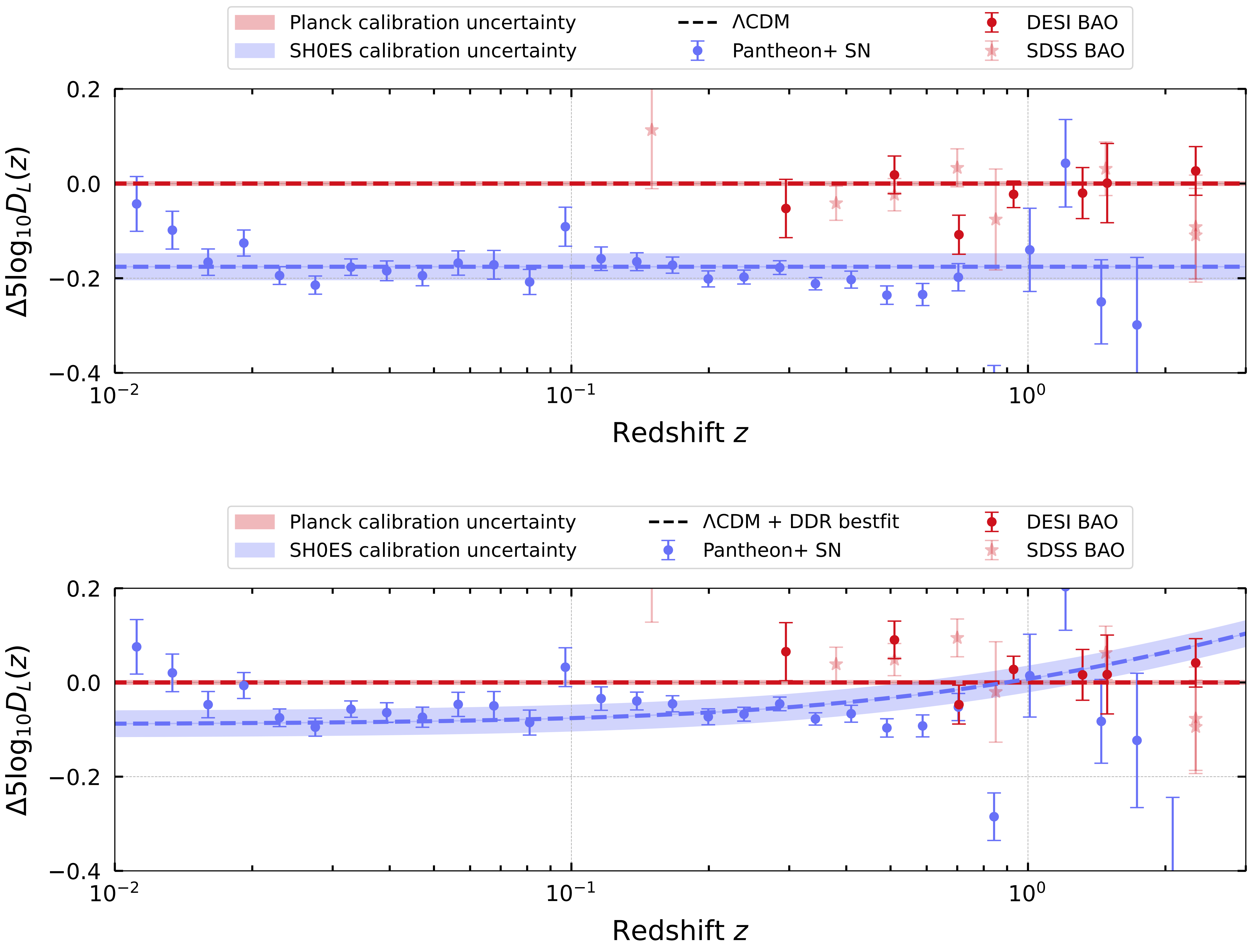
- The constant dof can reconcile distances at all z and yield a lower H_0 Universe
- Similar constant shift: $\alpha_0 = -0.056 \pm 0.017$
- Plus z-dependant shift: $\alpha_1 = -0.019 \pm 0.013$
- Consistent with M from SH0ES



