

# BAO Experiments in Tension



- **Methods**
- **Redshift Coverage**
- **Interpretation**

**Ruchika**

**University of Salamanca, Spain**

**GGI workshop 2026: Exploring New Frontiers in Cosmology**  
**Florence**

**GRAVITATION**  
**COSMOLOGY** and group at **USAL**



# Outline of the Talk!

---

- Brief introduction to **Baryon Acoustic Oscillations (BAO)**
- Tensions in  $\Lambda$ CDM cosmology : Hubble Tension
- BAO data suggests the need for introducing **Early Dark Energy**
- **2D vs 3D BAO** — what is the difference?
- Anomalies in 2D vs 3D BAO data
- SDSS vs DESI comparisons
- Final Take-away & Future Directions

# Outline of the Talk!

---

- Brief introduction to **Baryon Acoustic Oscillations (BAO)**
- Tensions in  $\Lambda$ CDM cosmology : Hubble Tension
- BAO data suggests the need for introducing **Early Dark Energy**
- **2D vs 3D BAO** — what is the difference?
- ✓ Anomalies in 2D vs 3D BAO data
- ✓ SDSS vs DESI comparisons
- Final Take-away & Future Directions



**BAO** are **frozen-in imprints** of acoustic waves that propagated in the hot baryon-photon plasma of the early Universe.

## Physical Picture

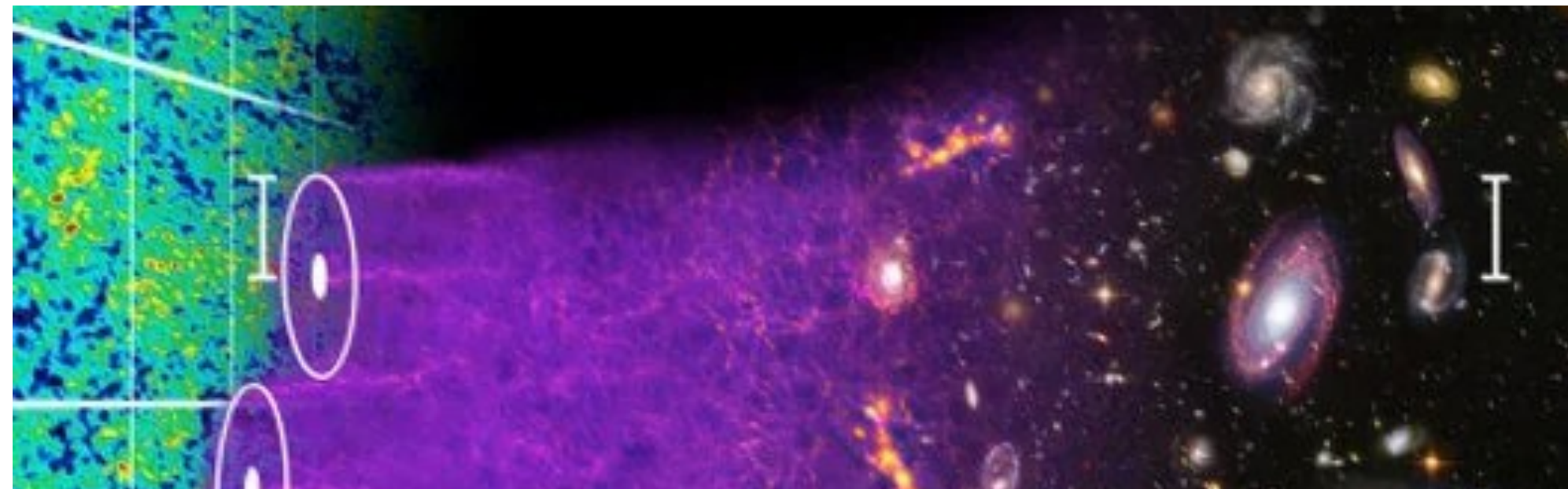
- Before recombination: photons & baryons coupled → sound waves propagate at  $c_s \approx c/\sqrt{3}$
- At **drag epoch** ( $z_d \approx 1060$ ): baryons released → sound waves "freeze"
- Maximum distance traveled = **sound horizon**  $r_d \approx 147$  Mpc
- Leaves preferred separation between galaxies — a **standard ruler**

$$r_d = \int_0^{t(z_d)} c_s(1+z) dt$$

## Why is BAO Powerful?

- Calibrated by **early-Universe physics** (CMB)
- Measured at **low redshift** via galaxy surveys
- Connects two sides of the Universe
- Robust to many systematics

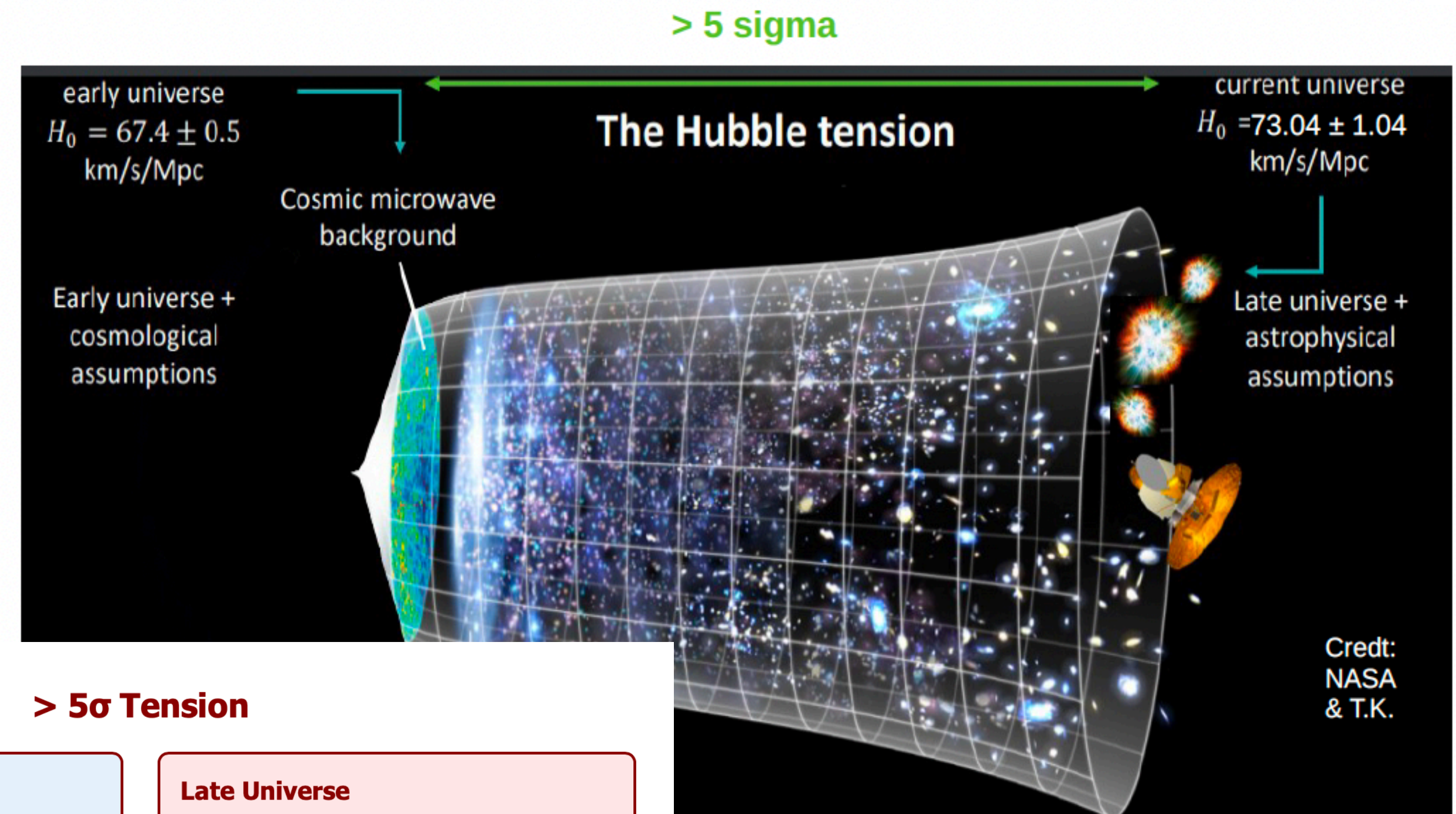
Sound horizon  $r_d$  and Hubble constant  $H_0$  are **complementary anchors**.





# The Hubble Tension: Two Ends of Cosmic History Disagree

- ▶ **Standard ruler:** CMB acoustic scale — early universe
- ▶ **Standard candle:** Type Ia SNe + Cepheids — late universe
- ▶ Two independent methods → statistically significant disagreement



**> 5 $\sigma$  Tension**

**Early Universe**

$$H_0 = 67.4 \pm 0.5$$

**km/s/Mpc**

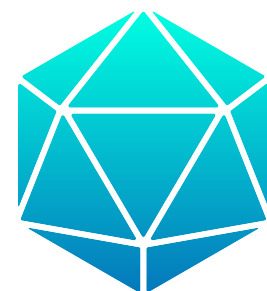
From CMB (Planck) + cosmological model assumption

**Late Universe**

$$H_0 = 73.04 \pm 1.04$$

**km/s/Mpc**

From Cepheids + SN Ia (SH0ES) + astrophysical assumptions





## What and how does BAO add to the picture?



**BAO measures the product of  $H_0$  and  $r_d$**



**$H_0$**  : absolute anchor at **low redshift**



**$r_d$**  : absolute anchor at **high redshift** 

*(opposite ends of the observable Universe)*



**How can BAO contribute to the Hubble Tension?**

### Two key questions:

**1**

**Is  $H_0$  tension correlated to any other Cosmological Parameter?**

→ **Yes**, since BAO measures the combination  $r_d \cdot H_0$ .

**2**

**Can we break this degeneracy of  $r_d H_0$ ?**

→ **Yes**, if we measure  $H_0$  independently, then we can estimate  $r_d$ .



# Data Used:

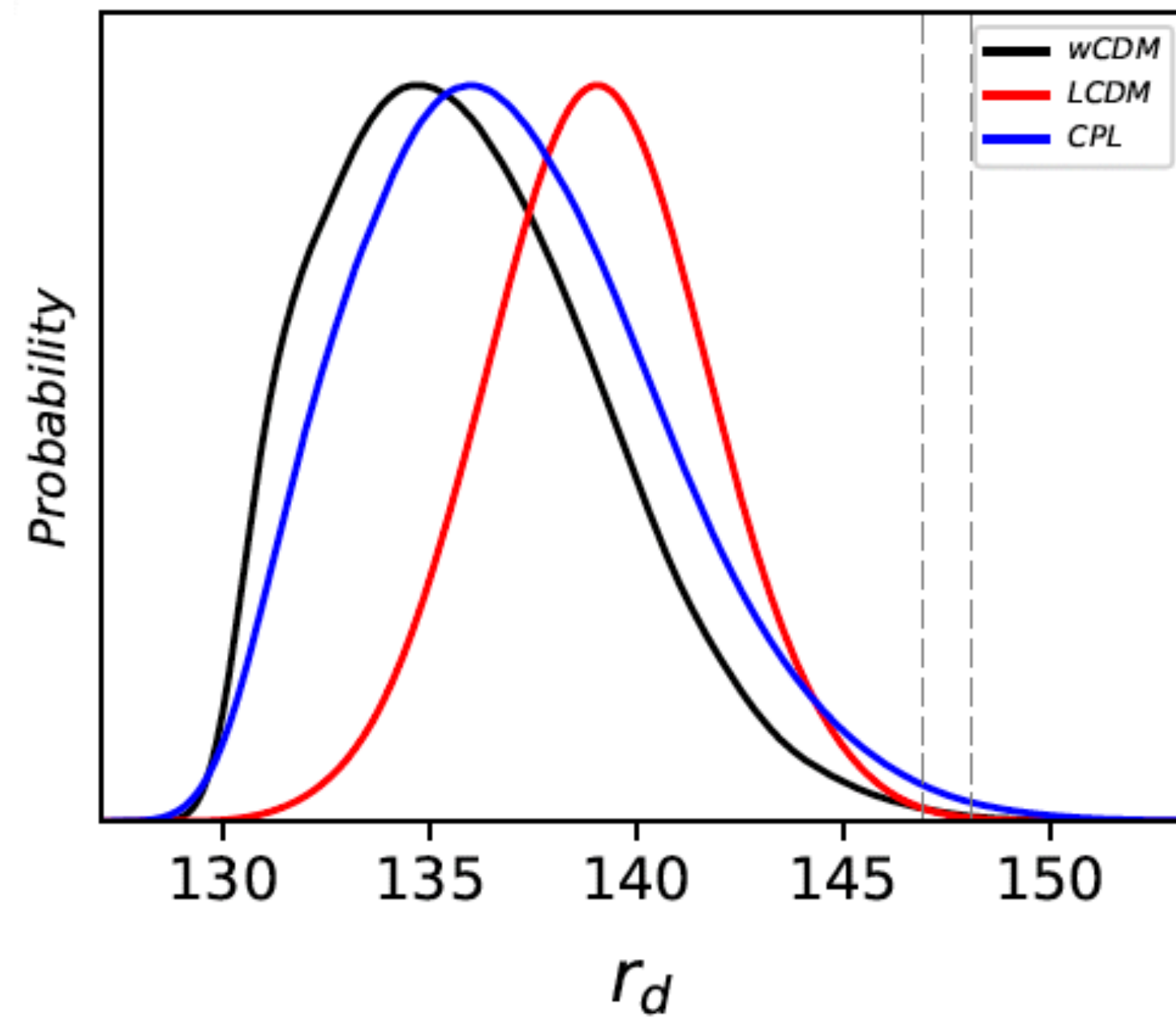
- BAO from 6dF, MGS, eBOSS, BOSS DR12 incl. Lyman- $\alpha$  forest
- Time-delay distances via Strong Lensing — H0LiCOW
- Angular diameter distances for galaxies UGC3789, NGC6264, NGC5765b
- $H_0 = 73.24 \pm 1.24$  km/s/Mpc — Riess et al. (2016)

# Results: ML values & 1D 68% confidence intervals

|               | $\Omega_{m0}$     | $r_d$ [Mpc]                       | $w_0$            | $w_a$           |
|---------------|-------------------|-----------------------------------|------------------|-----------------|
| $\Lambda$ CDM | $0.295 \pm 0.019$ | <b><math>139.2 \pm 3.2</math></b> | —                | —               |
| wCDM          | $0.277 \pm 0.027$ | <b><math>135.3 \pm 3.8</math></b> | $-0.76 \pm 0.14$ | —               |
| CPL           | $0.241 \pm 0.084$ | <b><math>136.4 \pm 3.9</math></b> | $-0.77 \pm 0.17$ | $0.44 \pm 0.53$ |

