Anomalies and Tensions in Cosmological data

June 13th, 2025
CosmoFONDUE - Cosmological Fundamental Observables and Novel Discoveries in Universe Evolution
Genève

Eleonora Di Valentino
Royal Society Dorothy Hodgkin Research Fellow
School of Mathematics and Statistics
University of Sheffield (UK)

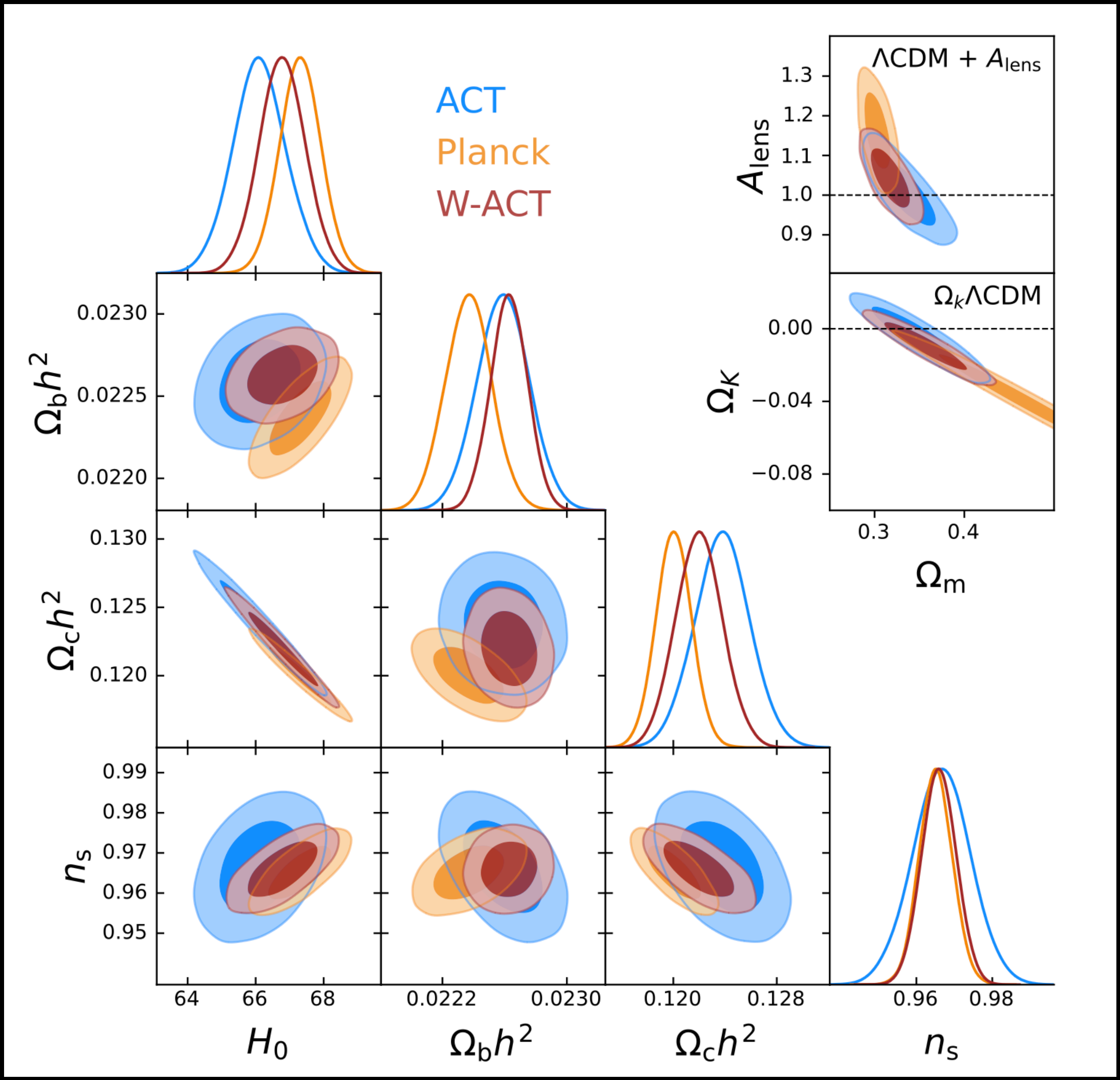
University of Sheffield

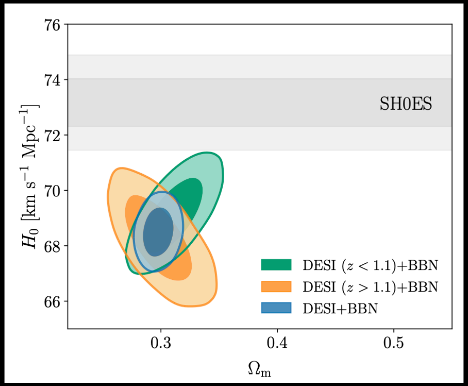
THE ROYAL SOCIETY

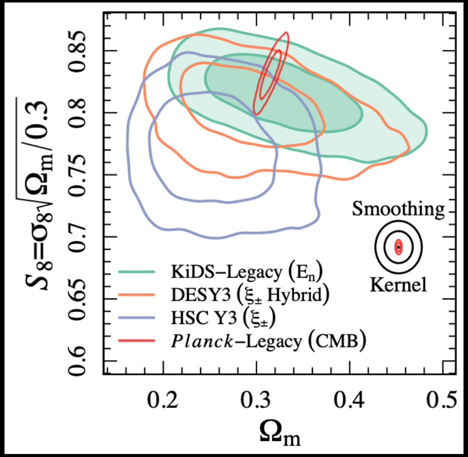
A flat LCDM model is in agreement with most of the data

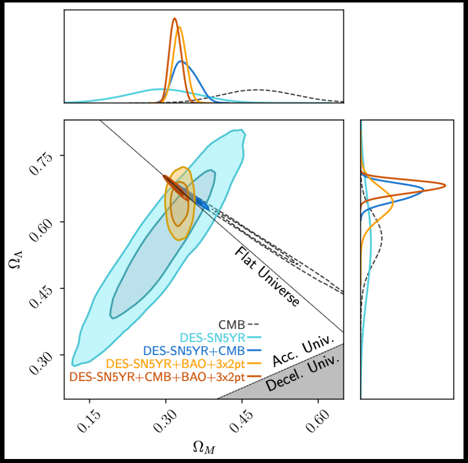
Among the various cosmological models proposed in literature, the Lambda cold dark matter (LCDM) scenario has been adopted as the standard model, due to its simplicity and its ability to accurately describe a wide range of astrophysical and cosmological observations.

A flat LCDM model is in agreement with most of the data









But what does it mean that LCDM agrees well with each probe?

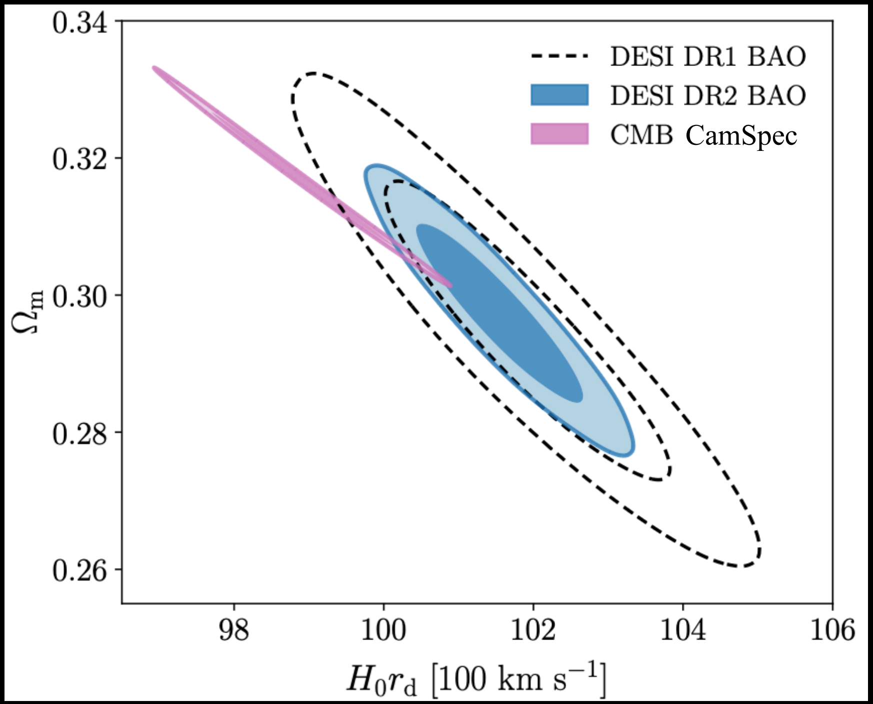
In a Bayesian framework, all models can, in principle, agree with the data.
What matters is whether they are disfavoured due to a poor fit
or because another model is preferred.
Therefore, to me, this means that LCDM provides a good fit to the data
and shows no clear signs of deviation, even when extended.

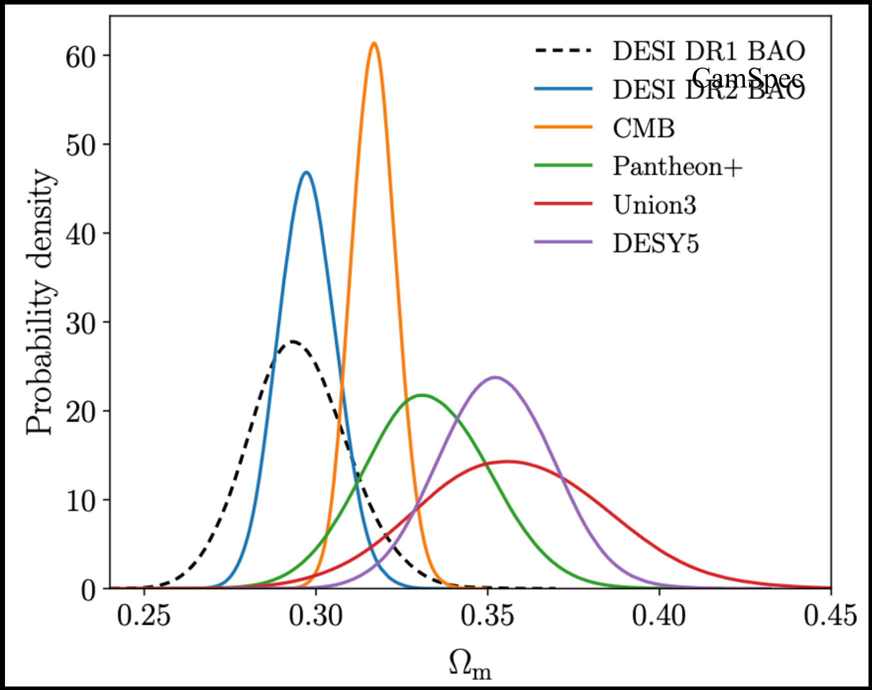
However, currently the cosmological parameters inferred
from different probes are not the same.