Exponent DDR



Strong evidence



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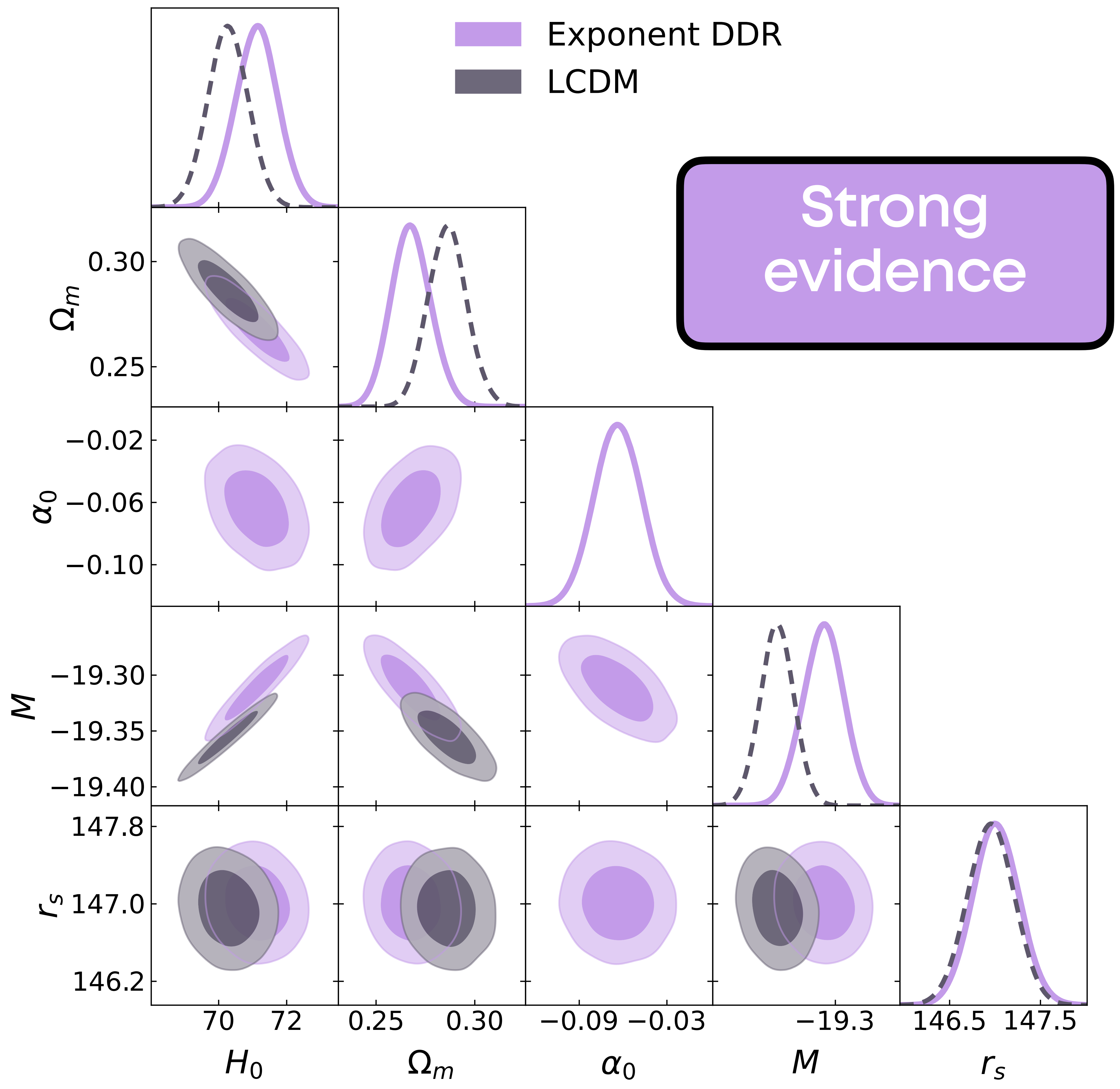
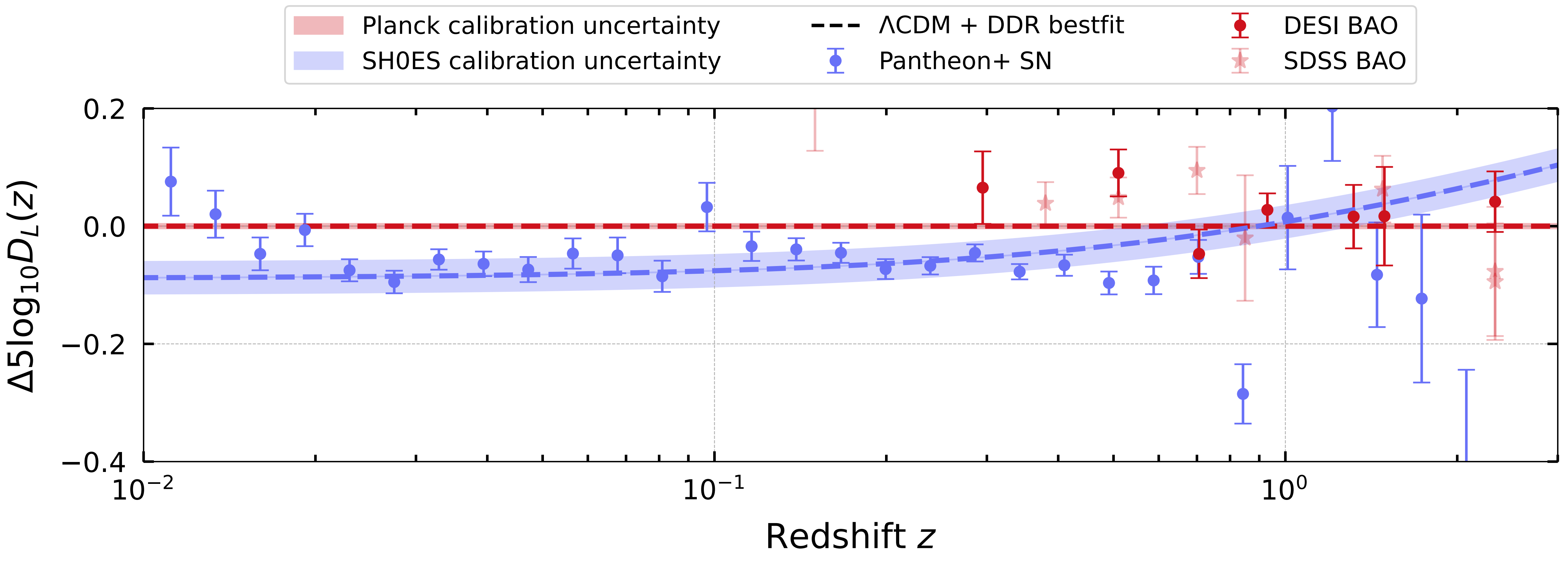