Model-independent  $r_d = 136.41 \pm 3.82$  Mpc Pade Approximation

Refs: Evslin, Sen, Ruchika, PRD 97, 103511 (2018); Capozziello, Ruchika, Sen, MNRAS 484 (2019) 4484

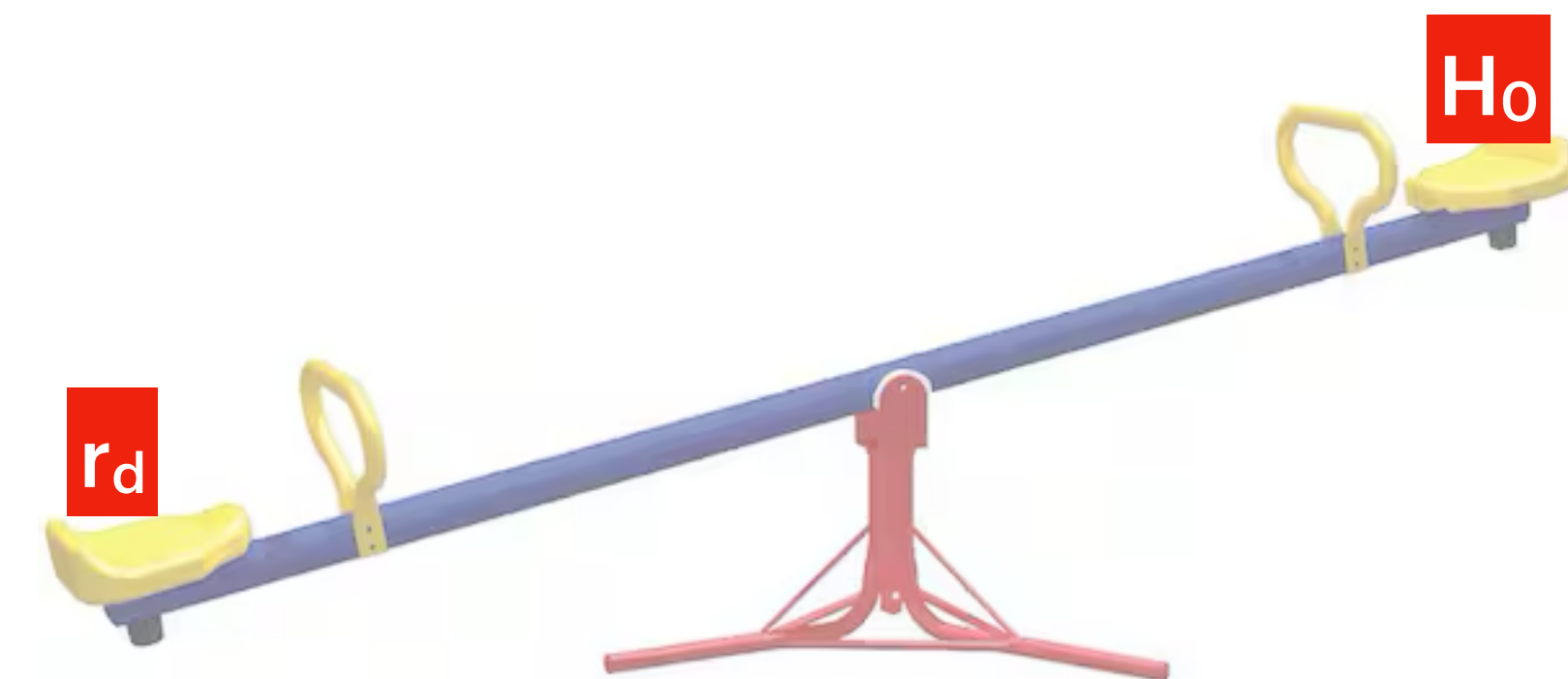


$$r_d = 147.26 \pm 0.29 \text{ Mpc (Planck)}$$

- $\Lambda$ CDM: 2.52  $\sigma$  away from Planck
- $w$ CDM : 3.14  $\sigma$  away from Planck
- CPL : 2.79  $\sigma$  away from Planck

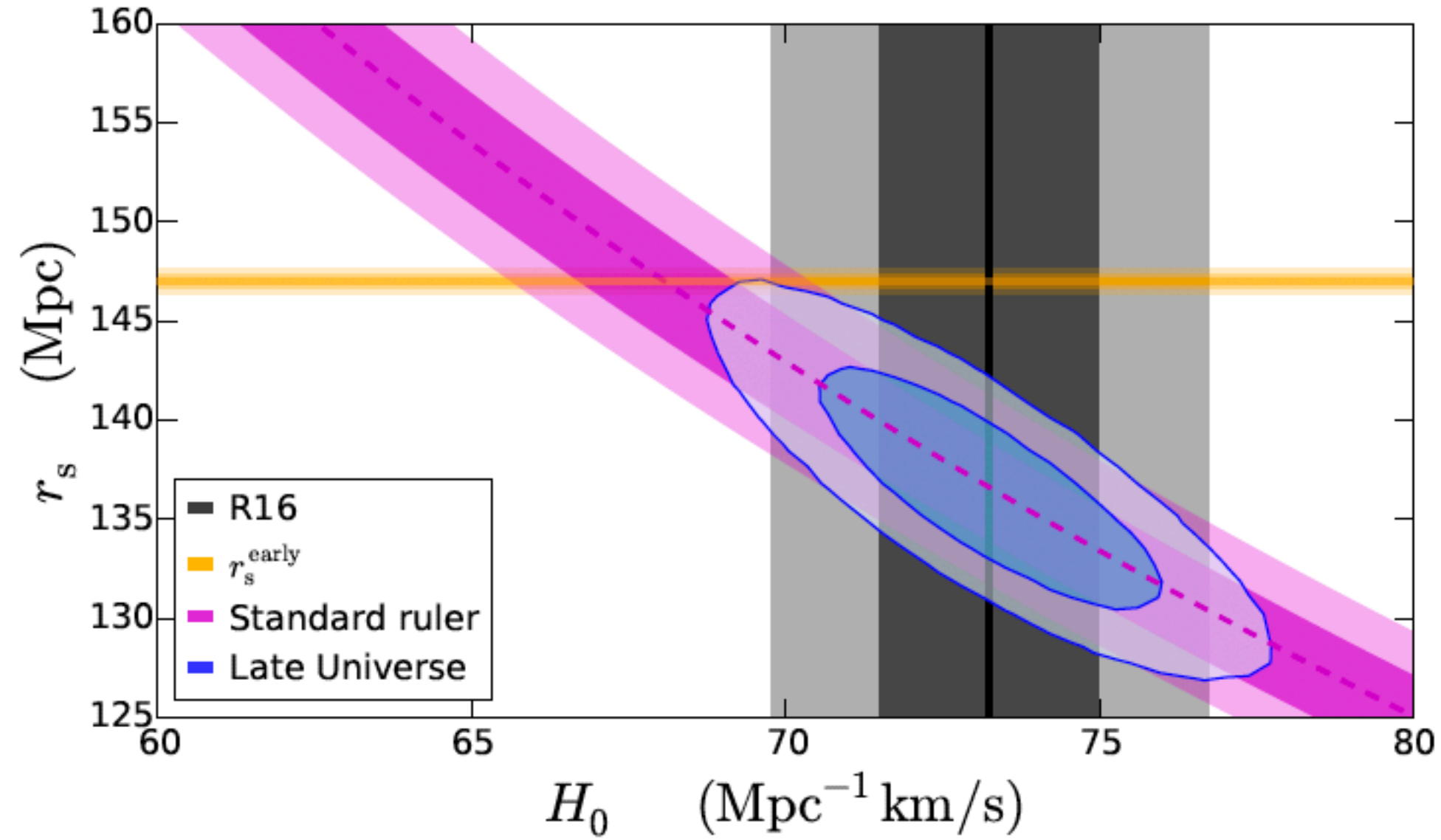
So, our results are quite model independent.

So, The Price of shift in Hubble constant is the shift in  $r_d$ .

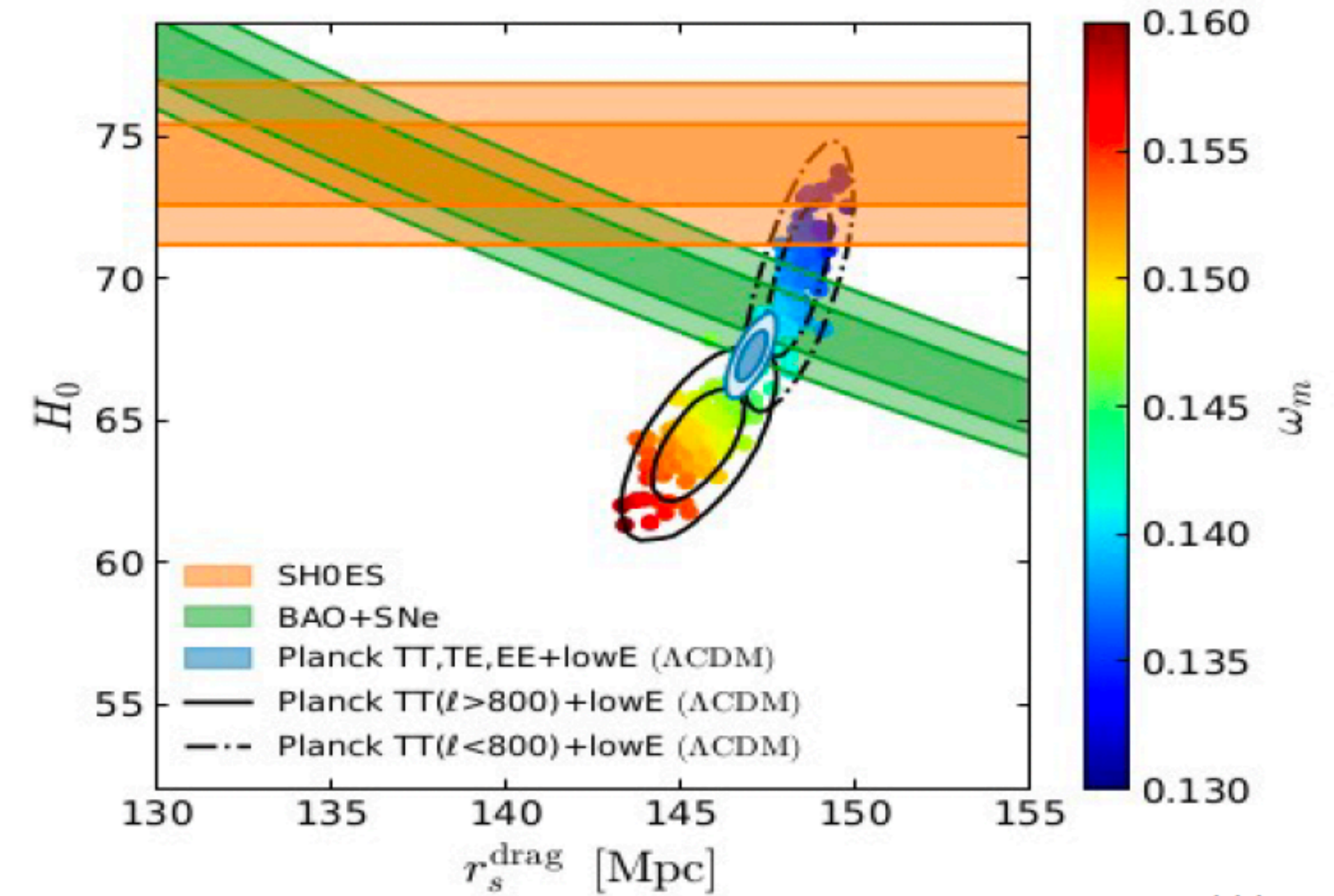




# Other Results in similar direction!



Same is also seen by [Bernal, Verde, Riess, JCAP 2016](#)



Hubble Hunter's Guide  
Knox et al. 2019

**# Late Universe suggests : Price of shift in  $H_0$  is the shift in  $r_d$**   
Increase in  $H_0$  require decreased  $r_d$

|       | Planck (Early Universe)                         |               | Local (Late Universe)                               |
|-------|-------------------------------------------------|---------------|-----------------------------------------------------|
| $H_0$ | $67.37 \pm 0.54 \text{ km/s/Mpc}$               | $\Rightarrow$ | <b><math>73.24 \pm 1.24 \text{ km/s/Mpc}</math></b> |
| $r_d$ | <b><math>147.26 \pm 0.29 \text{ Mpc}</math></b> | $\Leftarrow$  | $139.2 \pm 3.2 \text{ Mpc}$                         |

**To find Early Universe solutions to Hubble Tension** — i.e. to increase  $H_0$  at high redshift — we need to **decrease  $r_d$  around recombination**.





$$r_d = \int_0^{t(z_d)} c_s (1+z) dt = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)} dz$$

**Physics:** Sound waves propagate in early Universe until radiation and matter decouple.

### **Lower $r_d$ compared to Planck suggests:**

- ~~Changing  $z_d$  (drag-epoch redshift)~~
- ~~Modifying the speed of sound  $c_s$~~
- ~~Changing primordial fluctuations~~
- Changing the age (expansion history) of universe at drag epoch — most viable!

Increasing  $H(z)$  at recombination (e.g. via extra energy component) **reduces**  $r_d$ .

- Along with **Hubble Tension**, there is a similar tension involving **sound horizon at drag epoch** from low-redshift and Planck measurements.
- It does **not depend on dark energy behaviour** (late-time)
- Since  $r_d$  is governed by **early universe physics**, to reduce  $r_d$  or increase  $H_0$  around recombination, one needs to **modify the early universe cosmology**.

## ✨ **Solution proposed: Early Dark Energy (EDE)**

EDE adds a transient dark-energy-like component active near recombination that decays away afterward, reducing  $r_d$  while leaving late-time cosmology intact.



## The Key Question

“

Can some data give

🌟  $r_d$  compatible with CMB

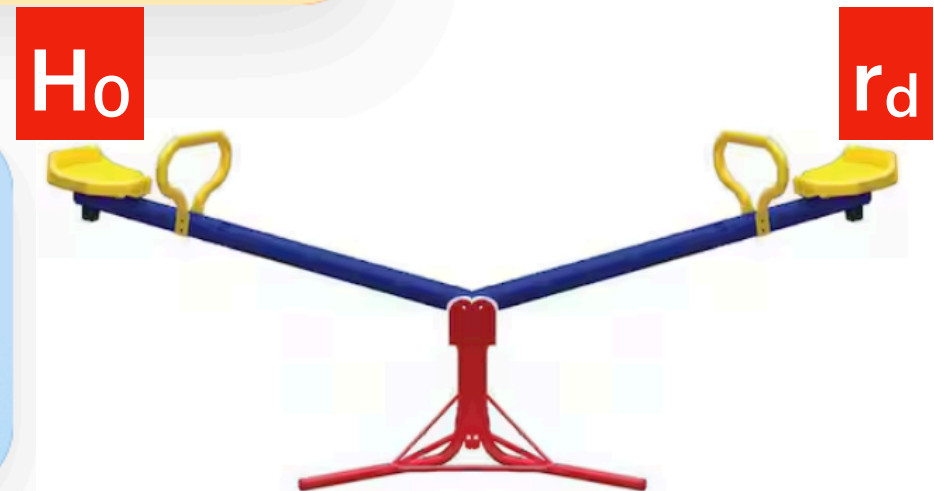
AND

🌌  $H_0$  compatible with SH0ES

both higher ?