So LCDM appears different for the different data!

Tensions and Disagreements in LCDM

DESI collaboration, Abdul Karim et al., arXiv:2503.14738



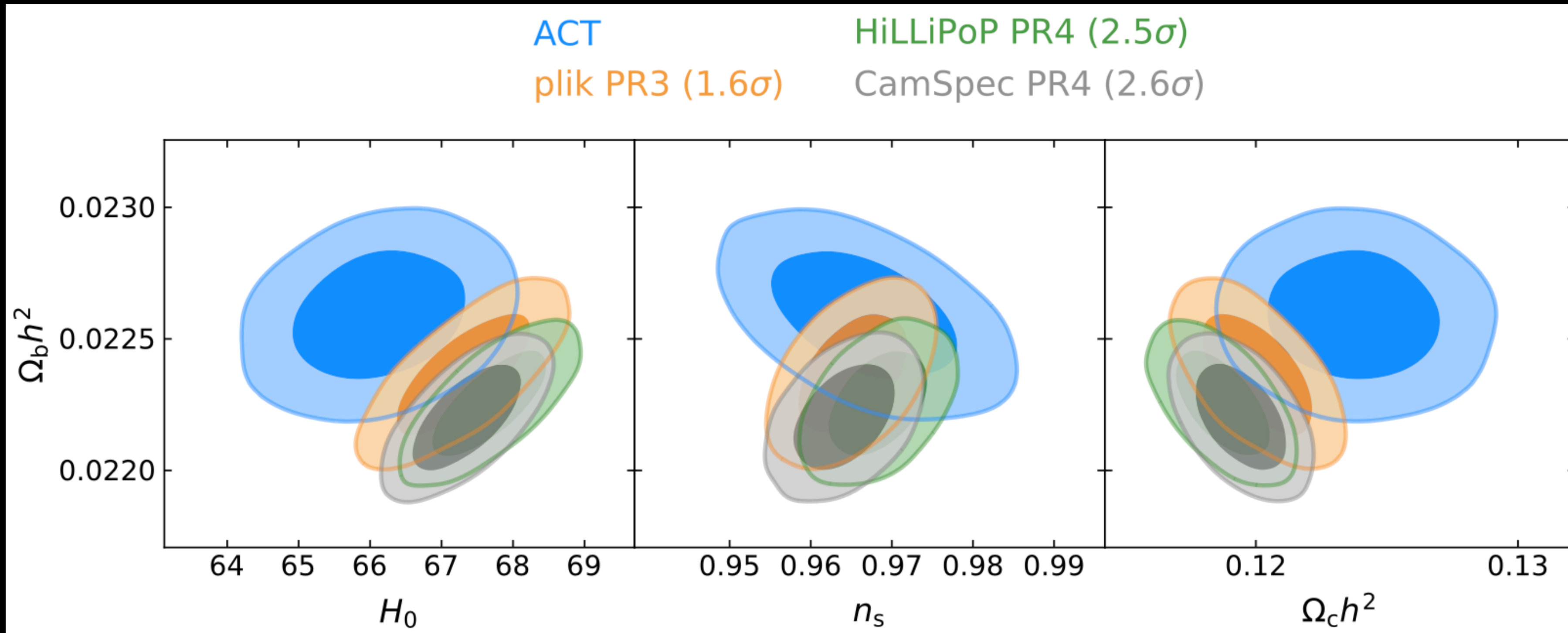


the corresponding 2×2 posterior parameter covariances. Converting this χ^2 into a probability-to-exceed (PTE) value, we find it is equivalent to a 2.3σ discrepancy between BAO and CMB in ΛCDM, increased from 1.9σ in DR1. However, we note that this reduces to 2.0σ if CMB lensing is excluded. This discrepancy is part of the reason why more models with a more flexible background expansion history than ΛCDM, such as the evolving dark

Finally, as in [38], we note a mild to moderate discrepancy between the recovered values of Ω_m from DESI and SNe in the context of the ΛCDM model. This is shown in the marginalized posteriors in Figure 10: the discrepancy is 1.7σ for Pantheon+, 2.1σ for Union3, and 2.9σ for DESY5, with all SNe samples preferring higher values of Ω_m though with larger uncertainties. For ΛCDM we do not report joint constraints on parameters from any combination of DESI and SNe data. However, as with

The same LCDM cannot fit 2 datasets together!

CMB tension in LCDM



In Figure 37 we show the comparison of the ACT DR6 results with those from different versions of the *Planck* likelihoods, as discussed in §8. The agreement between ACT and *Planck* is closest for the Plik PR3 at 1.6σ, neglecting correlations between the data and using the four-dimensional parameter distribution that discards the amplitude and optical depth; the PR4 analyses for both Camspec and Hillipop have small shifts to lower baryon and CDM densities compared to PR3, and result in an overall 2.6σ separation in the four-dimensional parameter space.

ACT collaboration, Louis et al., arXiv:2503.14452

Consequences? Indication for DDE

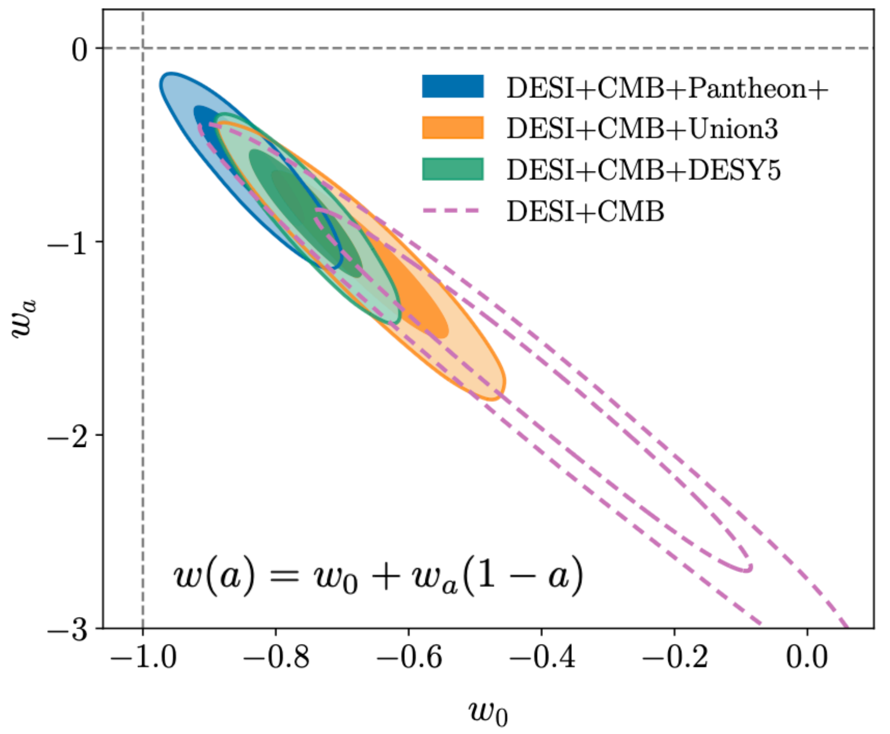
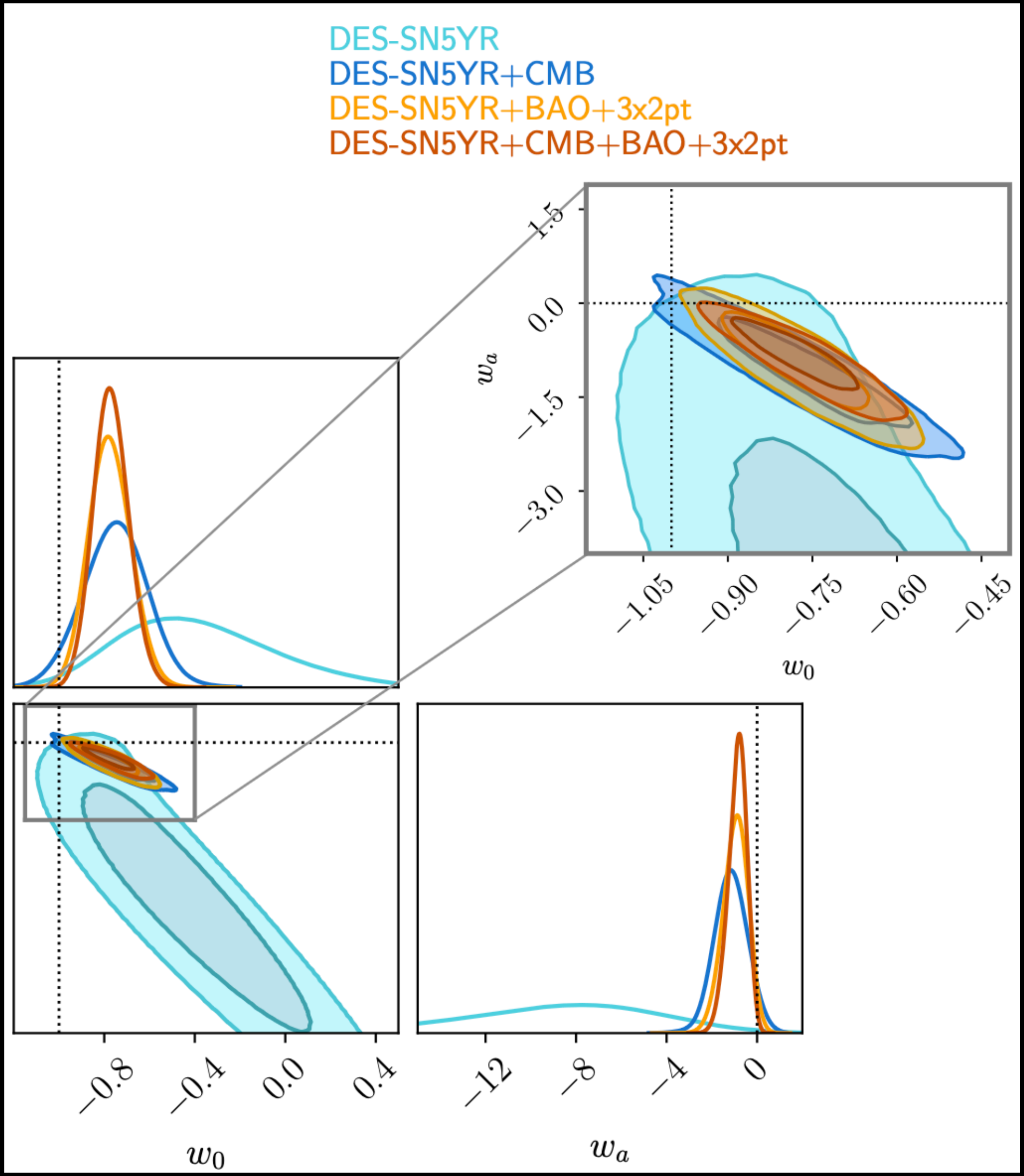