Strong evidence

- The z-dependence is not enough to lower H_0 because of the lower redshift SN
- Need smaller Ω_m to preserve ω_m
- Bestfit of z exponent: $\alpha_0 = -0.064 \pm 0.016$
- Compromise of M between SH0ES and CMB



What this tells us…

- All parametrisations give significantly better fits than ΛCDM despite the additional 1 or 2 dof
- The constant $\eta(z)$ gives the better fit with only 1 dof for the parametrisations considered
- Need the constant shift to restore the low H_0 Universe for the low redshift
- Parametric analysis not enough to exclude z-dependence - possible additional effects in the common z range
- Physical breaking of the DDR: how does it reflect in other observables? Non-conservation of photons by astrophysical effects or exotic physics?

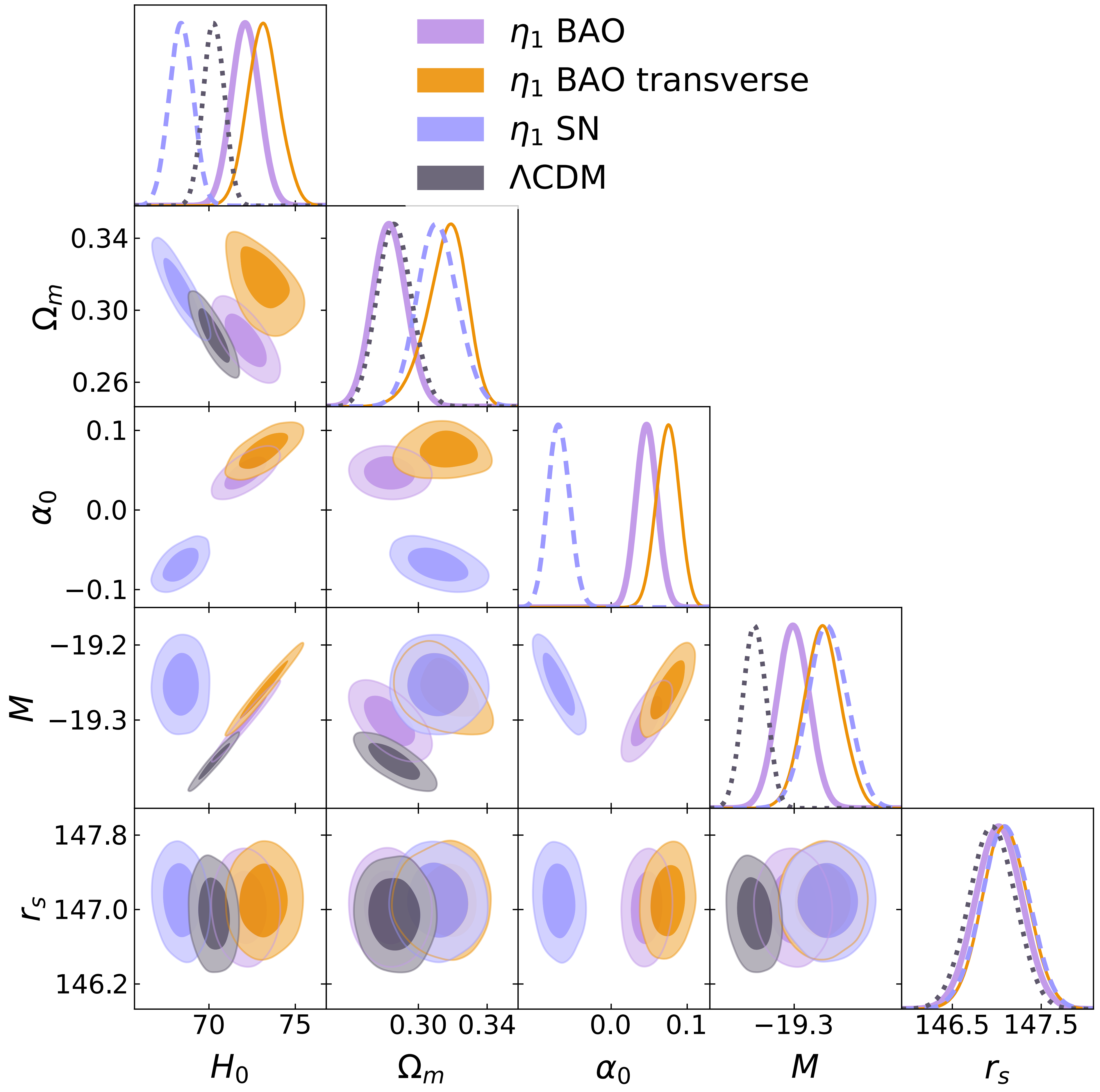
Conclusions

- ΛCDM model facing challenges with increasing precision in cosmology
- Incompatibility of early- and late-Universe measurements
- Recast the H_0 tension as a tension in distances
- Apparent preference for a constant shift in the calibration of the SN and BAO distances
- All parametrisations give significantly better fits than ΛCDM despite the additional 1 or 2 dof
- Full reconstruction instead of parametrisations
- Check compatibility with CMB data (direct measurements of T at different z)
- Understand physical mechanisms and/or systematics that can explain the DDR break

Thank you for your attention!

Illustration Credits: Inês Viegas Oliveira (ivoliveira.com)