Do we expect it from BAO?





# The Key Question

“

Can some data give

🌟  $r_d$  compatible with CMB ( $\approx 147$  Mpc)

AND

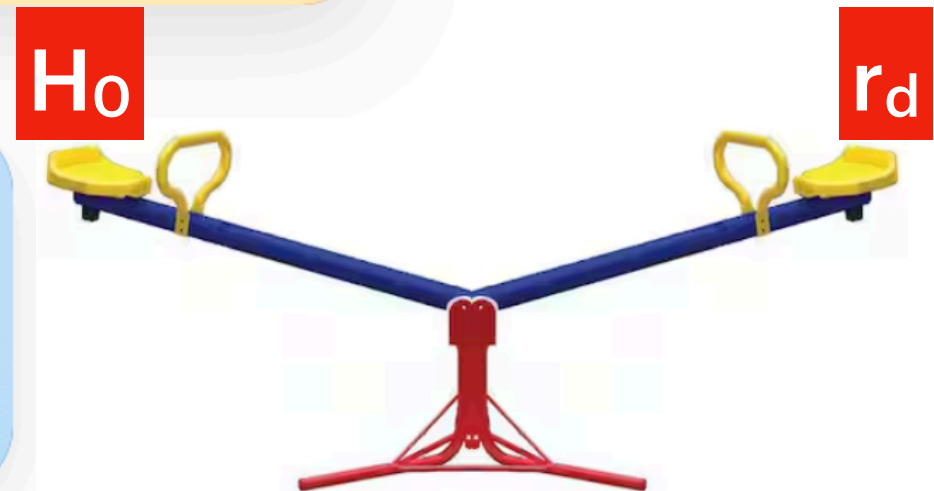
🌌  $H_0$  compatible with SH0ES ( $\approx 73$  Km/s/Mpc)

both higher ?

( $\approx 67.5$  Km/s/Mpc)  
Compatible with  
CMB



Do we expect it from BAO?





## The Key Question

“

~~No~~

Can some data give

🌟  $r_d$  compatible with CMB ( $\approx 147$  Mpc)

AND

🌌  $H_0$  compatible with SH0ES ( $\approx 73$  Km/s/Mpc)

both higher ?

Yes!



Do we expect it from BAO?

No!

# Reviewing Anomalies in BAO: 2D vs 3D BAO

Ruchika

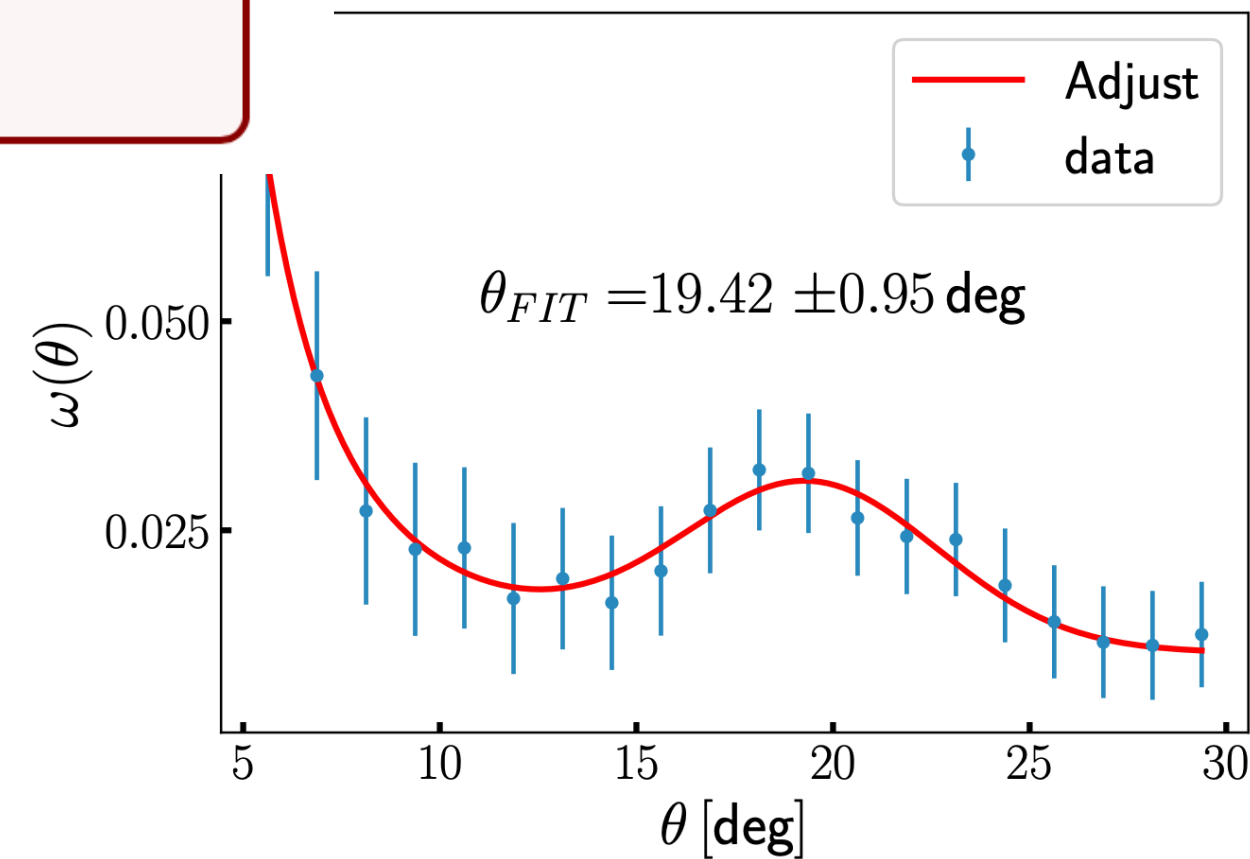
*Phys.Rev.D* 112 (2025) 6, 6



# Two Methodologies, Two Stories!

## 2D BAO (angular / transverse)

- Uses **angular two-point correlation** in **thin redshift shells**
- Measures purely **angular scale**  $\theta_{\text{BAO}}(z)$
- **Less** dependent on fiducial cosmology assumed in data analysis
- Provides  $\theta_{\text{BAO}} = r_d / [(1+z)D_A(z)]$
- Examples: SDSS DR10/11/12 angular measurements

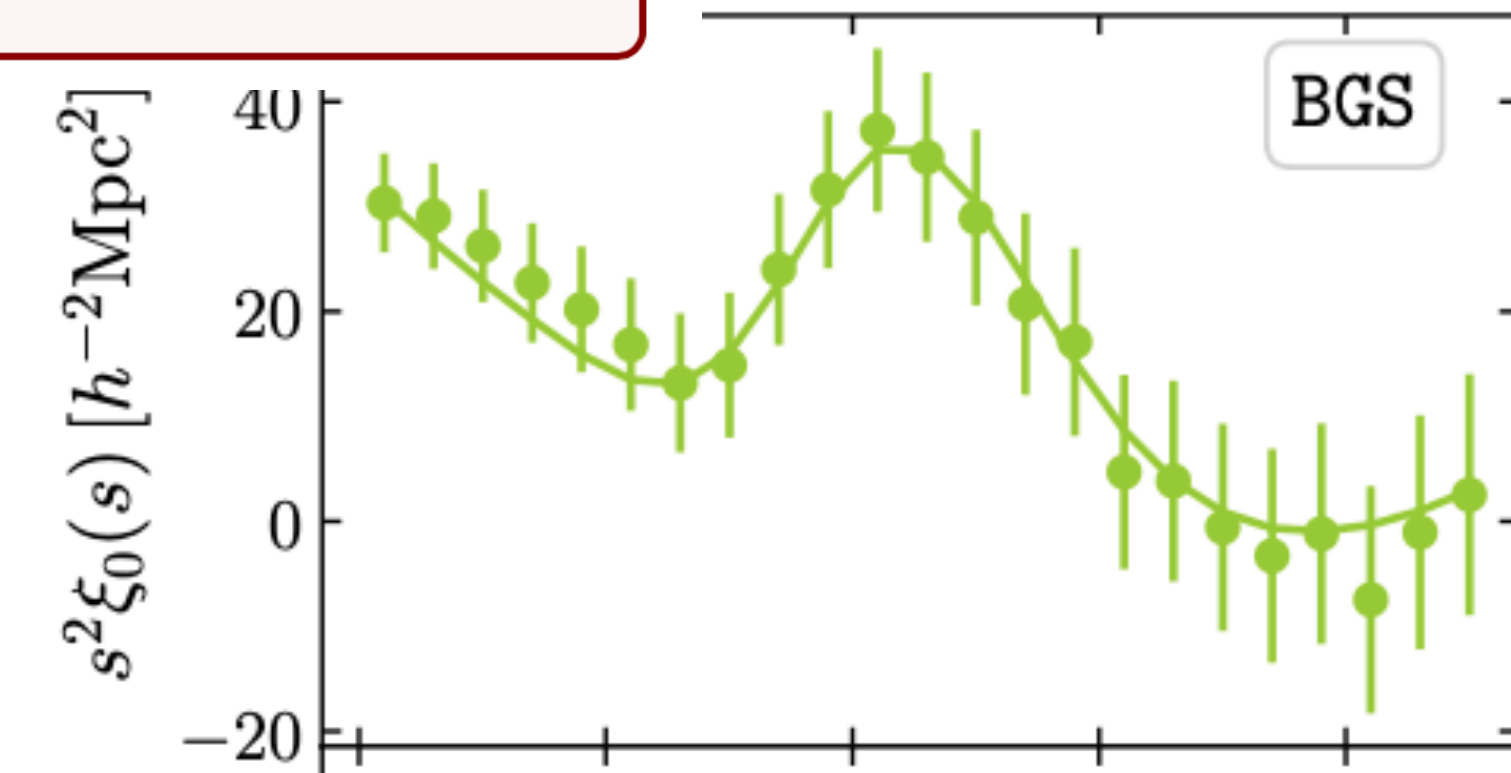


$$\omega(\theta) \equiv \frac{DD(\theta) - 2DR(\theta) + RR(\theta)}{RR(\theta)}$$

$$\omega(\theta) = A + B\theta^\gamma + C \exp^{-(\theta - \theta_{\text{FIT}})^2 / 2\sigma_{\text{FIT}}^2}$$

## 3D BAO (anisotropic / isotropic)

- Uses **full 3D galaxy clustering** (correlation function  $\xi(s)$  or power spectrum  $P(k)$ )
- Requires **fiducial cosmology** to convert redshifts  $\rightarrow$  distances
- Reports **shift parameters**  $\alpha_{\parallel}, \alpha_{\perp}$
- Provides  $D_M(z)/r_d$  and  $D_H(z)/r_d$
- Examples: BOSS, eBOSS, DESI



$$P(k) = [P_{\text{lin}}(k) - P_{\text{nw}}(k)] \exp \left[ - \left( \frac{k \Sigma}{h} \right)^2 \right] + P_{\text{nw}}(k).$$

# Two Methodologies, Two Stories!

## Observables Used

- Luminosity Distance<sub>measured</sub>

$$M = m - 5 \log_{10} \frac{D_L}{10 \text{ pc}}$$

- Angular Diameter Distance & Volumetric Distance<sub>inferred</sub>

$$D_L = (1 + z)^2 D_A, \quad D_H \text{ \& \& } D_M(z).$$

$$D_V(z) = \left[ (1 + z)^2 D_A^2(z) z D_H \right]^{1/3},$$

- 2D BAO measurements from angular separation of pairs of galaxies<sub>measured</sub>

$$\theta_{BAO}(z) [^\circ]$$

## Data Used

- Supernoave Type-Ia

Pantheon Plus Sample which comprises 1701 SNe data points ranging in the redshift interval  $0.01 \leq z \leq 2.3$

- 3D BAO data including DESI

Anisotropic: BOSS DR12  
Isotropic: 6dF, MGS, eBOSS

- 2D BAO data / Thin redshift slice

11  $\theta_{BAO}(z)$  measurements obtained from public data of the Sloan Digital Sky Survey (SDSS), namely DR10, DR11, and DR12



# Where does the model dependence enter?

## Measured Quantities

- Flux/Apparent Magnitude<sub>measured</sub>

$$M = m - 5 \log_{10} \frac{D_L}{10 \text{ pc}}$$

- Ratio of Distances/ rd

$$\alpha_{\perp} = \frac{D_M(z) r_{d, \text{fid}}}{D_M^{\text{fid}}(z) r_d}; \quad \alpha_{\parallel} = \frac{H^{\text{fid}}(z) r_{d, \text{fid}}}{H(z) r_d}$$

- Theta measurements

$$\theta_{BAO}(z) [^{\circ}]$$

$$= \frac{r_d}{(1+z) D_A(z)}$$

measured

## Model Used:

$$\frac{H^2(z)}{H_0^2} = \Omega_{m0}(1+z)^3 + (1 - \Omega_{m0}),$$

## Data Used

- Supernovae Type-Ia

MB used from both high and low redshift experiments.