FIG. 11. Results for the posterior distributions of w_0 and w_a, from fits of the w_0w_aCDM model to DESI in combination with CMB and three SNe datasets as labelled. We also show the contour for DESI combined with CMB alone. The contours enclose 68% and 95% of the posterior probability. The gray dashed lines indicate $w_0 = -1$ and $w_a = 0$; the ΛCDM limit ($w_0 = -1$, $w_a = 0$) lies at their intersection. The significance of rejection of ΛCDM is 2.8σ, 3.8σ and 4.2σ for combinations with the Pantheon+, Union3 and DESY5 SNe samples, respectively, and 3.1σ for DESI+CMB without any SNe.

Datasets	$\Delta\chi^2_{\mathrm{MAP}}$	Significance	Δ(DIC)
DESI	−4.7	1.7σ	−0.8
DESI+$(\theta_*, \omega_b, \omega_{bc})_{\mathrm{CMB}}$	−8.0	2.4σ	−4.4
DESI+CMB (no lensing)	−9.7	2.7σ	−5.9
DESI+CMB	−12.5	3.1σ	−8.7
DESI+Pantheon+	−4.9	1.7σ	−0.7
DESI+Union3	−10.1	2.7σ	−6.0
DESI+DESY5	−13.6	3.3σ	−9.3
DESI+DESY3 (3×2pt)	−7.3	2.2σ	−2.8
DESI+DESY3 (3×2pt)+DESY5	−13.8	3.3σ	−9.1
DESI+CMB+Pantheon+	−10.7	2.8σ	−6.8
DESI+CMB+Union3	−17.4	3.8σ	−13.5
DESI+CMB+DESY5	−21.0	4.2σ	−17.2

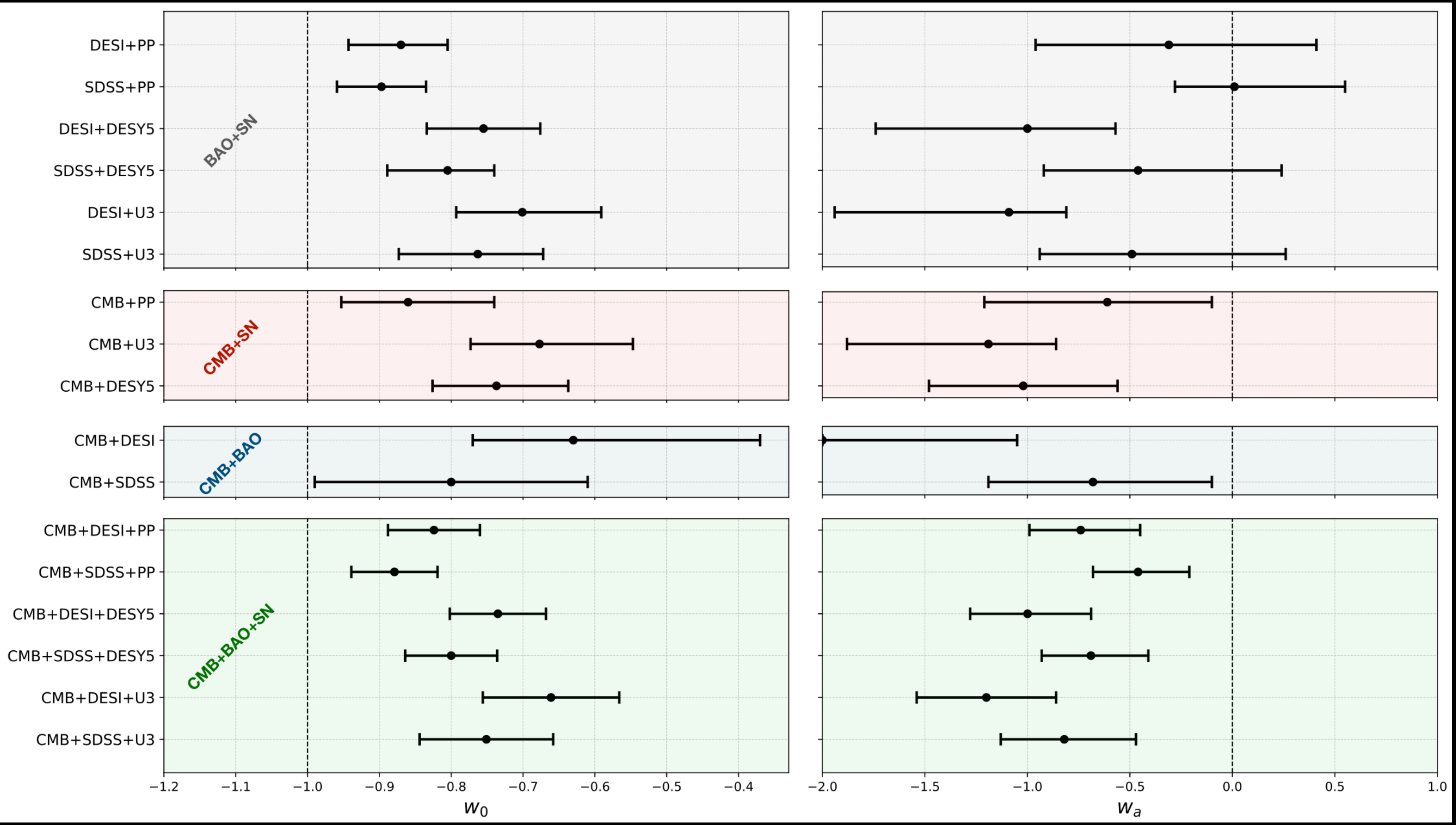
DESI collaboration, Abdul Karim et al., arXiv:2503.14738

Consequences? Indication for DDE



DESY5 collaboration: Abbott et al., arXiv:2401.02929

Hints for DDE robust changing datasets

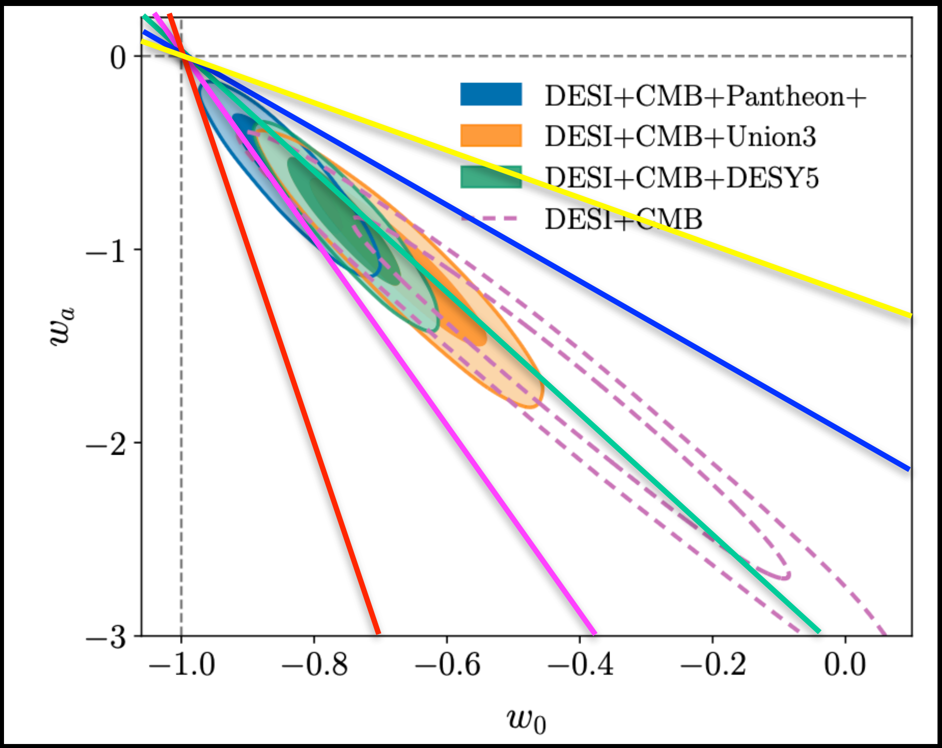


Overall, our findings highlight that combinations that *simultaneously* include PantheonPlus SN and SDSS BAO significantly weaken the preference for DDE. However, intriguing hints supporting DDE emerge in combinations that do not include DESI-BAO measurements: SDSS-BAO combined with SN from Union3 and DESY5 (with and without CMB) support the preference for DDE.