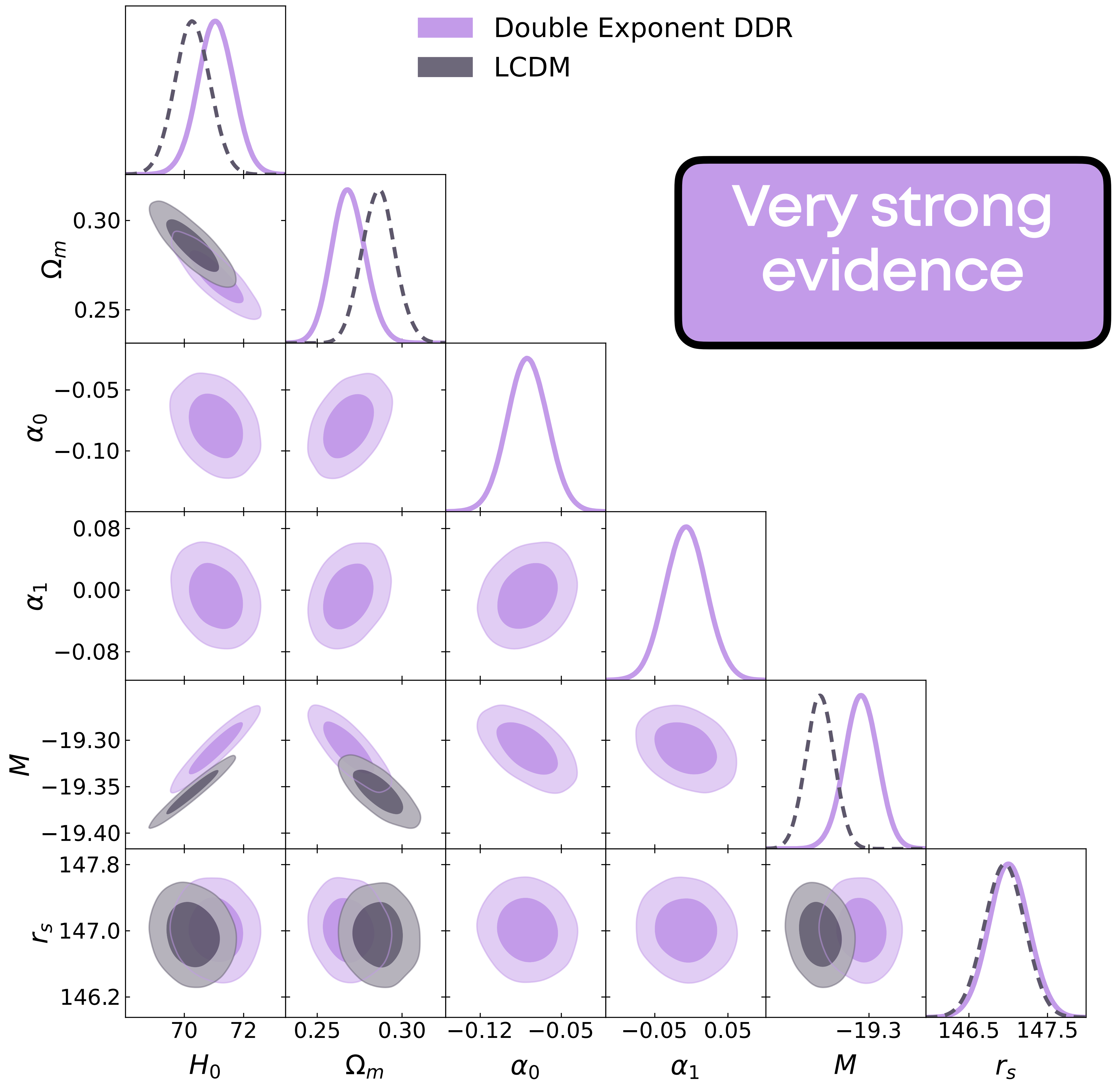
Constant DDR



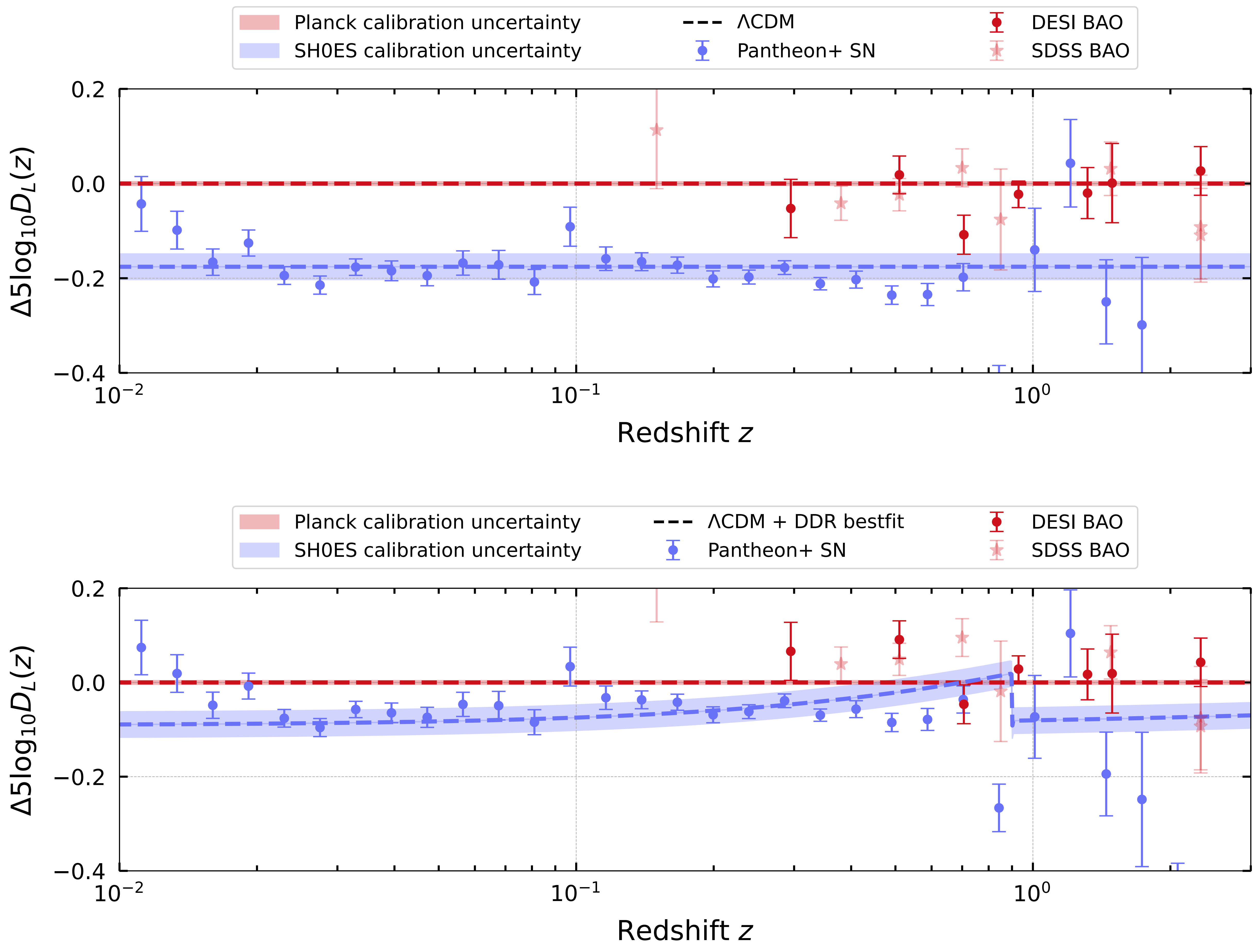
- We've tested breaking the DDR in the D_A of BAO
- We see that this is inconsistent and ineffective because:

1. Enforces higher values of H_0 for the same matter density which will be inconsistent e.g. with CMB
2. Modifies only the transverse BAO making it hard to accomodate the same cosmology to each data set resulting in a bad fit
3. Easier to justify/search for systematics in D_L of SN

Double Exp. DDR



Very strong evidence



Bayesian Parameter Inference

Given a data set d, we want to sample posteriors on the model parameters θ that maximise the likelihood

$$p\left(\theta \mid d\right) = \frac{p\left(d \mid \theta\right) \, p\left(\theta\right)}{p\left(d\right)} \Leftrightarrow \text{Posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{evidence}}$$

Modified version of Einstein-Boltzmann code CLASS interfaced with the MontePython sampler
[Blas, Lesgourgues, Tram: JCAP 1107 (2011) 034; Audren et al.: JCAP 1302 (2013) 001; Brinckmann, Lesgourgues: Phys. Dark Univ. 24 (2019) 100260]

Employ an MCMC sampling method and analyse results in GetDist [Lewis: arXiv:2008.11284]

Model Comparison

In summary, the Bayes factor strikes a balance between fit quality and additional model complexity. It rewards highly predictive models whilst penalising models with unnecessary extra parameters. This principle is often referred to as Occam's razor.

$$B_{N;M} = \frac{\int \mathrm{d}\theta_N p(d|\theta_N; N)}{\int \mathrm{d}\theta_M p(d|\theta_M; M)} \frac{(\Delta\theta_1^M ... \Delta\theta_{n_M}^M)}{(\Delta\theta_1^N ... \Delta\theta_{n_N}^N)} .$$

$\lvert \ln B_{N;M} \rvert$	Fractional Odds	Model's Probability	Evidence
< 1.0	$< 3:1$	< 0.750	Inconclusive
1.0 to 2.5	$< 12:1$	0.923	Weak to Moderate
2.5 to 5.0	$< 150:1$	0.993	Moderate to Strong
> 5.0	$> 150:1$	> 0.993	Very strong or decisive

Table 4.1: Jeffreys scale to evaluate the strength of the evidence of a model N over another model M, in terms of the absolute value of $\ln B_{N;M}$, with a positive (negative) value indicating support for model N (M).