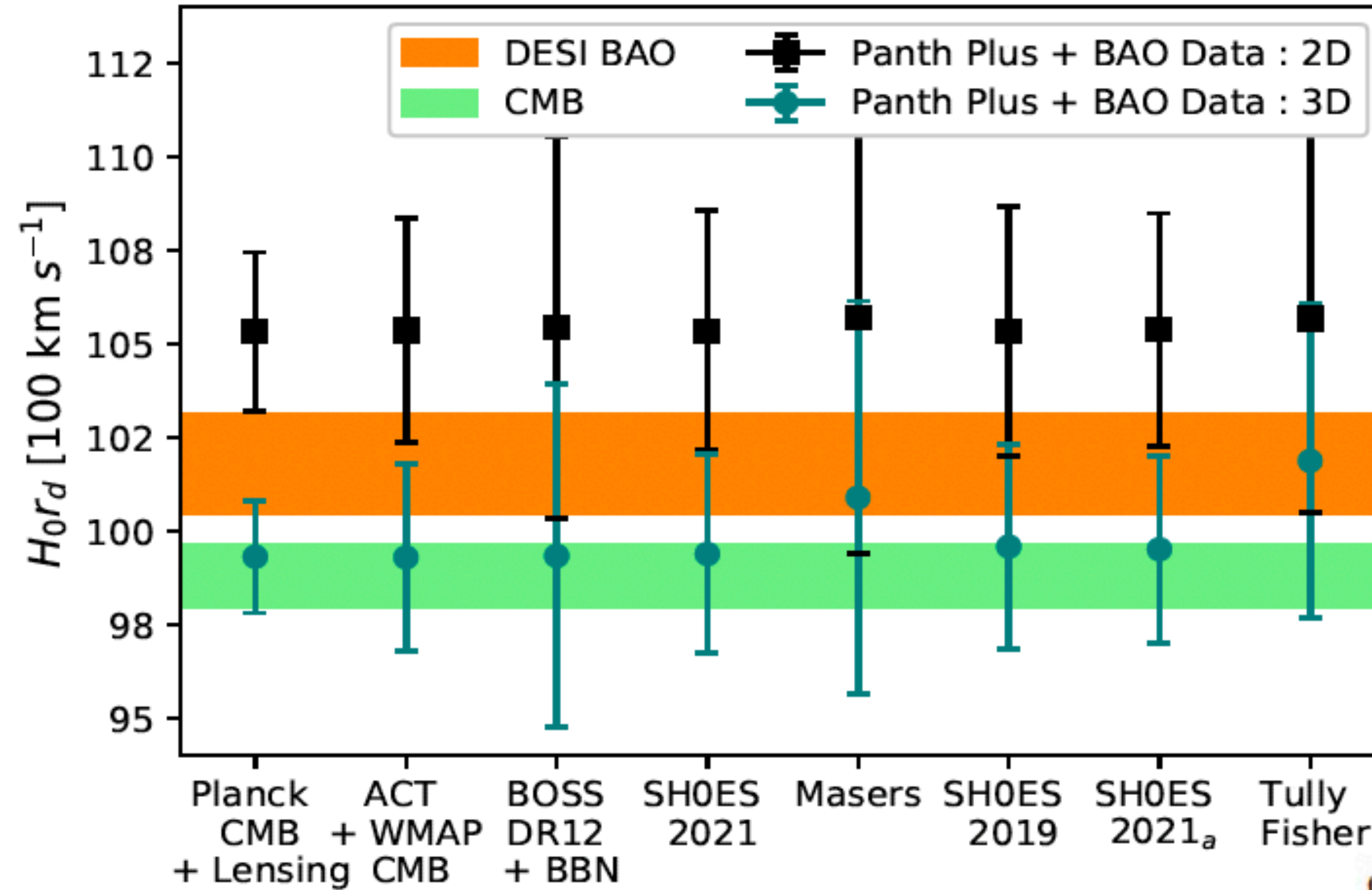
- 3D BAO data

Measures shift from fiducial cosmology parameters.

- 2D BAO data / Thin redshift slice

Utilises fiducial cosmology to extract true baryonic theta.

# Two Methodologies, Two Results but same redshift!



Assumption:  
Standard Cosmological Model

**Result:** Product  $H_0 r_d$  from 2D and 3D BAO agrees within less than 1.5 sigma interval irrespective of SN calibration.

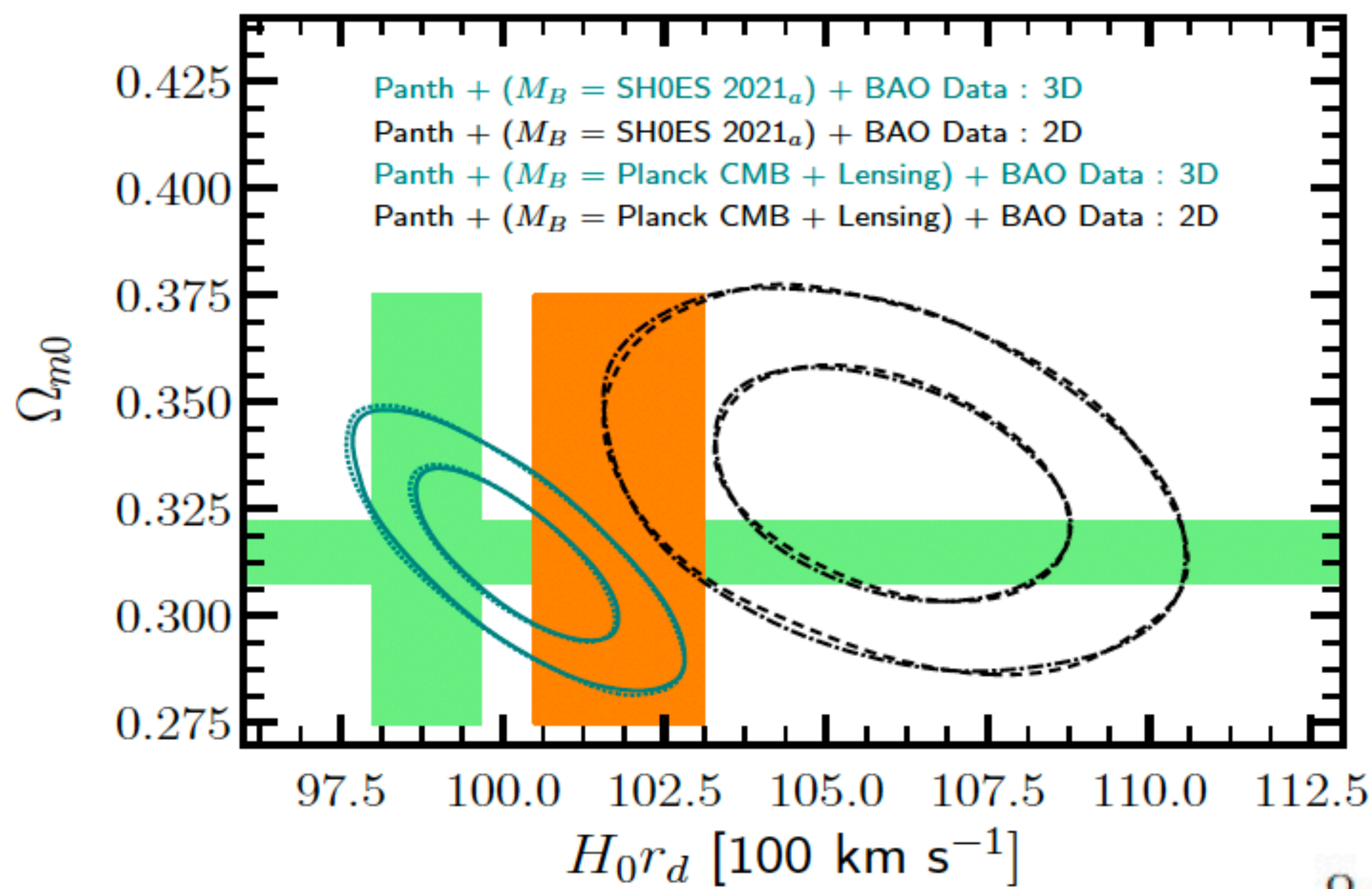
$$\left. \begin{aligned} \Omega_{m0} &= 0.314 \pm 0.0132 \\ r_d h &= 100.72 \pm 2.42 \text{ Mpc} \end{aligned} \right\} \text{BAO : 3D + PP}$$

$$\left. \begin{aligned} \Omega_{m0} &= 0.331 \pm 0.018 \\ r_d h &= 105.95 \pm 3.11 \text{ Mpc} \end{aligned} \right\} \text{BAO : 2D + PP}$$

MB= SH0ES'21<sub>a</sub>



Same redshift, Different results; so the BAO Anomaly!



Assumption:  
Standard Cosmological Model

Is it trouble to  
- Standard Cosmological  
Model we assumed?

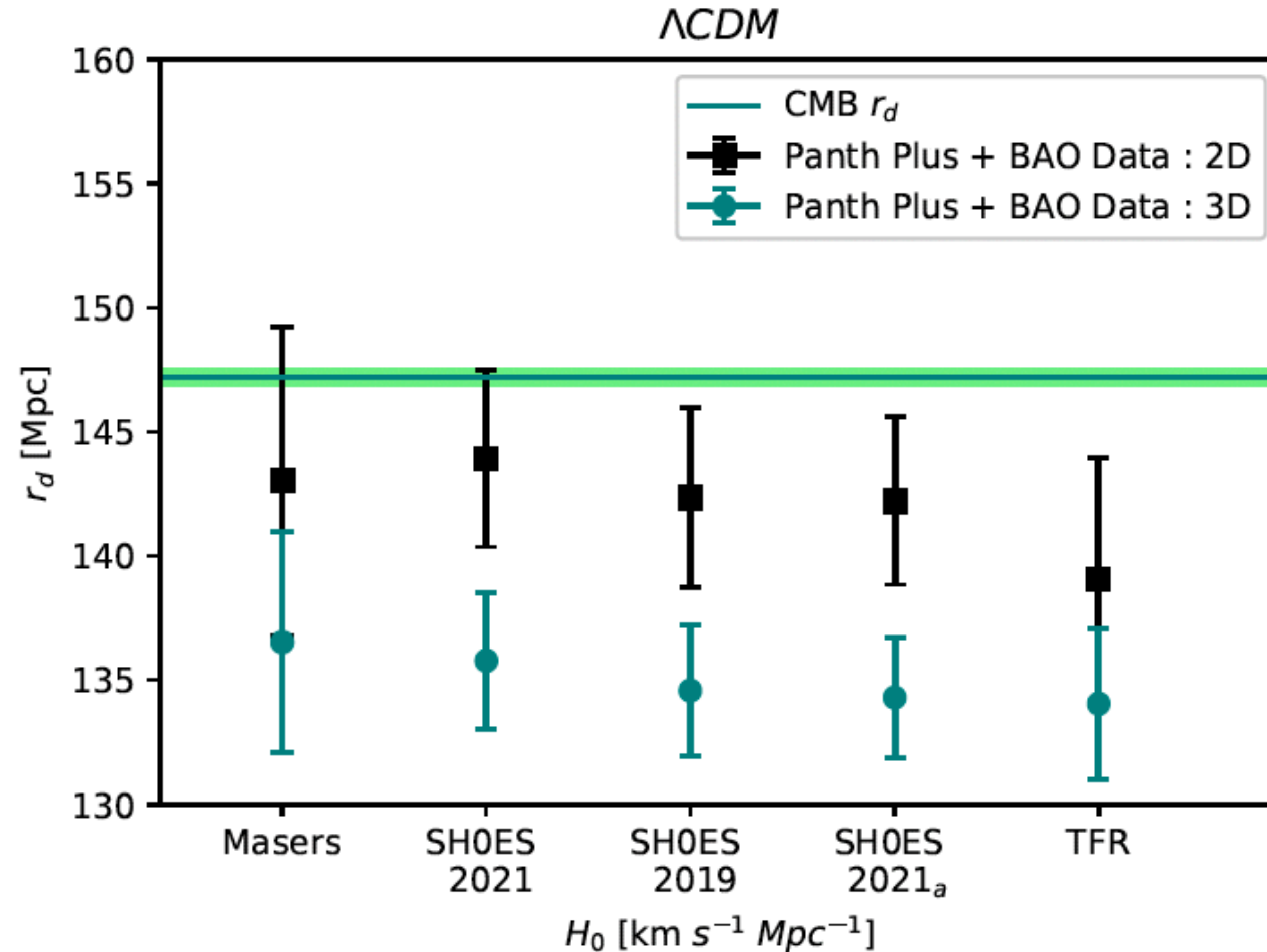
DESI BAO  
CMB

$$\left. \begin{aligned} \Omega_{m0} &= 0.314 \pm 0.0132 \\ r_d h &= 100.72 \pm 2.42 \text{ Mpc} \end{aligned} \right\} \text{BAO : 3D + PP}$$

$$\left. \begin{aligned} \Omega_{m0} &= 0.331 \pm 0.018 \\ r_d h &= 105.95 \pm 3.11 \text{ Mpc} \end{aligned} \right\} \text{BAO : 2D + PP}$$

MB= SH0ES'21<sub>a</sub>

# Conclusion: Concluding what not to conclude



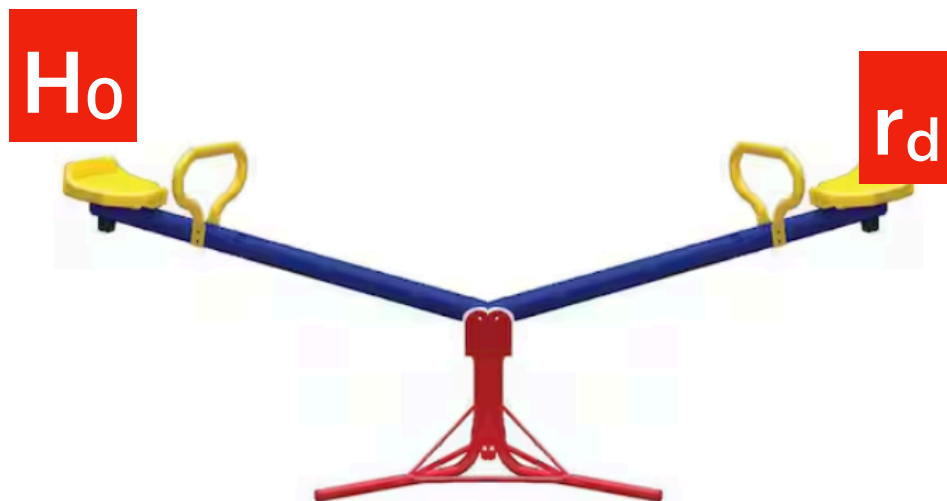
Reminder: 2D BAO  
measures higher  $H_0 r_d$ .

**Result:**

$r_d$  obtained from 2D BAO is  
compatible with Planck  $r_d$  (higher  
value) and higher  $H_0$ .

**Conclusion:**

That is why, we should be very  
careful when we propose new  
cosmological models to solve  
cosmological tension such as  
Hubble tension while using 2D  
BAO Dataset.