Giarè, Mahassen, Di Valentino, & Pan, *Phys.Dark Univ.* 48 (2025) 101906

Crossing of the Phantom Dividing Line

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



The scale factor of the PDL crossing, which we call ac, needs to satisfy:

$$w(a_c) = -1.$$

In fact, there is always a solution

$$a_c = 1 + \frac{1 + w_0}{w_a}$$

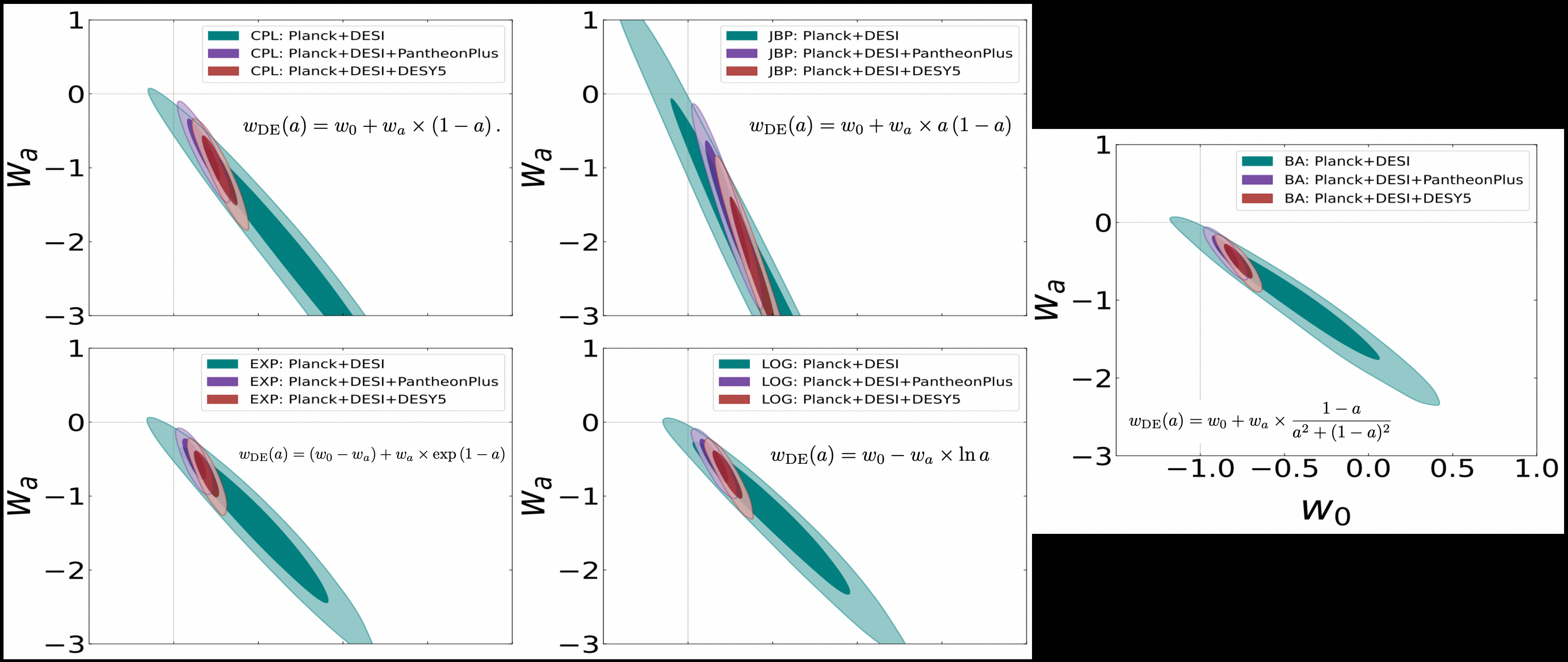
Therefore, at a given value of ac corresponds to a line in the w0 – wa plane whose slope is 1/(1 – ac).
Thus, a strong correlation of the parameters w0 and wa would result in a strong determination of ac.

All lines of ac intersect at the vertex point (w0 = –1, wa = 0) corresponding to the cosmological constant.

Ozulker, Di Valentino, Giarè, in preparation

Hint for DDE robust changing w(z) parametrizations

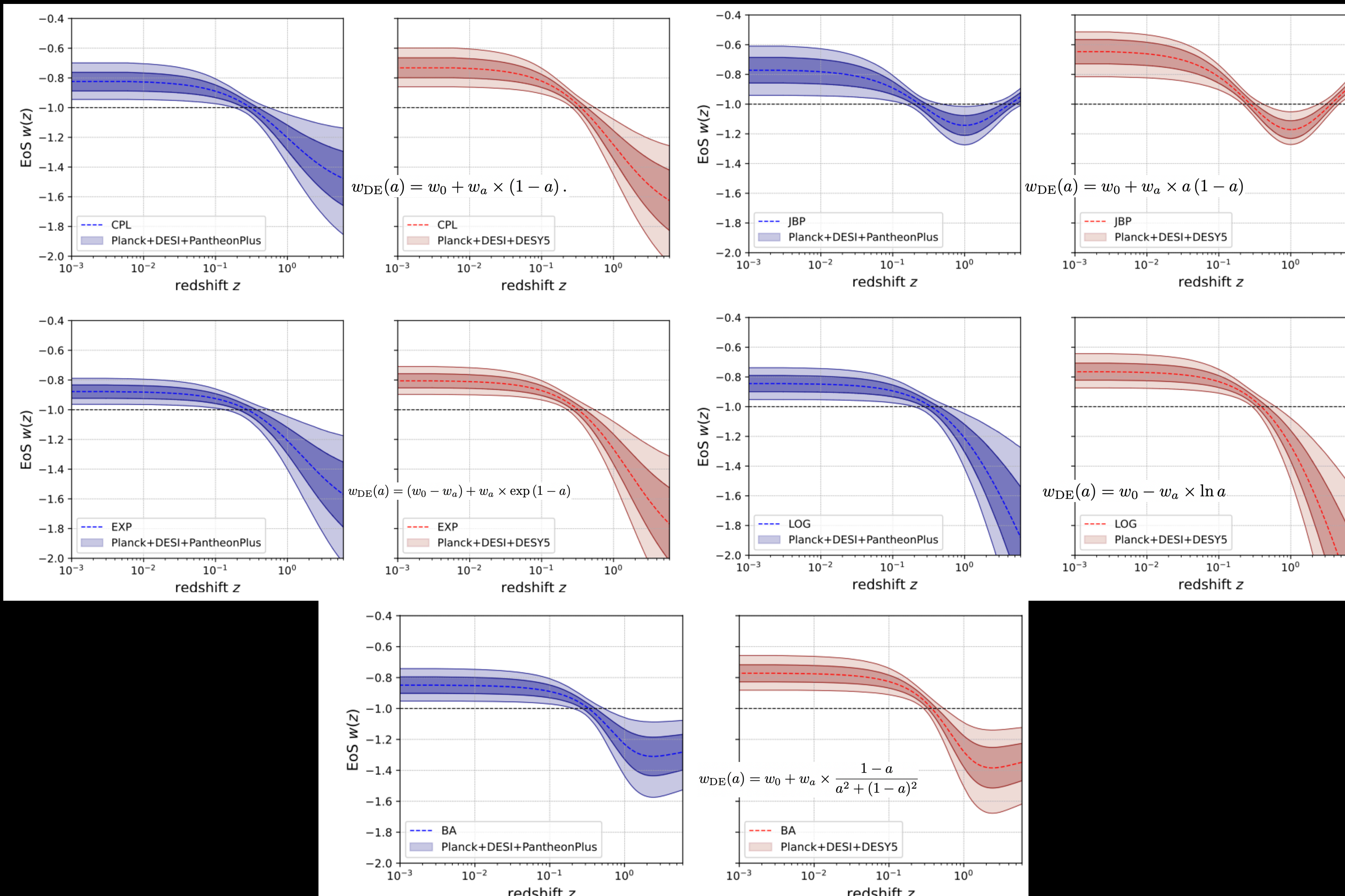
Giarè, Najafi, Pan, Di Valentino & Firouzjaee, *JCAP* 10 (2024) 035



linear Chevallier-Polarski-Linder (CPL) parameterization $w(a) = w_0 + w_a(1-a)$ to describe the evolution of the DE equation of state (EoS). In this paper, we test if and to what extent this assumption impacts the results. To prevent broadening uncertainties in cosmological parameter inference and facilitate direct comparison with the baseline CPL case, we focus on 4 alternative well-known models that, just like CPL, consist of only two free parameters: the present-day DE EoS (w_0) and a parameter quantifying its dynamical evolution (w_a). We demonstrate that the preference for DDE remains robust regardless of the parameterization: w_0 consistently remains in the quintessence regime, while w_a consistently indicates a preference for a dynamical evolution towards the phantom regime. This tendency is significantly strengthened by DESY5 SN measurements. By comparing the best-fit χ^2 obtained within each DDE model, we notice that the linear CPL parameterization is not the best-fitting case. Among the models considered, the EoS proposed by Barboza and Alcaniz consistently leads to the most significant improvement.