$\Delta B = -8$

$\Delta B = -3.2$

$\Delta B = -5.9$

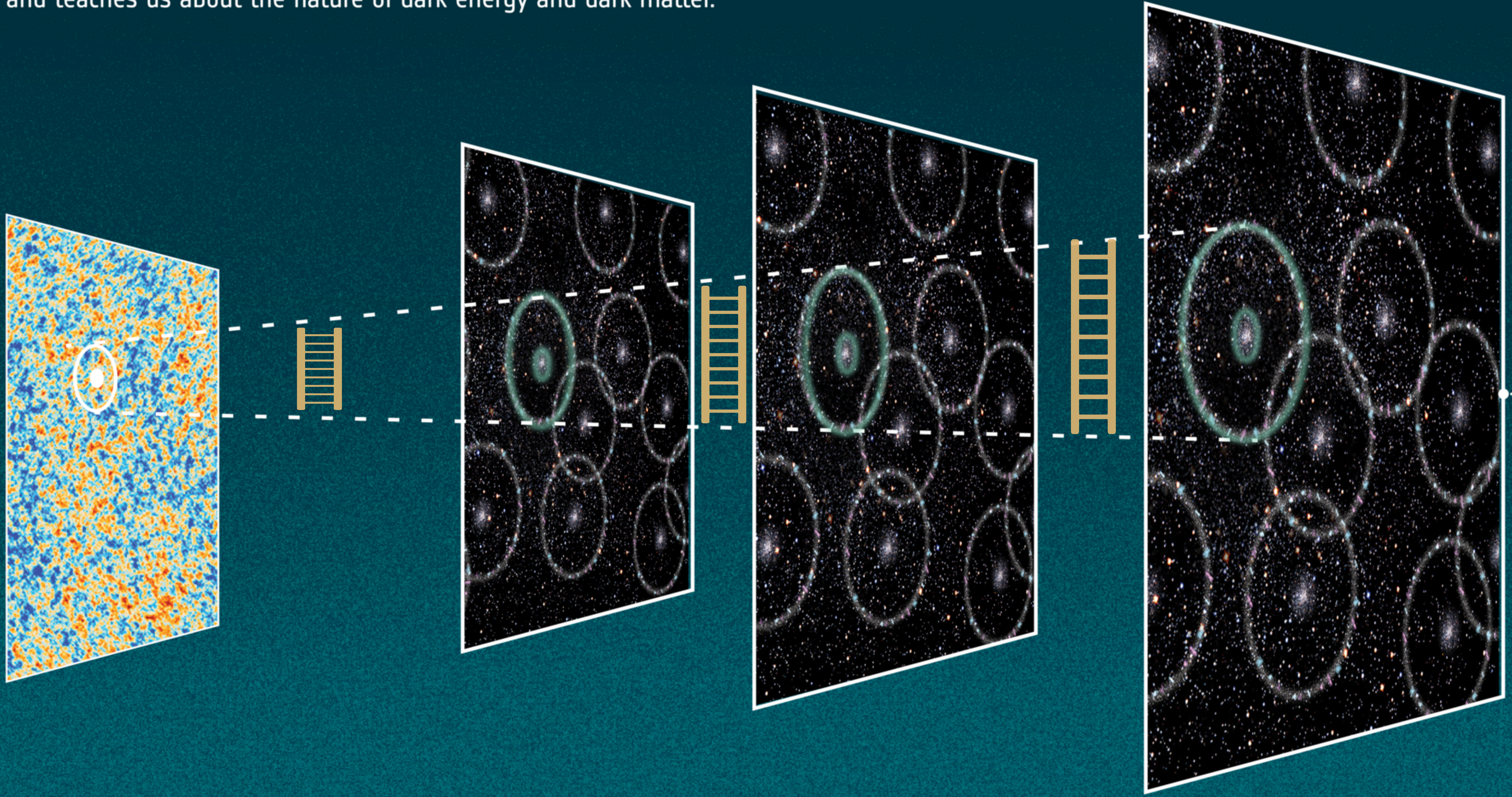
$\Delta B = -4.8$

$\Delta B = -5.1$

[CREDIT: NASA/ESA/HUBBLE]

WHAT EUCLID WILL MEASURE: BARYONIC ACOUSTIC OSCILLATIONS

When the early Universe first expanded, the formation of protons and neutrons created sound waves (bubbles) that rippled through the hot particle-radiation soup. About 300 000 years after the Big Bang, when the Universe had cooled down enough for atoms to form and light to travel freely, these waves froze in place. Over time, slightly more galaxies formed in clusters along the frozen ripples. The ripples stretched as the Universe expanded, increasing the distance between galaxies. Euclid will study the distribution of galaxies over immense distances, teasing out these ripple patterns and determining their size. This enables us to measure accurately the accelerated expansion of the Universe and teaches us about the nature of dark energy and dark matter.