## 🎯 Final Takeaway

①  $H_0$  tension is related to  $r_d$  tension (through BAO)

② If we change  $H_0$  to a high value at high redshift, then we need to **decrease**  $r_d$

③ **2D BAO measures  $H_0 r_d$  higher** than 3D BAO and DESI analyses under standard  $\Lambda$ CDM cosmology

★ Using **2D BAO**, a higher  $H_0$  compatible with **SH0ES** and a higher sound horizon  $r_d$  compatible with **Planck** can be achieved **even within  $\Lambda$  CDM framework**

⚠ **Caution must be taken** while concluding about cosmological tensions, especially while using the 2D BAO dataset



## 🎯 Final Takeaway

①  $H_0$  tension is related to  $r_d$  tension (through BAO)

② If we change  $H_0$  to a high value at high redshift, then we need to **decrease**  $r_d$

③ **2D BAO measures  $H_0 r_d$  higher** than 3D BAO and DESI analyses under standard  $\Lambda$ CDM cosmology

★ Using **2D BAO**, a higher  $H_0$  compatible with **SH0ES** and a higher sound horizon  $r_d$  compatible with **Planck** can be achieved **even within  $\Lambda$  CDM framework**

⚠ **Caution must be taken** while concluding about cosmological tensions, especially while using the 2D BAO dataset

## 🔬 Ongoing Work

🔍 **Finding the cause of 2D and 3D BAO anomaly**

Collaboration — (Salamanca team: Jose Beltrán, Marcello Musso), Shadab Alam



# Comparing BAO Results: SDSS vs DESI

Anna Chiara Ferri · Ruchika · Alessandro Melchiorri



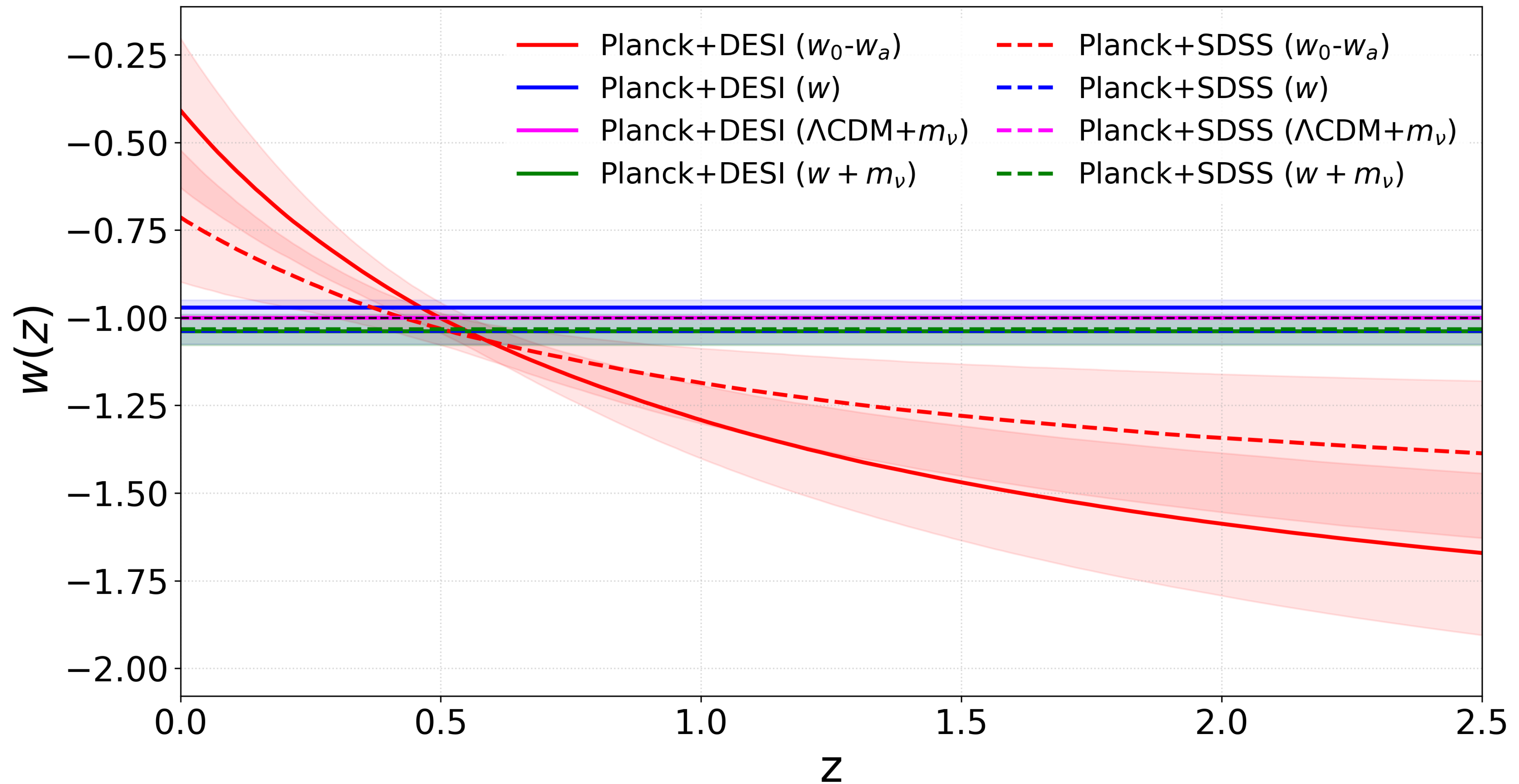
**BASED ON**

*"Present Day Cosmic Acceleration from SDSS and DESI BAO:  
A Call for Finer Tomography of the DESI Bright Galaxy Survey"*

e-Print: [arXiv:2607.07348](https://arxiv.org/abs/2607.07348)

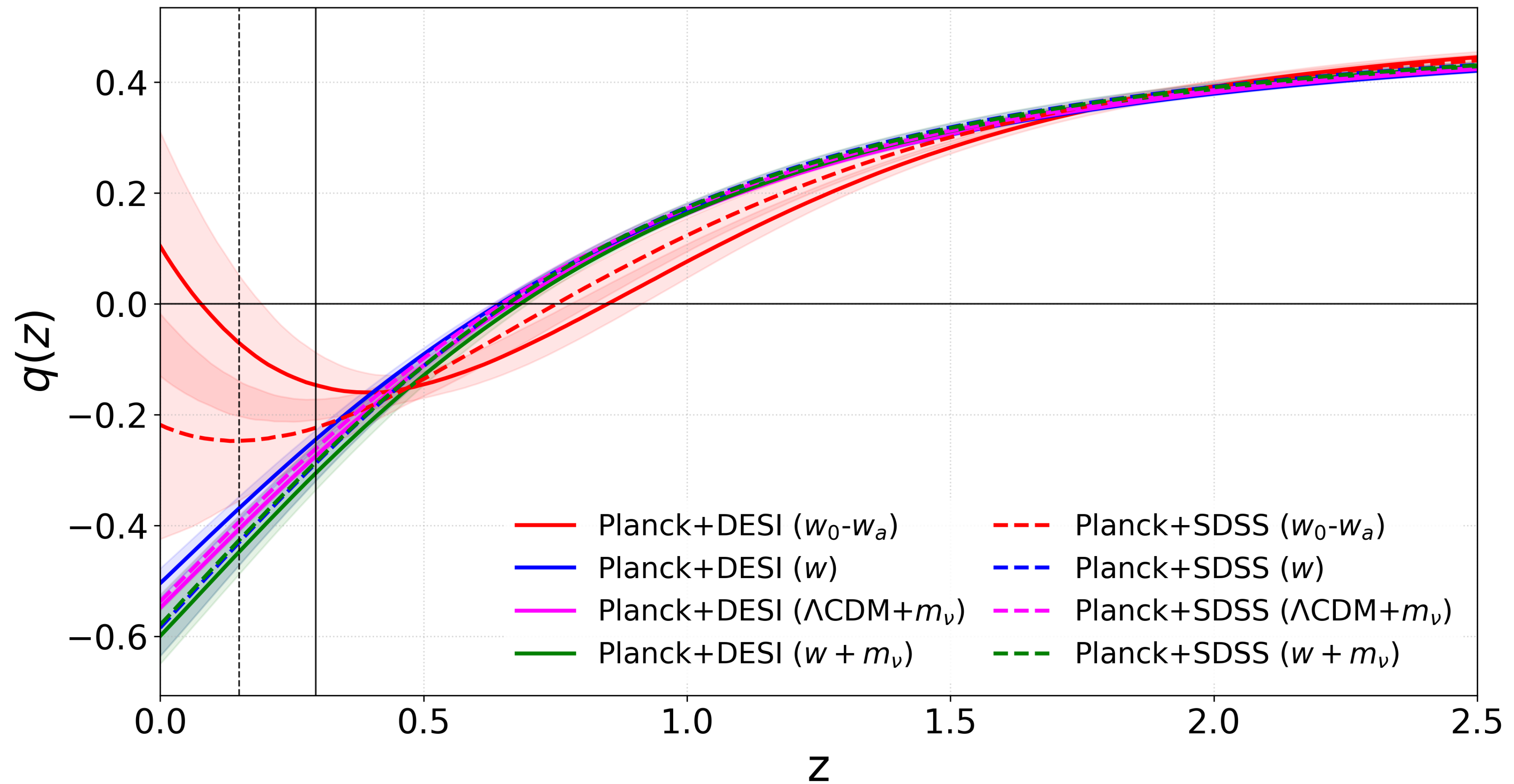


# Evolution of Dark Energy Equation of State

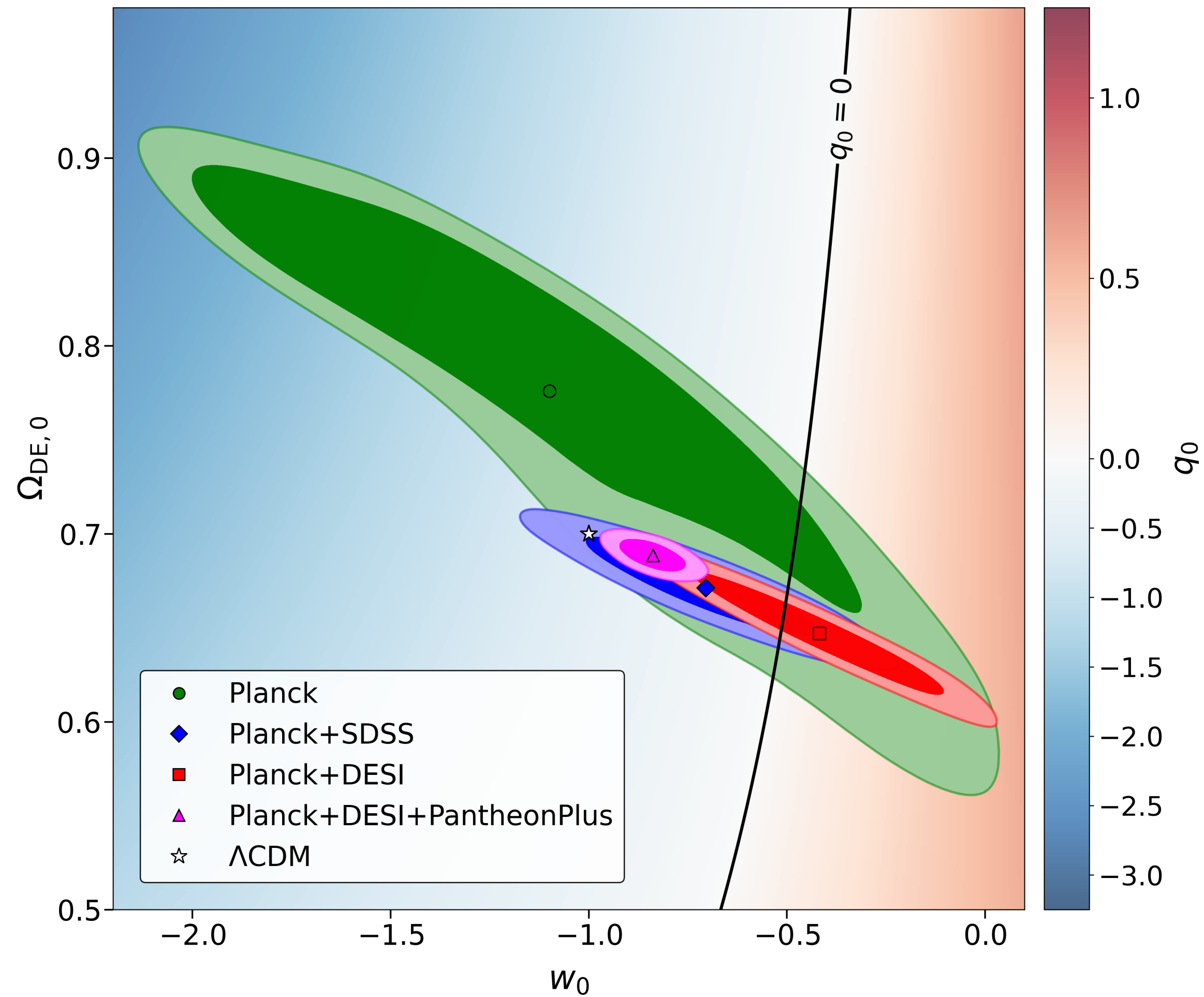




# Evolution of De-acceleration Parameter



# DESI DR2 vs SDSS: Diverging Views of Dark Energy



## SDSS + Planck

$$w_0 = -0.71^{+0.19}_{-0.18}$$

$$q_0 = -0.22^{+0.20}_{-0.21}$$

*accelerated expansion today*

## DESI + Planck

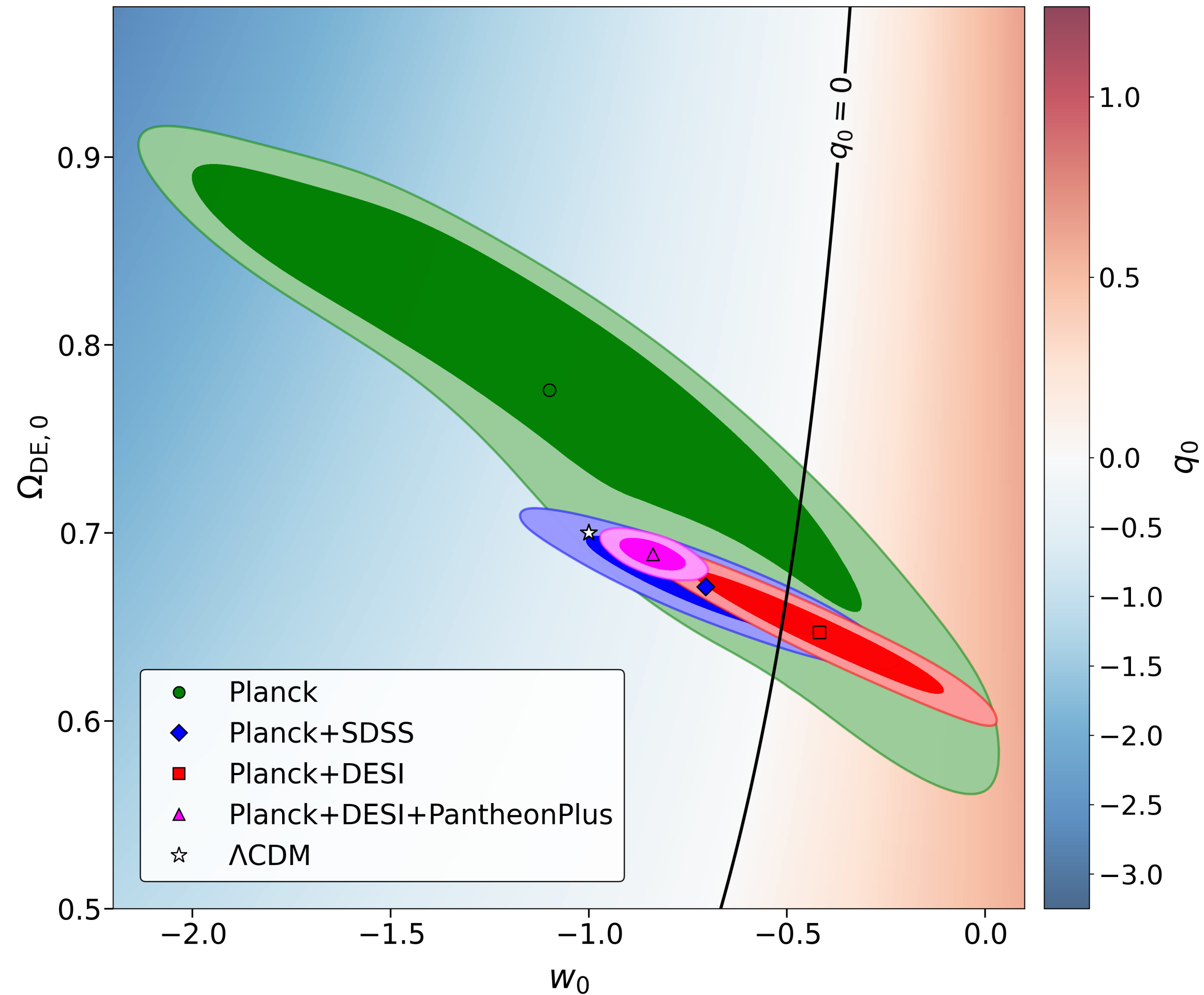
$$w_0 = -0.41^{+0.21}_{-0.22}$$

$$q_0 = +0.10^{+0.21}_{-0.23}$$

*median on decelerating side (consistent with  $q_0 = 0$  at  $1\sigma$ )*



# Take Away:



$$q_0 = \frac{1}{2}\Omega_m + \frac{1}{2}(1 + 3w_0)\Omega_{\text{DE}}.$$

1

DESI+Planck favors a **higher**  $w_0$  than SDSS+Planck — a stronger pull away from  $\Lambda$ CDM ( $w_0 = -1$ ).