Hint for DDE robust changing w(z) parametrizations

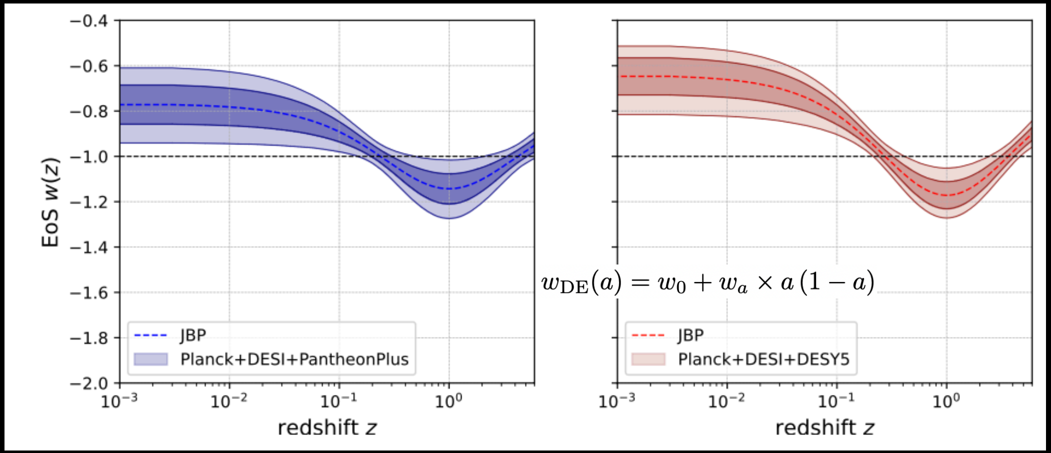
Giarè, Najafi, Pan, Di Valentino & Firouzjaee, *JCAP* 10 (2024) 035



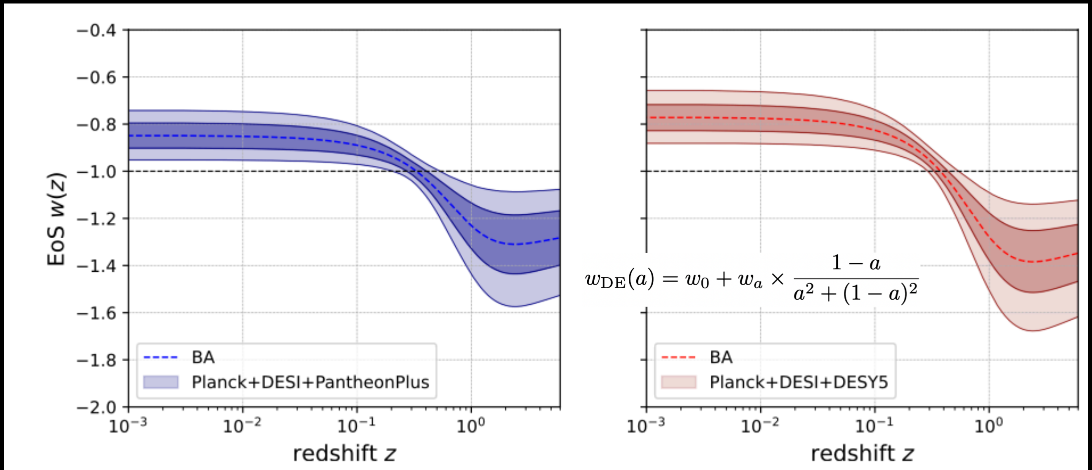
Hint for DDE robust changing w(z) parametrizations

Giarè, Najafi, Pan, Di Valentino & Firouzjaee, *JCAP* 10 (2024) 035

Due to its quadratic nature in the scale factor, the evolution of the EoS within the JBP parameterization crosses w =−1 twice.

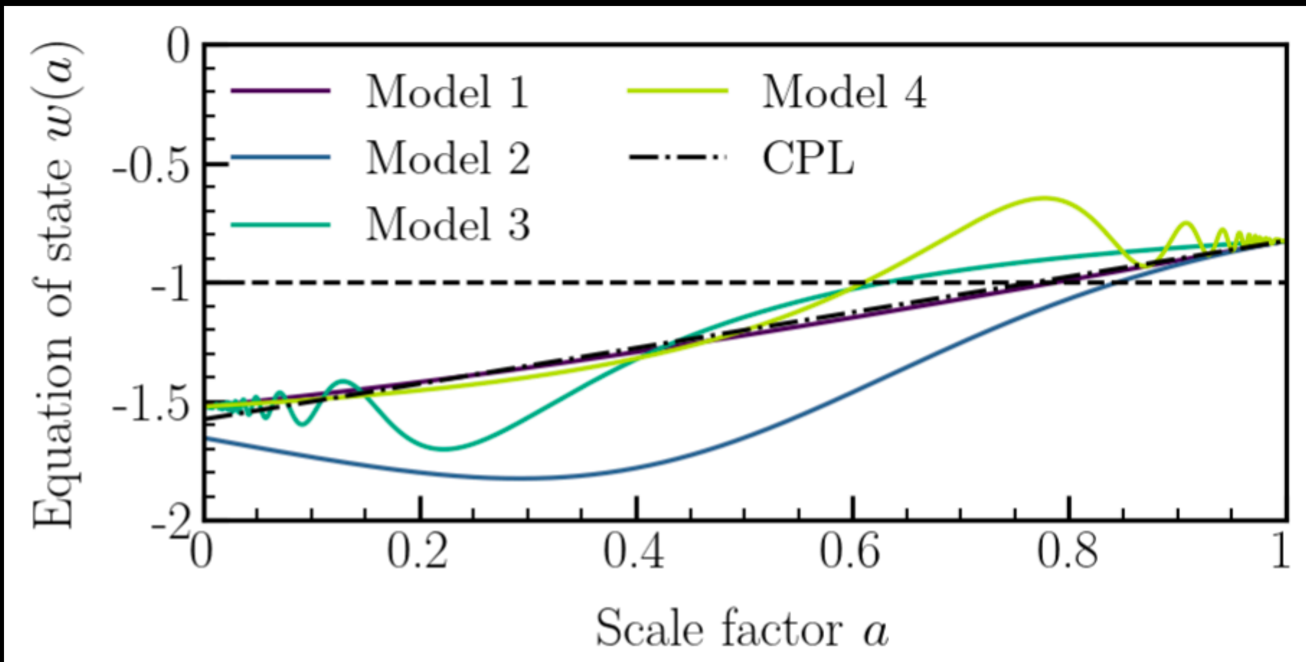


For z≳ 1, the evolution of w(z) in the BA model remains phantom but does not trend towards very negative values. Instead, w(z) stabilizes on a sort of second plateau that is distinctive of the BA model.



Hints for oscillations in the DE

Non-parametric reconstructions of the dark energy equation of state consistently find oscillating features during late times ($a \gtrsim 2/3$).



Kessler, Escamilla, Pan, & Di Valentino, arXiv:*2504.00776*

$$\text{Model 1:} \quad w(a) = w_0\left[1 + \sin(1-a)\right]$$

$$\text{Model 2:} \quad w(a) = w_0\left[1 + \frac{1-a}{a^2 + (1-a)^2}\right]$$

$$\text{Model 3:} \quad w(a) = w_0\left[1 - a\sin\left(\frac{1}{a}\right) + \sin 1\right]$$

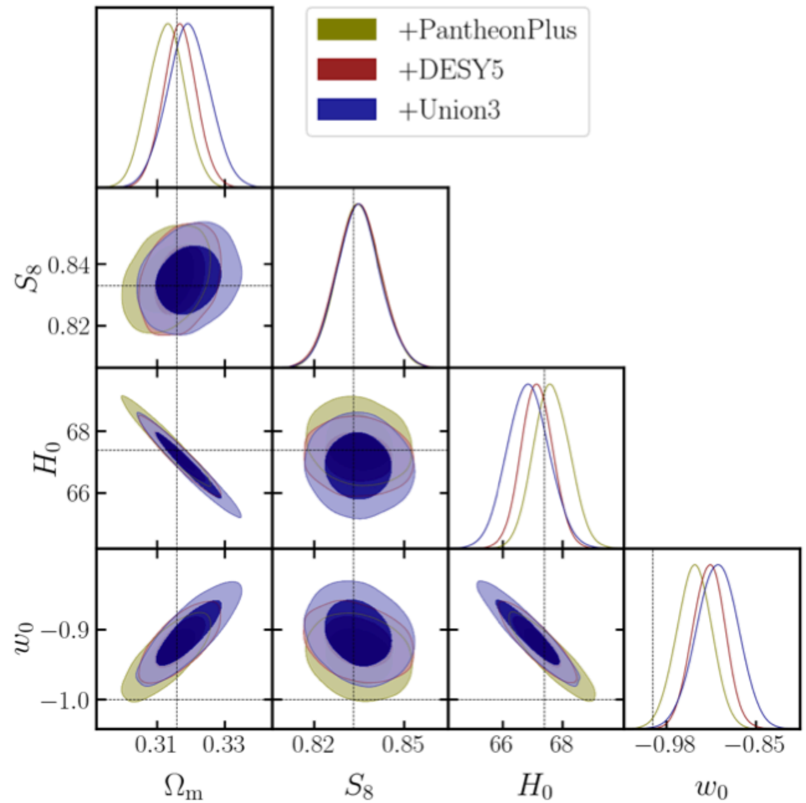
$$\text{Model 4:} \quad w(a) = w_0\left[1 + (1-a)\sin\left(\frac{1}{1-a}\right)\right].$$

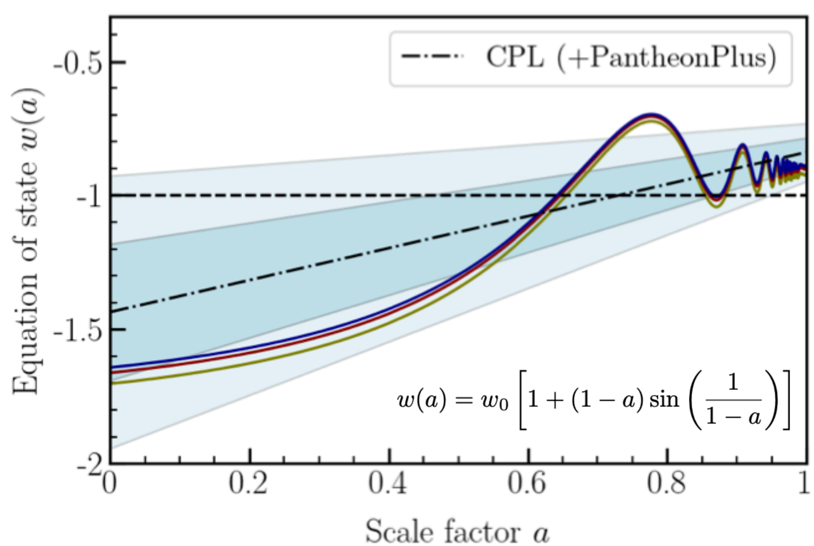
The first parametrization (Model 1) was explored in [79] and arises from a simple elementary function (the sine function) that does not require an additional parameter to control the slope: its average slope naturally aligns with the CPL preference found by DESI [124]. This model has the lowest frequency of oscillations and is the only one to remain monotonic over $a \in [0, 1]$. Model 2 is obtained by equating the two parameters of the Barboza–Alcaniz proposal [57]. This model has a single "oscillation," decreasing until $a \sim 0.3$ before increasing toward the present day.