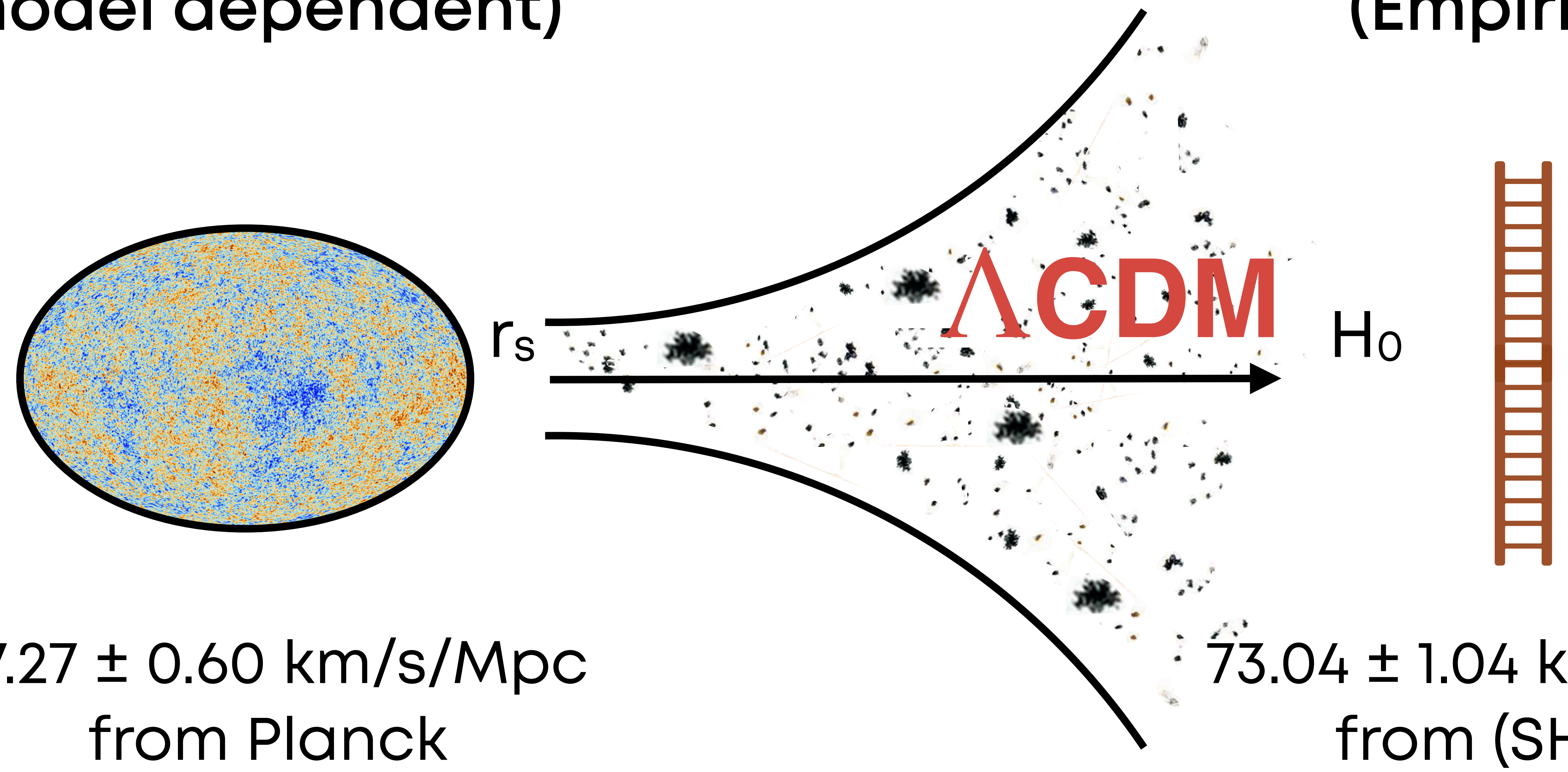
Artist's impression of the pattern of baryonic acoustic oscillations imprinted on the large-scale distribution of galaxies (exaggerated)

Source: ESA and the Planck Collaboration / Gabriela Secara / Perimeter Institute

Cosmological Tensions

CMB
(model dependent)

Local
(Empirical)



67.27 ± 0.60 km/s/Mpc
from Planck

73.04 ± 1.04 km/s/Mpc
from (SH0ES)