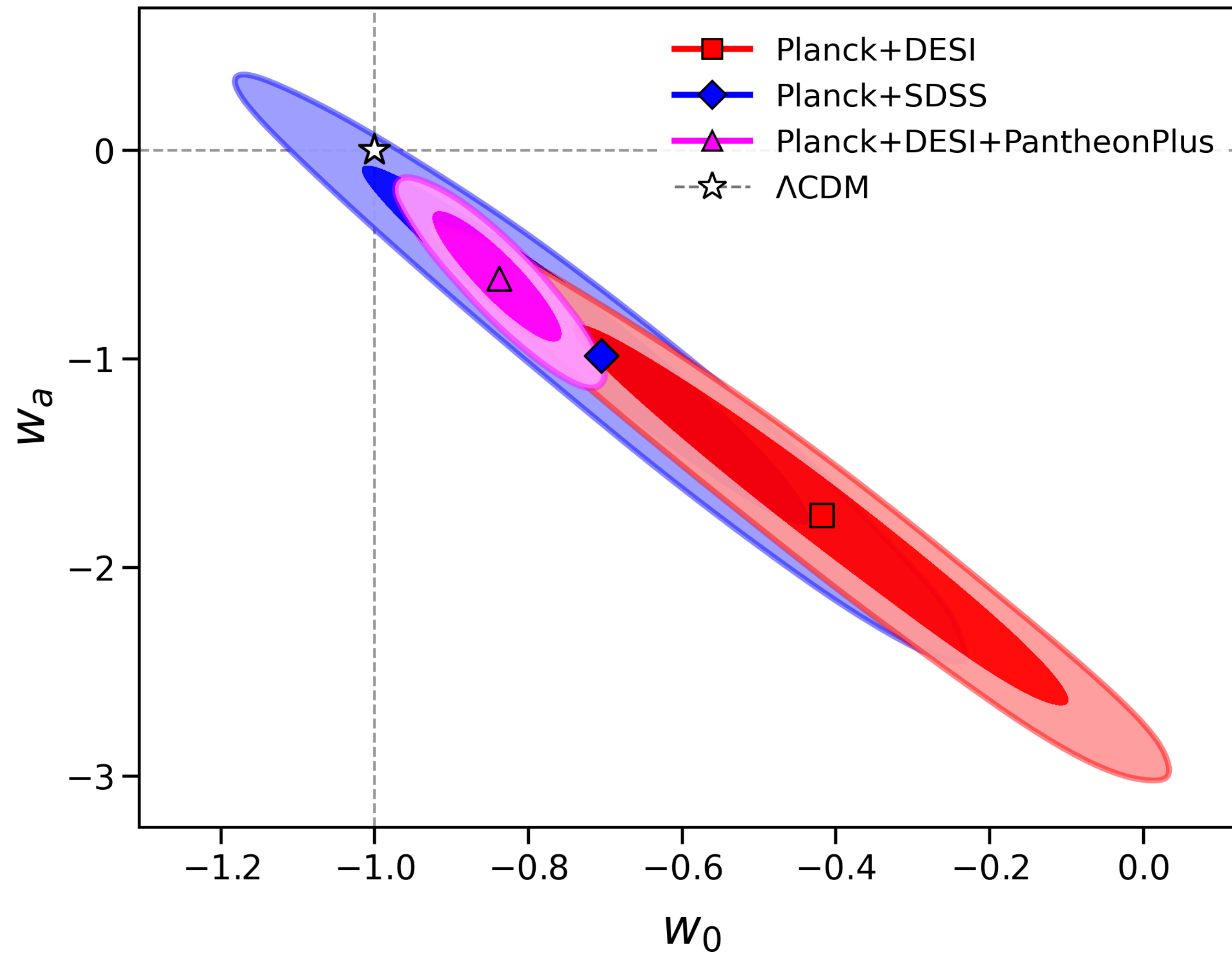
2

The **sign of  $q_0$  flips**: SDSS prefers present-day acceleration; DESI's median suggests **deceleration**.

3

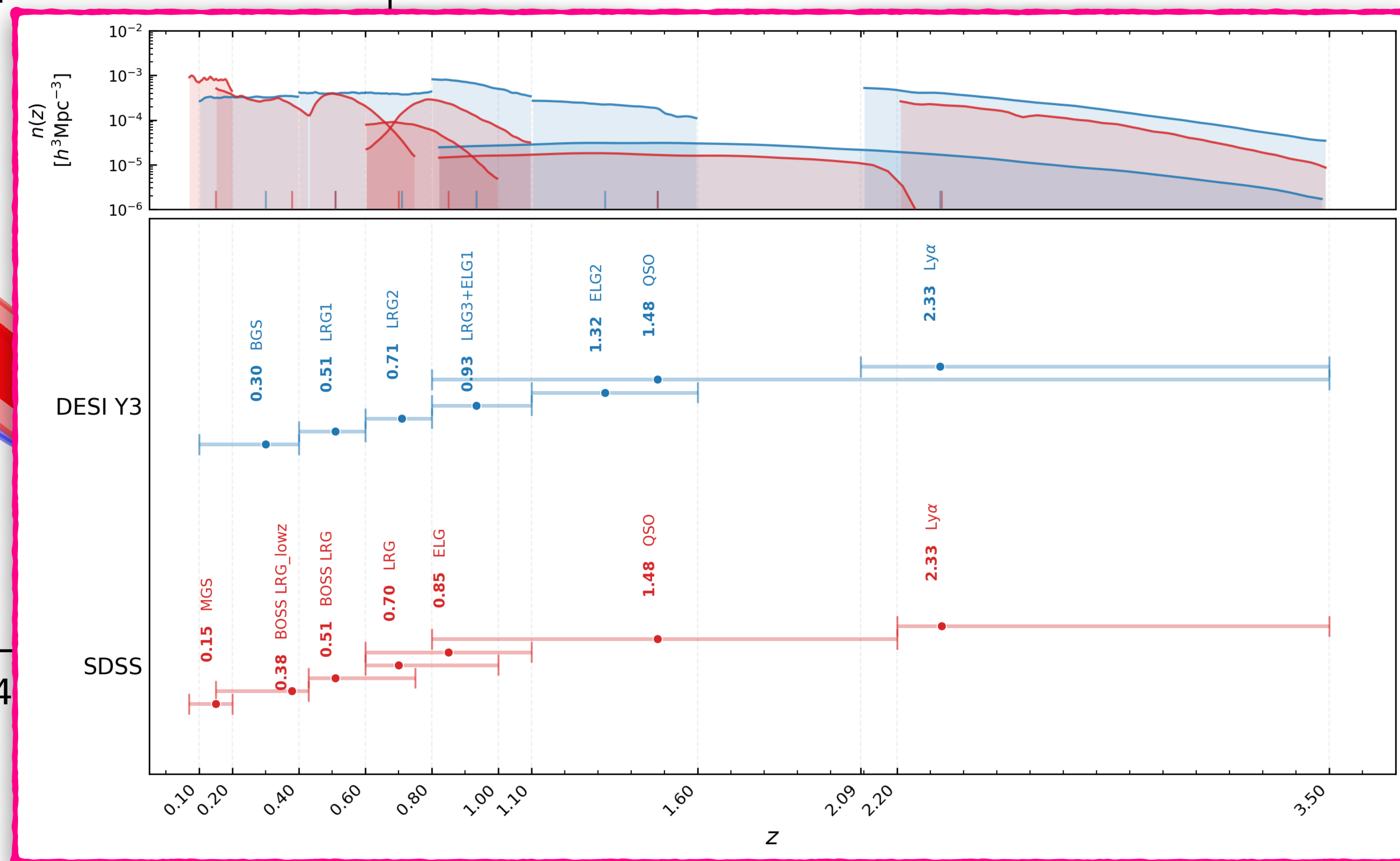
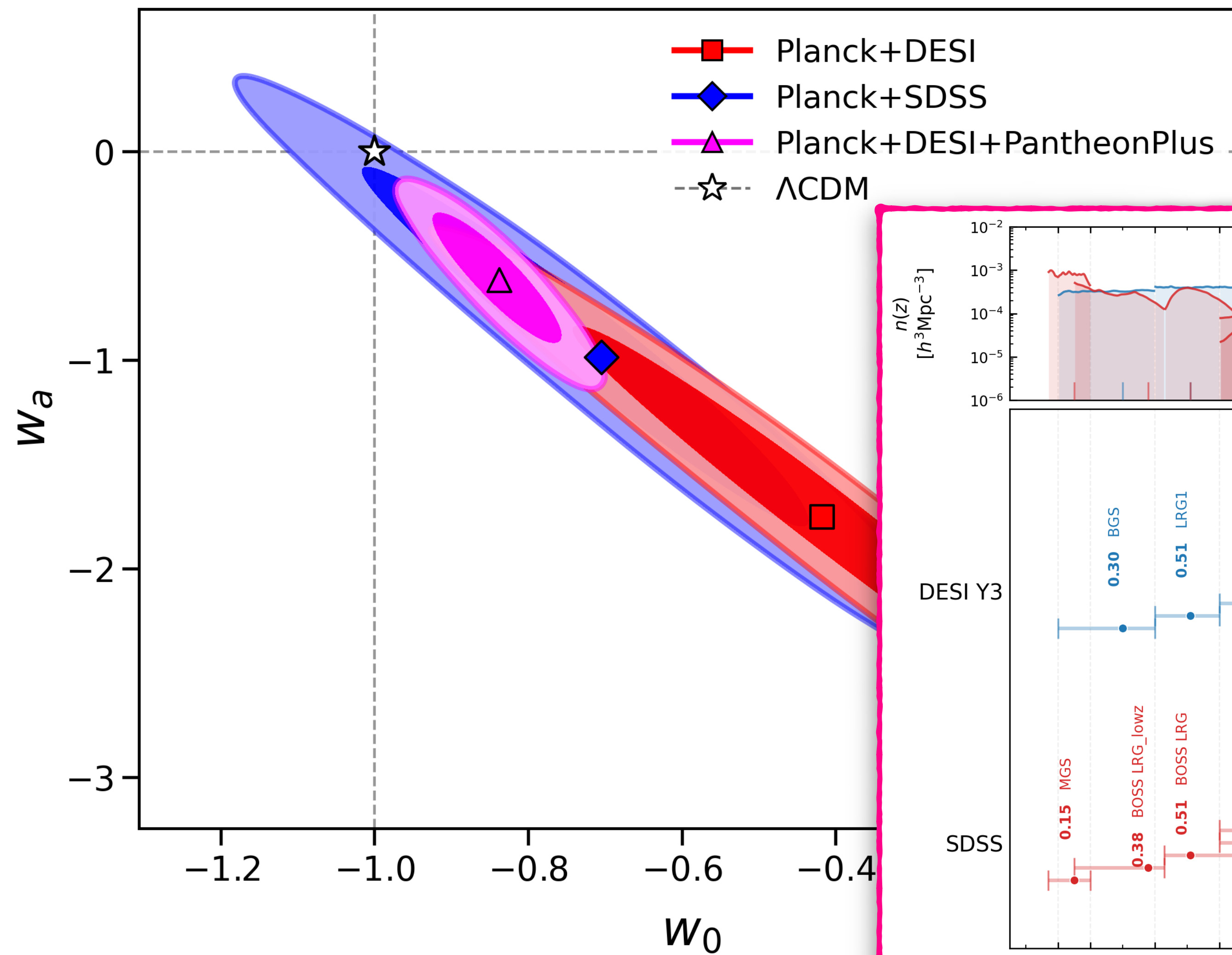
Likely cause: **lowest redshift probed** —  $z_{\text{eff}} \approx 0.295$  (DESI) vs  $z_{\text{eff}} \approx 0.15$  (SDSS).