The last two equations of state (Models 3 and 4) are inspired by the oscillating parametrization introduced by Ma and Zhang [60]. In both models, a linear envelope is supplemented by oscillations that rapidly increase in frequency after the beginning of the universe (Model 3) or before the present day (Model 4). Whereas the for-

at late times. In this work, we investigate four minimal one-parameter models of dark energy with non-linear dependence on the scale factor. These models are constrained using Cosmic Microwave Background (CMB) data from *Planck*, lensing reconstruction from ACT-DR6, Baryon Acoustic Oscillation (BAO) measurements from DESI-DR2, and three Type-Ia supernovae (SNe) samples (PantheonPlus, DESY5, and Union3), considered independently. Although our conclusions depend on the choice of SNe sample, we consistently find a preference, as measured by the chi-squared statistic and the Bayesian evidence, for these dynamical dark energy models over the standard ΛCDM model. Notably, with the PantheonPlus dataset, one model shows strong Bayesian evidence ($\Delta \ln B \simeq 4.5$) against CPL, favoring an equation of state that peaks near $a \simeq 0.7$ and oscillates near the present day. These results highlight the impact of SNe selection and contribute to the

Hints for oscillations in the DE





Parameter	PantheonPlus	DESY5	Union3
$\Omega_c h^2$	0.12008 ± 0.00072	0.11984 ± 0.00074	0.11973 ± 0.00075
$\Omega_b h^2$	0.02237 ± 0.00013	0.02239 ± 0.00013	0.02240 ± 0.00013
$100\theta_{MC}$	1.04091 ± 0.00028	1.04094 ± 0.00029	1.04095 ± 0.00028
τ_{reio}	0.0524 ± 0.0068	0.0532 ± 0.0069	0.0539 ± 0.0070
n_s	0.9652 ± 0.0035	0.9657 ± 0.0034	0.9662 ± 0.0034
$\log(10^{10}A_s)$	3.039 ± 0.012	3.041 ± 0.013	3.042 ± 0.013
w_0	-0.940 ± 0.026	-0.918 ± 0.024	-0.906 ± 0.031
Ω_m	0.3128 ± 0.0055	0.3169 ± 0.0051	0.3194 ± 0.0064
σ_8	0.8179 ± 0.0084	0.8124 ± 0.0083	0.8093 ± 0.0097
S_8	0.8350 ± 0.0074	0.8349 ± 0.0077	0.8350 ± 0.0075
H_0	67.65 ± 0.60	67.15 ± 0.54	66.87 ± 0.71
r_{drag}	147.08 ± 0.20	147.13 ± 0.20	147.14 ± 0.20
$\Delta\chi^2_{min}$ ($\Delta \ln B$) ΛCDM	-12.6 (2.7)	-15.8 (3.9)	-12.7 (2.7)
$\Delta\chi^2_{min}$ ($\Delta \ln B$) CPL	-3.5 (4.6)	3.1 (0.3)	0.9 (0.6)

Kessler, Escamilla, Pan, & Di Valentino, arXiv:*2504.00776*

The w(a) of this model oscillates with increasing frequency and an amplitude that decreases over cosmic time, reaching zero at the present day. It features a phantom crossing at a≃2/3, and today it differs from –1 at more than 3σ significance. This model with PantheonPlus is significantly favored over the CPL parametrization by the Bayesian evidence.

Hint for DDE using the pressure parametrizations

We explore an extension of the ΛCDM model in which the pressure of the DE fluid evolves with the expansion of the Universe, expressed as a function of the scale factor a. The term that parametrizes the evolution of the DE pressure is expanded in a Taylor series around the present time, as

$$p = -p_0 + \sum_{n\geq 1} \frac{1}{n!}(1-a)^n p_n \,,$$

We consider the truncation of the Taylor series at second order, and the corresponding energy density ρ is derived from the continuity equation:

$$p = -\rho_{\rm DE,0} + \left(\frac{3}{4} - a\right) p_1 + \left(\frac{9}{20} - a + \frac{1}{2}a^2\right) p_2 \,.$$

and we introduce the dimensionless quantities:

$$\Omega_{1,2} \equiv \frac{3}{4}\frac{p_{1,2}}{\rho_{\rm crit}}$$

Under these assumptions, the equation-of-state parameter can be written as:

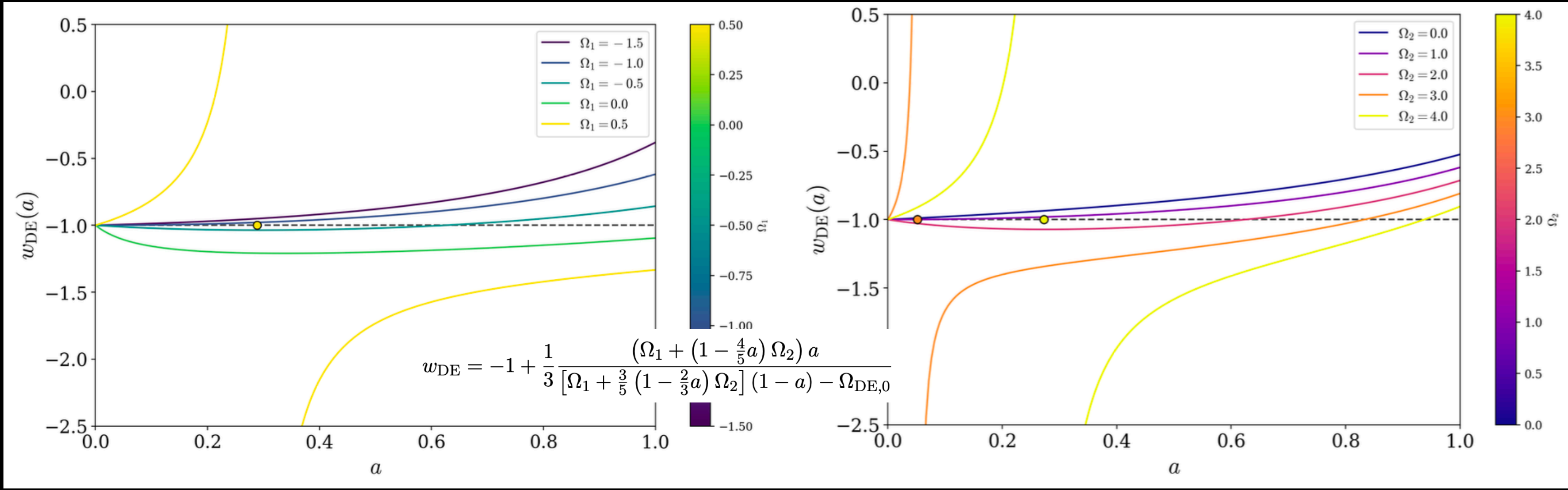
$$w_{\rm DE} = -1 + \frac{1}{3}\frac{\left(\Omega_1 + \left(1 - \frac{4}{5}a\right)\Omega_2\right)a}{\left[\Omega_1 + \frac{3}{5}\left(1 - \frac{2}{3}a\right)\Omega_2\right](1-a) - \Omega_{\rm DE,0}}$$

Cheng, Di Valentino, Escamilla, Sen, & Visinelli, arXiv:*2505.02932*

Hint for DDE using the pressure parametrizations

$$a_{\rm pole} = \frac{5}{4}\,\frac{(\Omega_1+\Omega_2) \pm \sqrt{(\Omega_1+\Omega_2)^2 - \frac{8}{5}\Omega_2\left(\Omega_1+\frac{3}{5}\Omega_2-\Omega_{\rm DE,0}\right)}}{\Omega_2}\,,$$

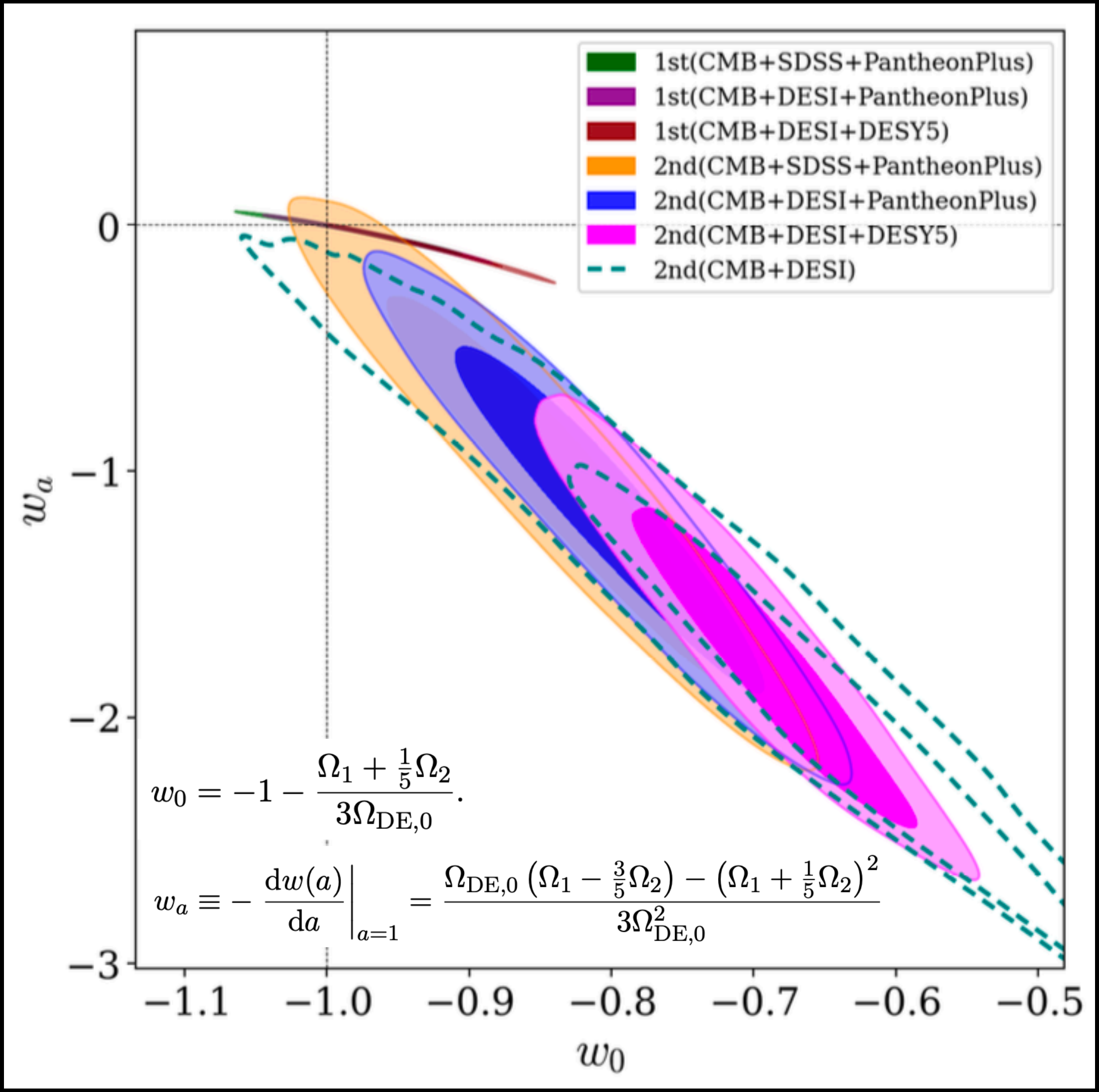
The reconstructed DE evolution in the second-order case reveals a distinctive non-monotonic behavior in w(a), including pure phantom, pure quintessence, and clear phantom-crossing.

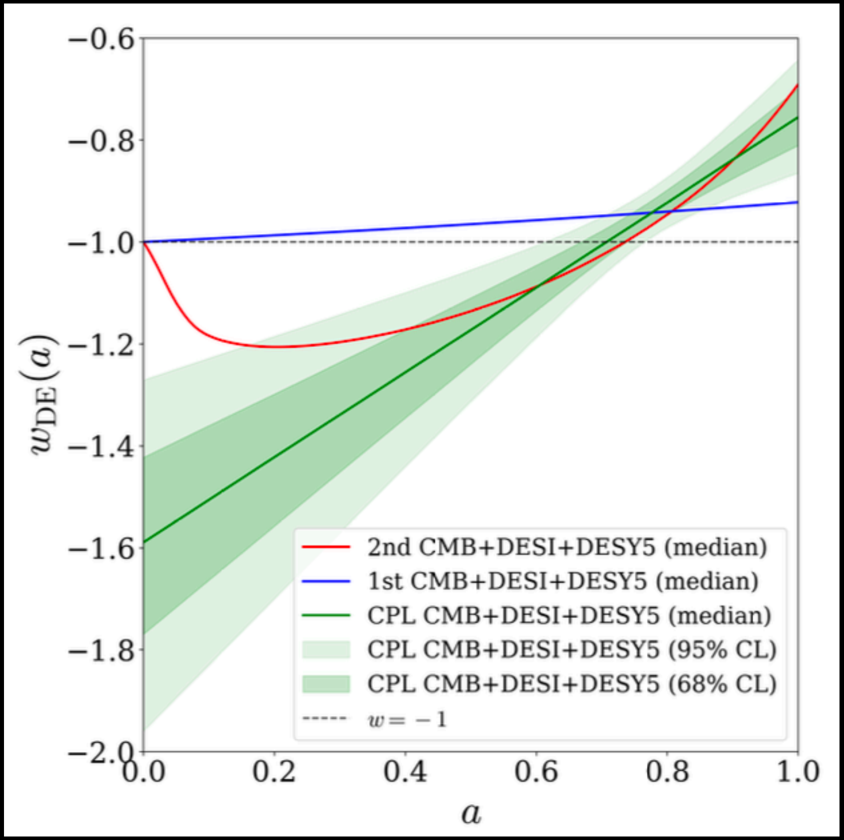


$$w_{\rm DE} = -1 + \frac{1}{3}\,\frac{\left(\Omega_1 + \left(1-\frac{4}{5}a\right)\Omega_2\right)a}{\left[\Omega_1+\frac{3}{5}\left(1-\frac{2}{3}a\right)\Omega_2\right](1-a)-\Omega_{\rm DE,0}}$$

Cheng, Di Valentino, Escamilla, Sen, & Visinelli, arXiv:*2505.02932*

Hint for DDE using the pressure parametrizations

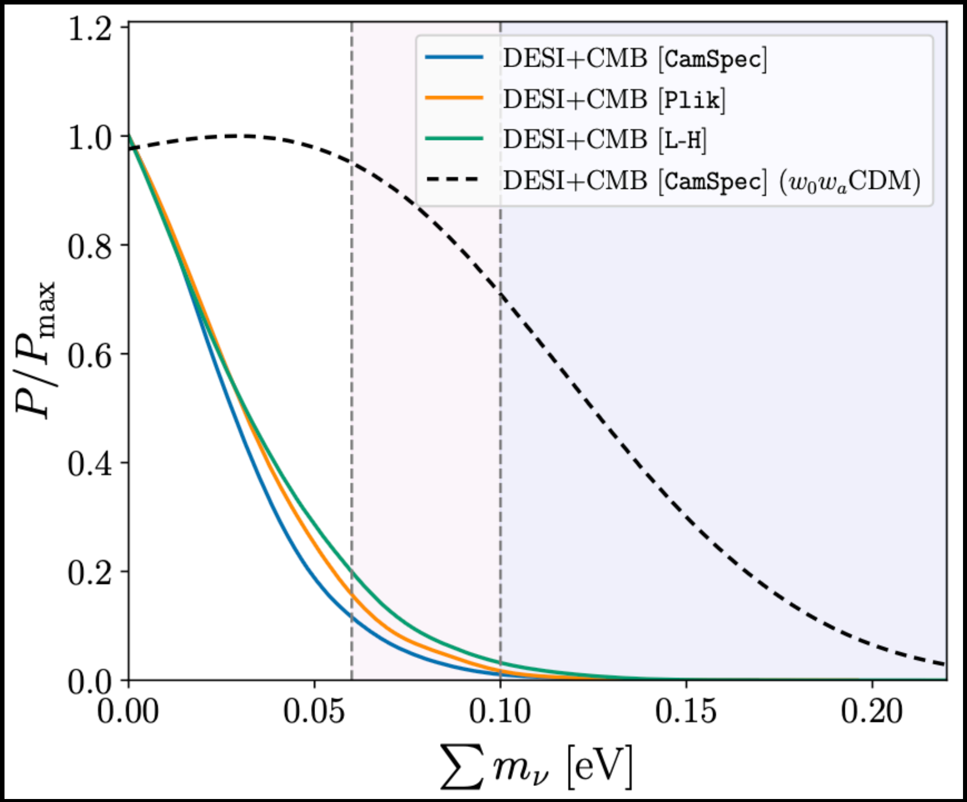




compare their performance against ΛCDM and the CPL parameterization. A joint analysis of *Planck* CMB, DESI, and DESY5 data yields the strongest evidence for DDE, with a 2.7σ deviation in the first-order model and over 4σ in the second-order model—providing strong statistical support for a departure from a cosmological constant. The reconstructed DE evo-

Cheng, Di Valentino, Escamilla, Sen, & Visinelli, arXiv:*2505.02932*

Consequences? Neutrino mass tension

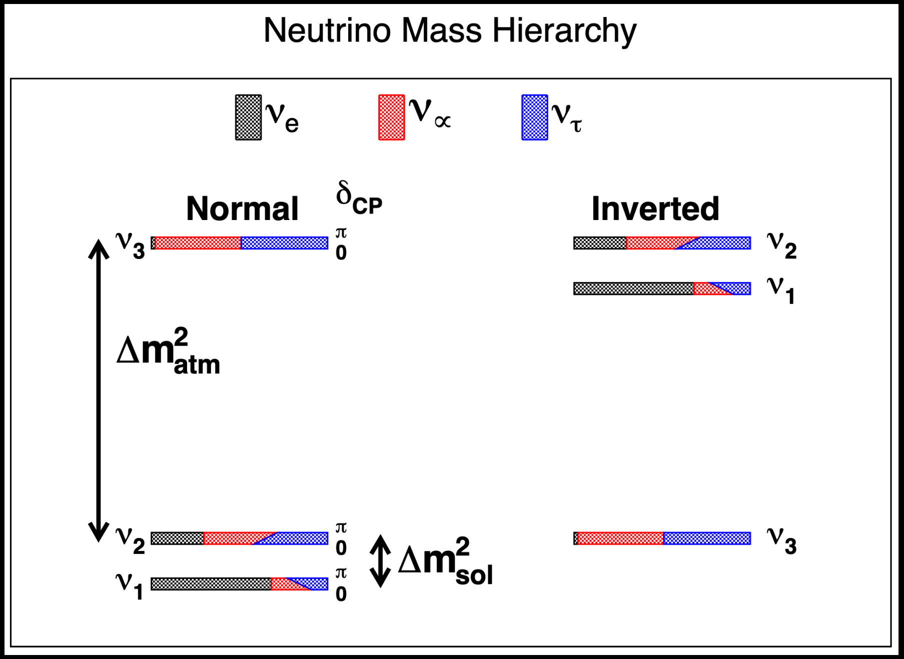


Model/Dataset	Ω_{m}	H_0 [km s^{-1} Mpc^{-1}]	$H_0 r_{\mathrm{d}}$ [100 km s^{-1}]	$\sum m_\nu$ [eV]
ΛCDM+$\sum m_\nu$				
DESI BAO+CMB [Camspec]	0.3009 ± 0.0037	68.36 ± 0.29	100.96 ± 0.48	< 0.0642
DESI BAO+CMB [L-H]	0.2995 ± 0.0037	68.48 ± 0.30	101.16 ± 0.49	< 0.0774
DESI BAO+CMB [Plik]	0.2998 ± 0.0038	68.56 ± 0.31	101.09 ± 0.50	< 0.0691

DESI collaboration, Abdul Karim et al., arXiv:2503.14738

Consequences? Neutrino mass tension

Even though the absolute masses of neutrinos ν are unknown, lower bounds on the total neutrino mass are established through global analyses of oscillation data. These analyses provide the best-fit values for the standard model mass splitting.