# Dynamical Dark Energy ???

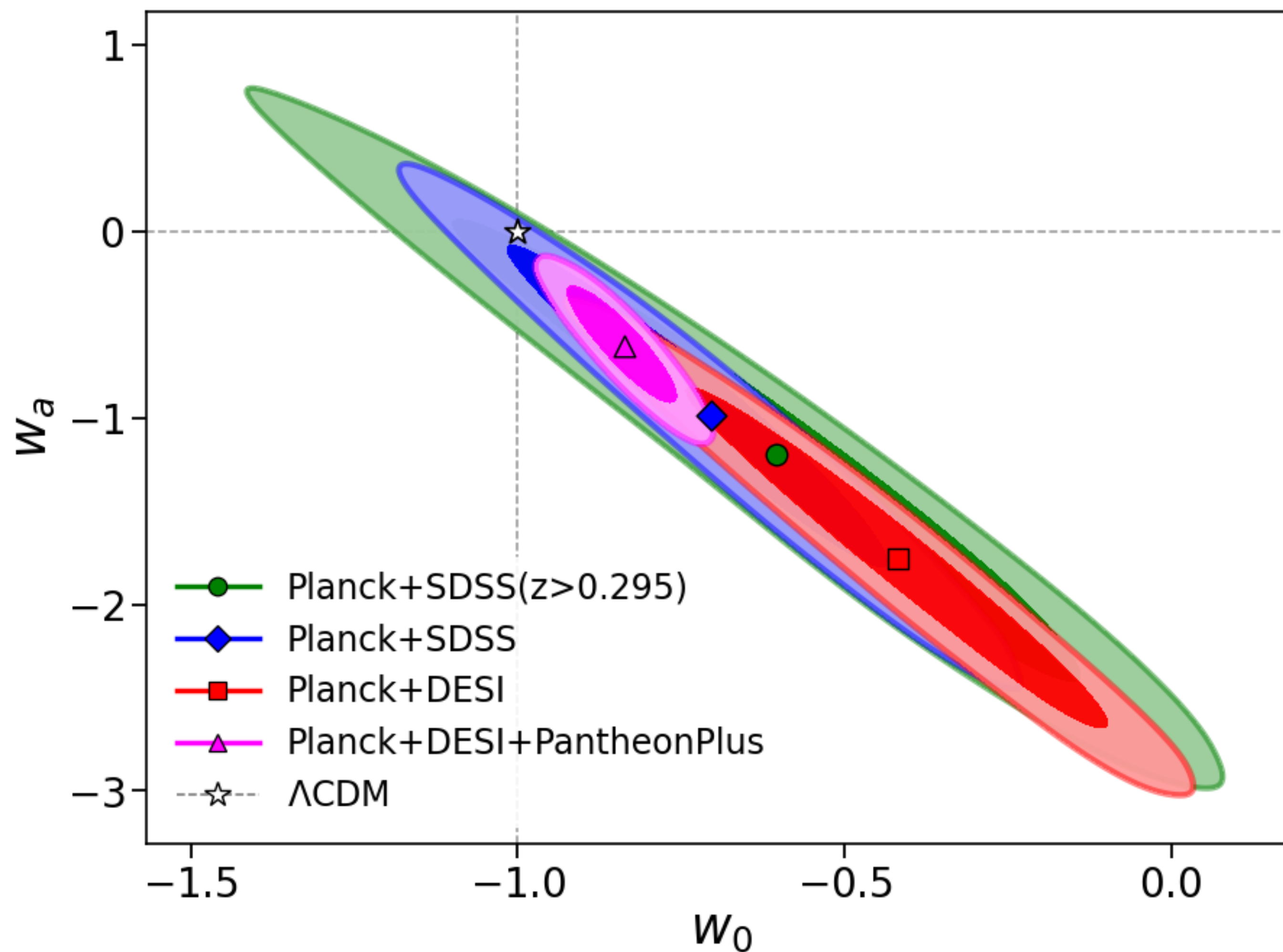




# Redshift Coverage of DESI and SDSS:



# Dynamical Dark Energy or a Low- $z$ Anchor Effect?



## THE TEST

Remove the lowest-redshift SDSS point (MGS,  $z_{\text{eff}} = 0.15$ ), keeping only  $z > 0.295$  — the same redshift floor as DESI.

## WHY

Without data below  $z \approx 0.3$ , SDSS constraints become **extrapolation-dependent** at low  $z$  — just like DESI's.

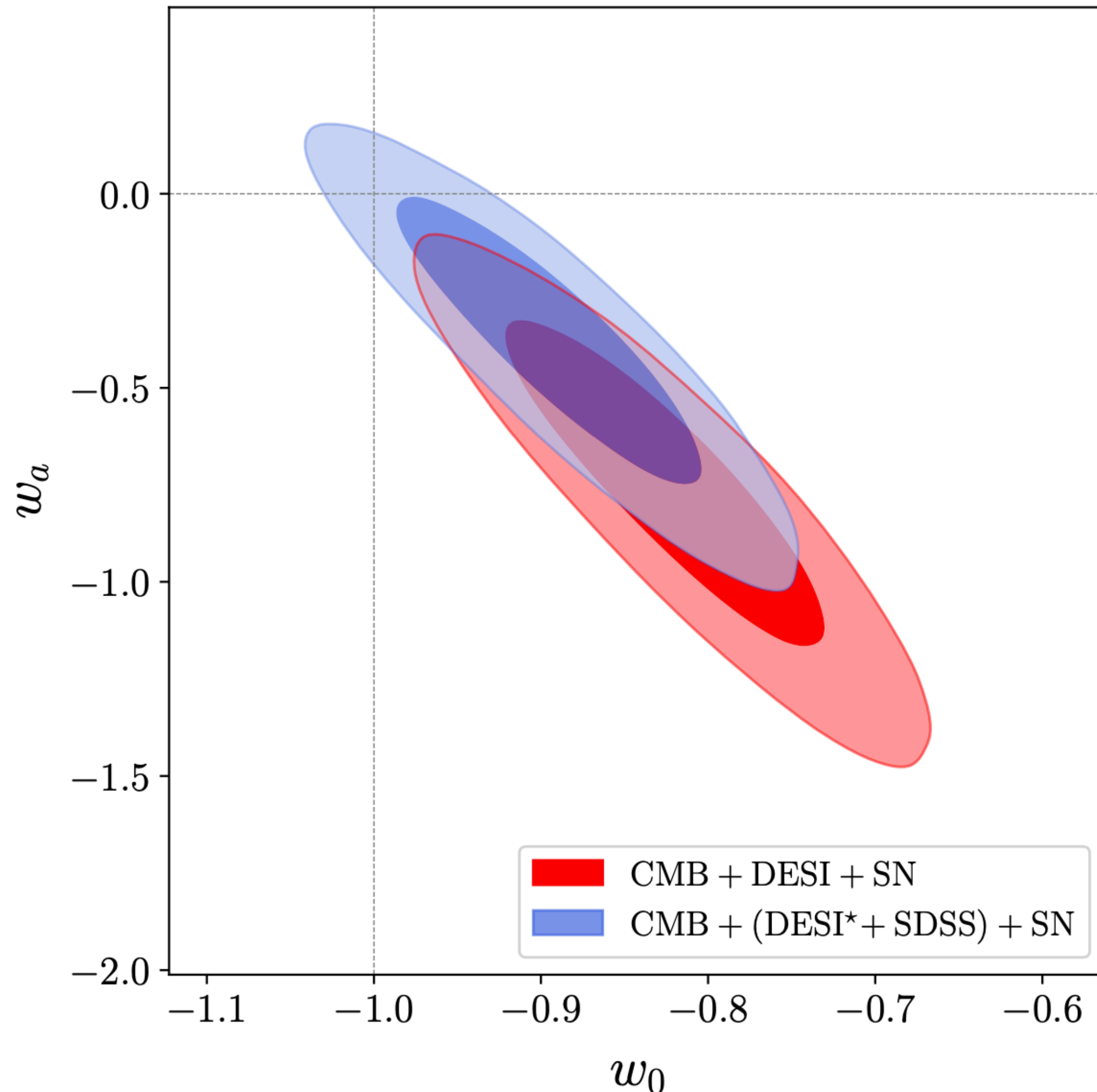
## RESULT

The SDSS ( $z > 0.295$ ) contour **shifts away from  $\Lambda$ CDM**, toward the DESI preference for  $w_0 > -1$ ,  $w_a < 0$ .

→ The apparent "dynamical dark energy" signal is sensitive to the lowest- $z$  BAO anchor — not just the survey



# DDE and effect of lower redshift data ( $z < 0.8$ )



To explore the effect of low-redshift BAO measurements, we construct a combined dataset which comprises SDSS BAO data in the low-redshift region  $z < 0.8$  and DESI BAO data in high-redshift region  $z > 0.8$ . In particular, we adopt the SDSS BAO distance measurements extracted from DR7 Main Galaxy Sample (MGS) [24] in  $0.07 < z < 0.2$ , BOSS DR12 galaxy samples in  $0.2 < z < 0.5$  and  $0.4 < z < 0.6$  [25], eBOSS DR16 galaxy sample in  $0.6 < z < 1.0$  [5] in place of the DESI BGS, LRG1 and LRG2 points. We use the label “DESI\*+SDSS” to refer to this composite dataset.

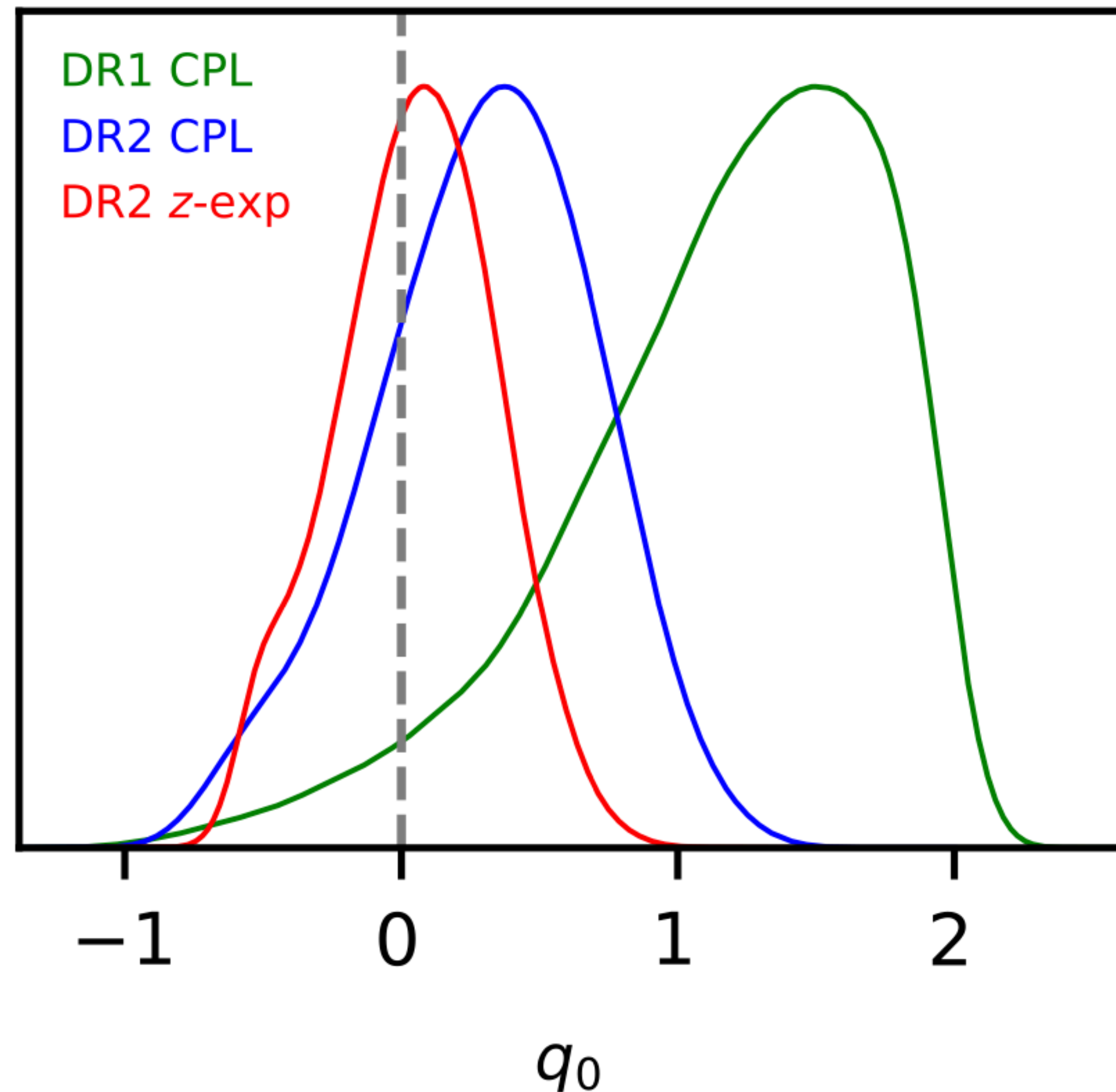
- **Combine SDSS sample ( $z < 0.8$ ) with DESI sample ( $z > 0.8$ ): DESI\* + SDSS**
- **DESI\* + SDSS inherits SDSS's low redshift anchors → results consistent with ( $\Lambda$ CDM) SDSS alone**

[Anton Chudaykin](#), [Martin Kunz](#)

*Phys.Rev.D* 110 (2024) 12, 123524

# How much has DESI dark energy evolved since DR1?

Eoin Ó Colgáin, Saeed Pourojaghi, M.M. Sheikh-Jabbari, Lu Yin



**Independent support for the late-time deceleration claim :**

- Planck + DESI yields a positive median  $q_0$
- Data cannot distinguish an accelerating from a non-accelerating Universe today

*Phys.Dark Univ.* 52 (2026) 102268  
e-Print: 2504.04417

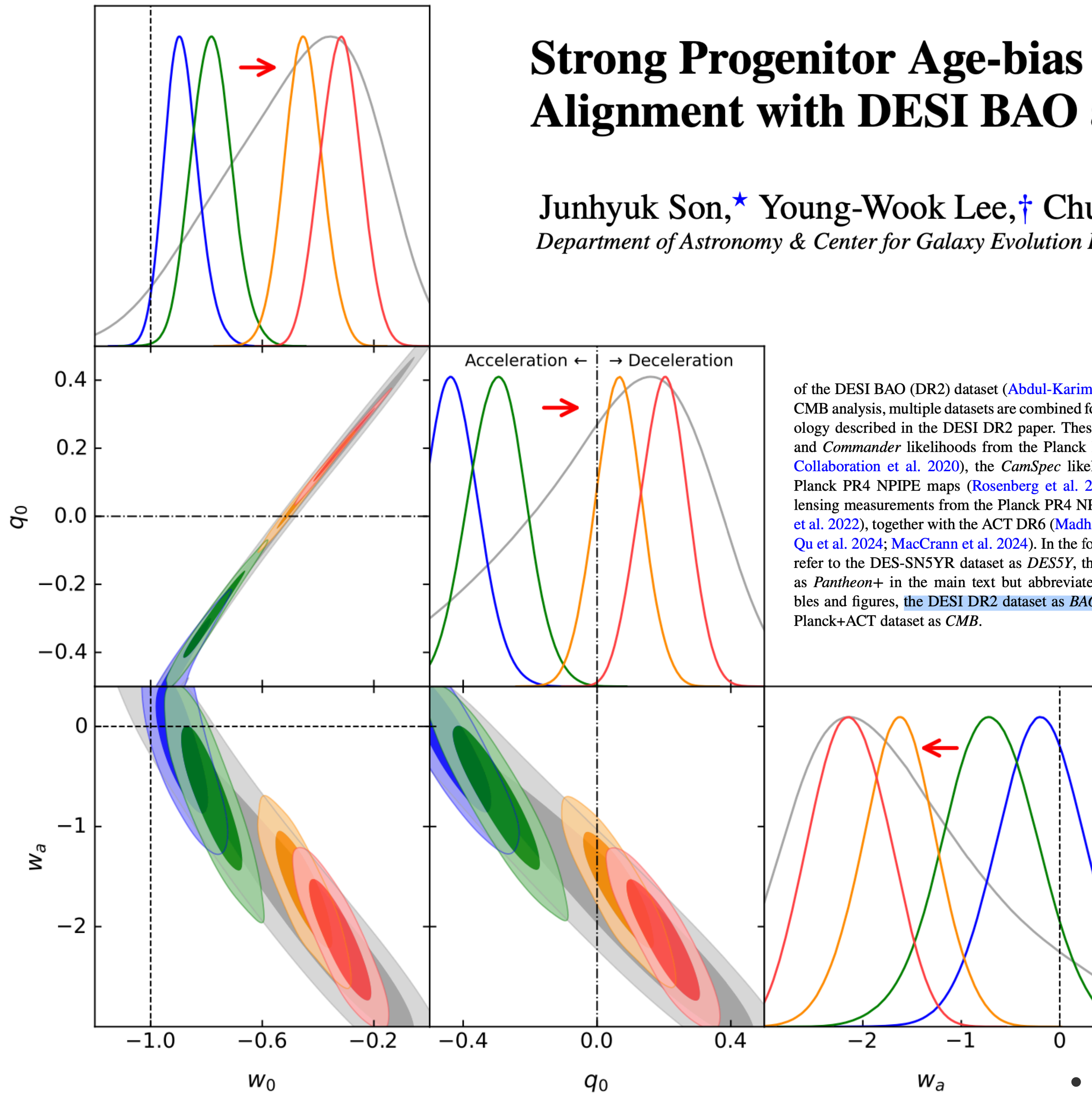
$$w_{\text{DE}}(z) = w_0 + z w_a,$$



# Strong Progenitor Age-bias in Supernova Cosmology. II. Alignment with DESI BAO and Signs of a Non-Accelerating Universe

Junhyuk Son,<sup>★</sup> Young-Wook Lee,<sup>†</sup> Chul Chung,<sup>‡</sup> Seunghyun Park and Hyejeon Cho

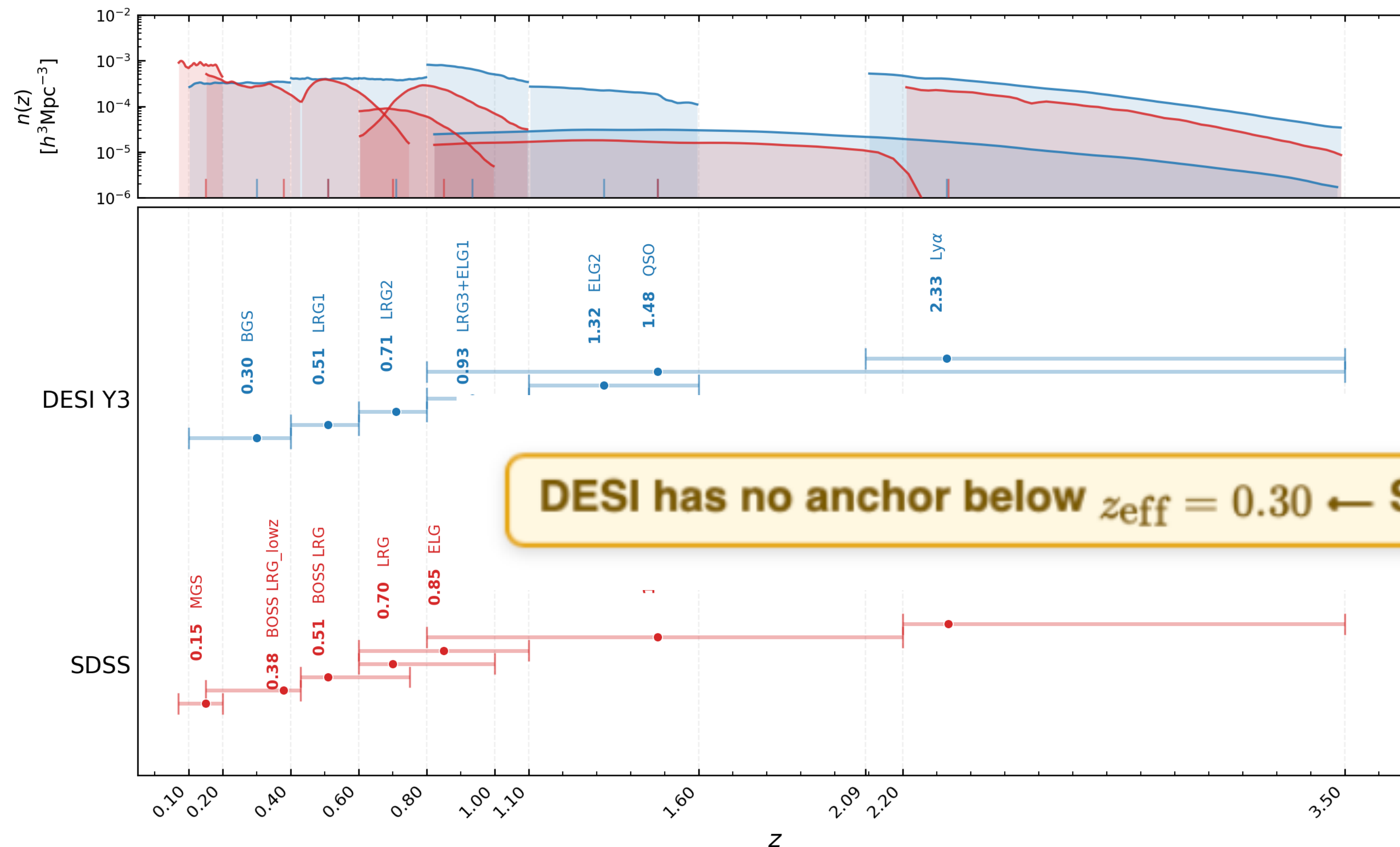
*Department of Astronomy & Center for Galaxy Evolution Research, Yonsei University, Seoul 03722, Republic of Korea*



- BAO
- BAO + Panth.
- BAO + DES5Y
- BAO + (corrected) Panth.
- BAO + (corrected) DES5Y

# Main Takeaway

→ To robustly test **dynamical dark energy** with DESI Y3, the BGS sample needs a **lower effective redshift** — or **tomographic binning** reaching  $z_{\text{eff}} \approx 0.15$  — analogous to the tomography already used for the LRG and ELG samples.





# Future Directions

## 1 Fisher forecast with tomographic BGS

Split the BGS sample into **multiple redshift bins** (e.g. down to  $z_{\text{eff}} \approx 0.15$ ) and quantify, via Fisher forecasting, how much a low- $z$  anchor improves DESI constraints on  $(w_0, w_a)$ .

## 2 Extend beyond CPL / $w_0w_a$ CDM

Repeat the extrapolation analysis on current data for **other dark energy parametrisations** and test whether the preference for **late-time deceleration** is robust or an artefact of the CPL form.

 **Goal: determine whether dynamical dark energy is a physical signal or an artefact of the CPL parametrisation together with missing low- $z$  BAO anchors**



✦ Thank you for your attention! ✦

**Ruchika**

University of Salamanca

✉ [ruchika.science@gmail.com](mailto:ruchika.science@gmail.com)

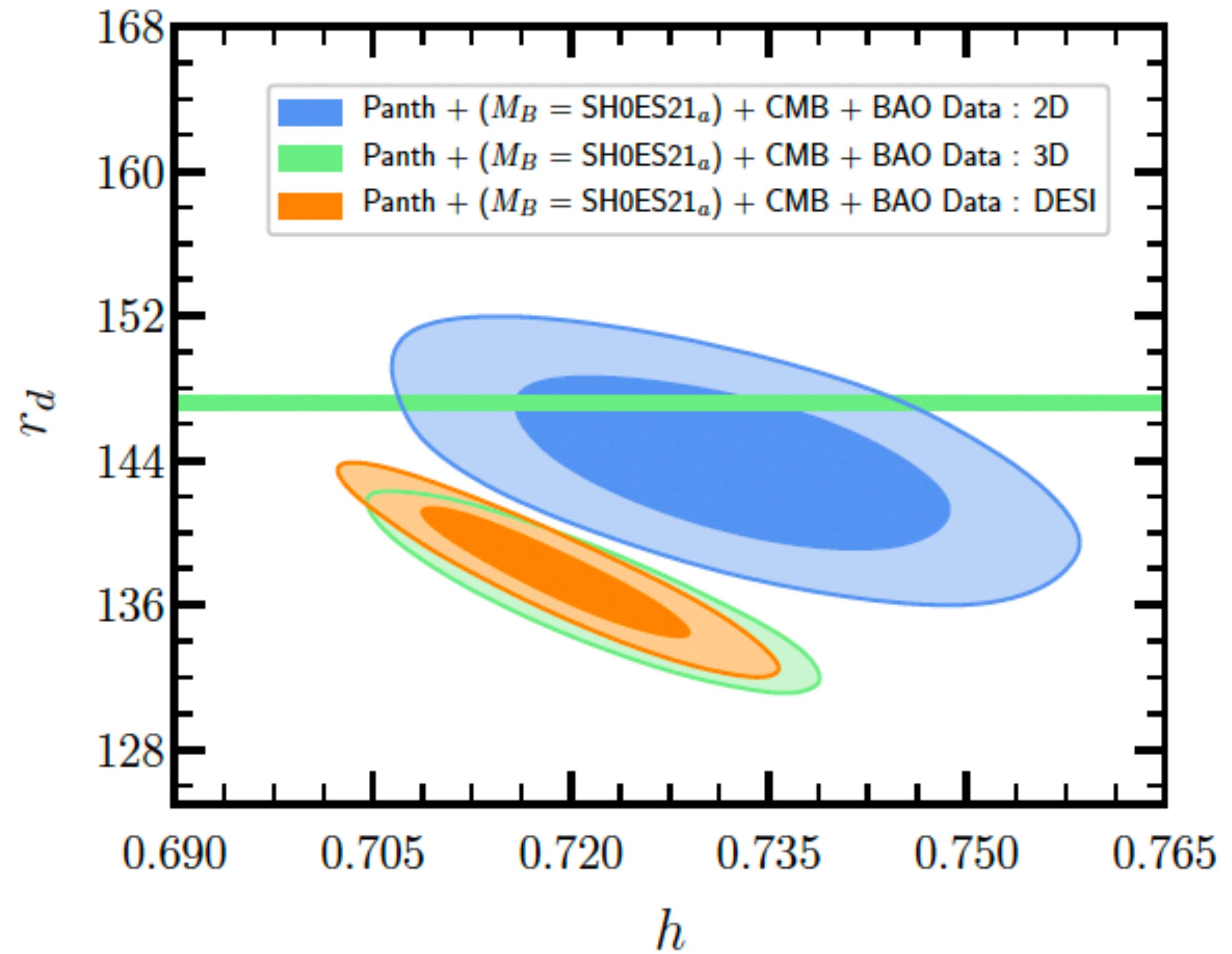
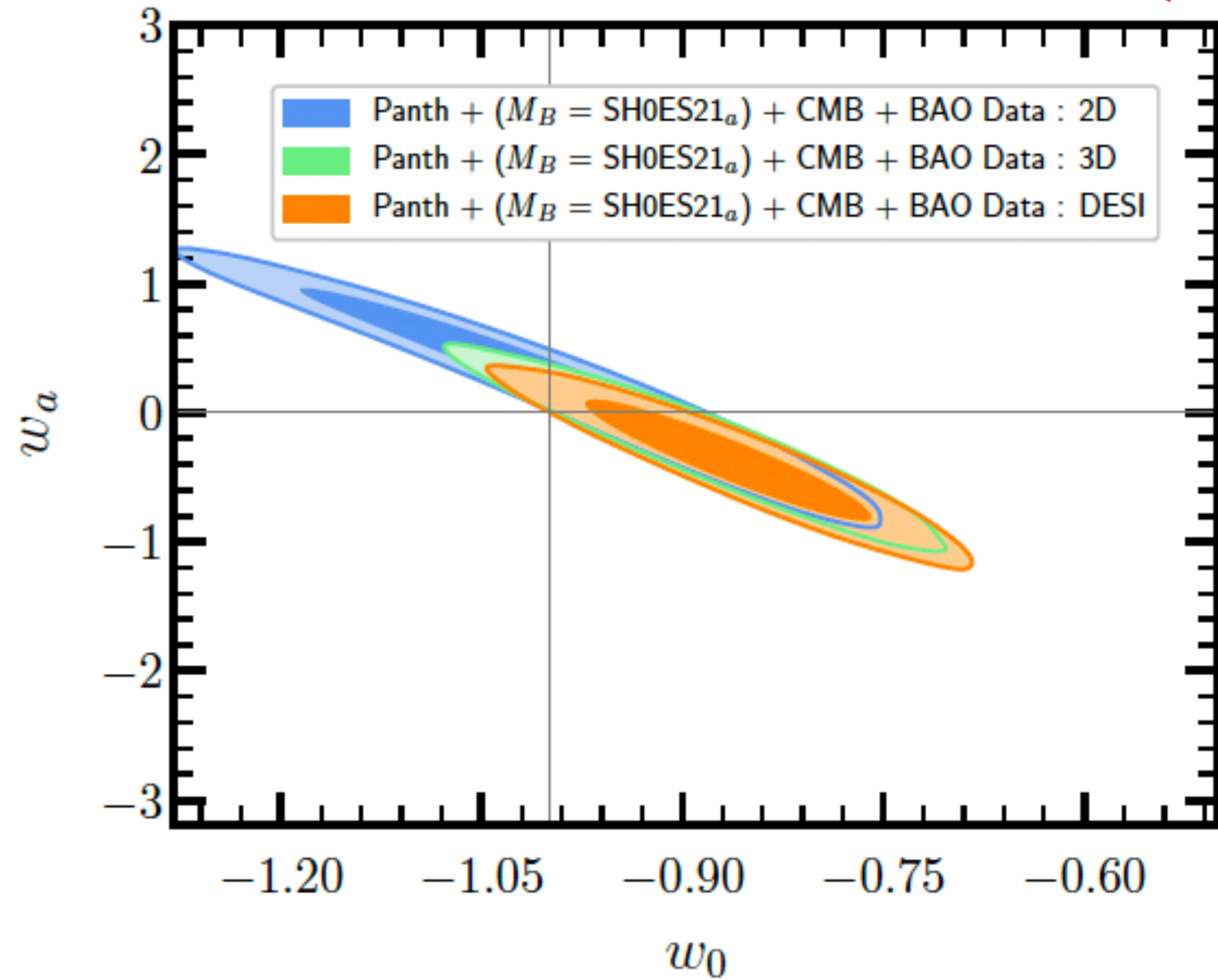
*2D vs 3D BAO*

*SDSS vs DESI*

**GGI workshop 2026**



## Adding DESI results in the picture...



\* Left: ( $w_0, w_a$  : -1.0, 0) is at the two sigma boundary for BAO+CMB+Pantheon Plus sample.

\* Right:  $r_d$  obtained from 2D BAO is compatible with Planck  $r_d$  (higher value) and higher  $H_0$ .

It is an artifact solely due to the relatively higher product  $H_0 r_d$  measured by 2D BAO than 3D.