Qian and Vogel, arXiv:1505.01891

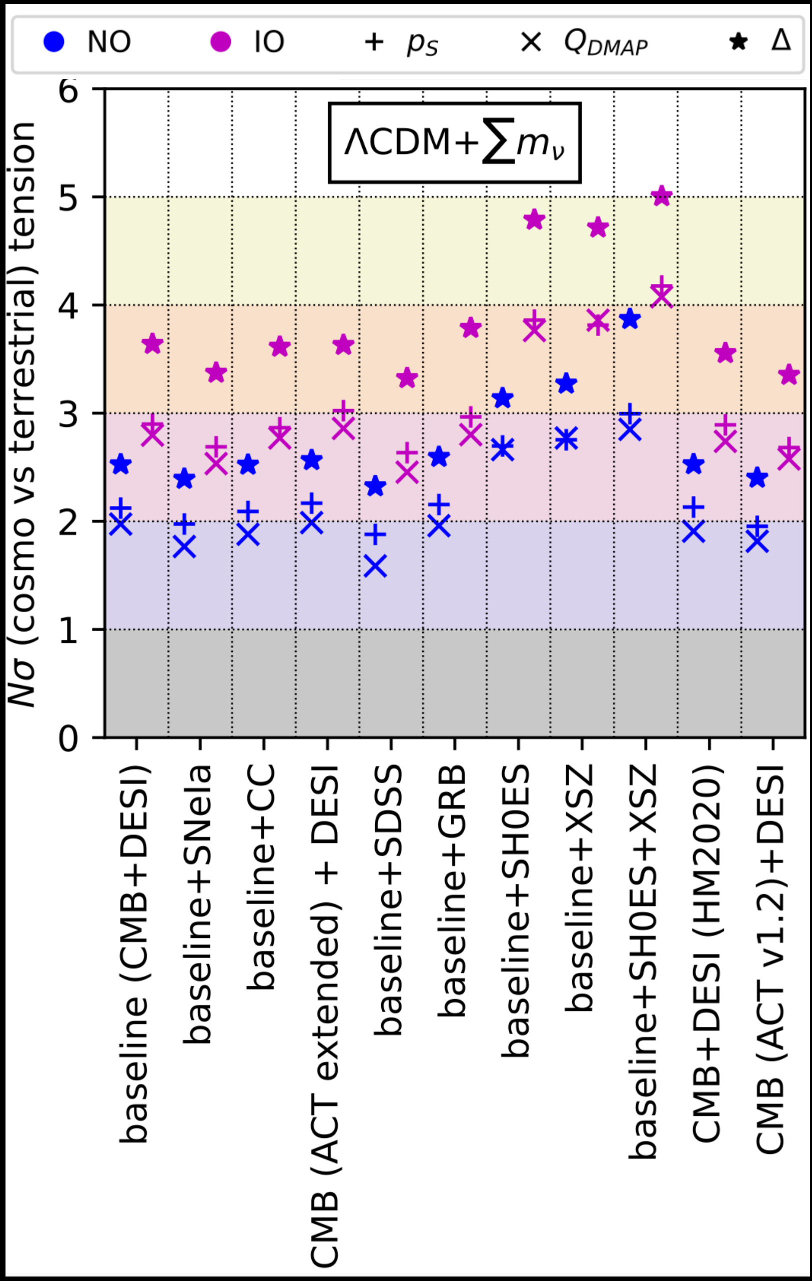
By setting the lightest neutrino mass to zero, we can determine the lower bounds on the total neutrino mass for the normal or inverted ordering:

$$\sum m_\nu > \begin{cases} (0.0591 \pm 0.00027)\,\mathrm{eV} & \mathrm{(NO)} \\ (0.0997 \pm 0.00051)\,\mathrm{eV} & \mathrm{(IO)} \end{cases}$$

Consequences? Neutrino mass tension

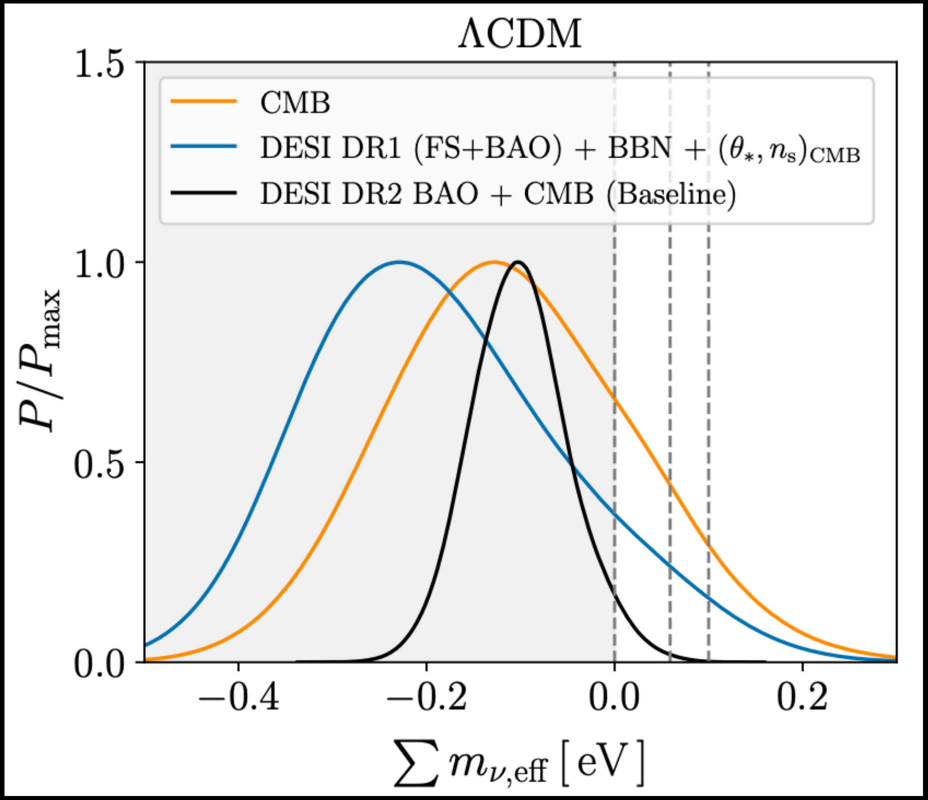
Dataset combination	ΛCDM+$\sum m_\nu$	
	$\sum m_\nu$ (eV)	$B_{\mathrm{NO,IO}}$
baseline (CMB + DESI)	< 0.072	8.1
baseline + SNeIa	< 0.081	7.0
baseline + CC	< 0.073	7.3
baseline + SDSS	< 0.083	6.8
baseline + SH0ES	< 0.048	47.8
baseline + XSZ	< 0.050	46.5
baseline + GRB	< 0.072	8.7
aggressive combination (baseline + SH0ES + XSZ)	< 0.042 eV	72.6
CMB (with ACT "extended" likelihood)+DESI	< 0.072	8.0
CMB+DESI (with 2020 `HMCode`)	< 0.074	7.5
CMB (with `v1.2` ACT likelihood)+DESI	< 0.082	7.4

Jiang, Giarè, Gariazzo, Dainotti, Di Valentino, et al., *JCAP* 01 (2025) 153



The level of tension between cosmological and terrestrial experiments for NO is around 2.5σ, and increases to approximately 3.5σ for IO, when excluding the most extreme cases involving SH0ES and XSZ.

Consequences? Indication for negative neutrino mass



Model/Dataset	Ω_m	H_0 [km s^{-1} Mpc^{-1}]	$\sum m_{\nu,\mathrm{eff}}$ [eV]
ΛCDM+$\sum \mathbf{m}_{\nu,\mathrm{eff}}$			
DESI BAO+CMB (Baseline)	0.2953 ± 0.0043	68.92 ± 0.38	$-0.101^{+0.047}_{-0.056}$
DESI BAO+CMB (`plik`)	0.2948 ± 0.0043	69.06 ± 0.39	$-0.099^{+0.050}_{-0.061}$
DESI BAO+CMB (`L-H`)	0.2953 ± 0.0044	68.89 ± 0.39	$-0.067^{+0.054}_{-0.064}$

DESI collaboration, Elbers et al., arXiv:2503.14744

There is a lot of literature trying to dissect BAO and SN data looking for possible problems.

arXiv > astro-ph > arXiv:2408.07175

Search...

Help | Adv

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 13 Aug 2024 (v1), last revised 3 Feb 2025 (this version, v3)]

Evolving Dark Energy or Supernovae Systematics?

George Efstathiou

Recent results from the Dark Energy Spectroscopic Instrument (DESI) collaboration have been interpreted as evidence for evolving dark energy. However, this interpretation is strongly dependent on which Type Ia supernova (SN) sample is combined with DESI measurements of baryon acoustic oscillations (BAO) and observations of the cosmic microwave background (CMB) radiation. The strength of the evidence for evolving dark energy ranges from ~3.9 sigma for the Dark Energy 5 year (DES5Y) SN sample to ~2.5 sigma for the Pantheon+ sample. The cosmology inferred from Pantheon+ sample alone is consistent with the Planck LCDM model and shows no preference for evolving dark energy. In contrast, the the DES5Y SN sample favours evolving dark energy and is discrepant with the Planck LCDM model at about the 3 sigma level. Given these difference, it is important to question whether they are caused by systematics in the SN compilations. A comparison of SN common to both the DES5Y and Pantheon+ compilations shows evidence for an offset of ~0.04 mag. between low and high redshifts. Systematics of this order can bring the DES5Y sample into good agreement with the Planck LCDM cosmology and Pantheon+. I comment on a recent paper by the DES collaboration that rejects this possibility.

arXiv > astro-ph > arXiv:2505.02658

Search...

Help | Adv

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 5 May 2025]

Baryon Acoustic Oscillations from a Different Angle

George Efstathiou

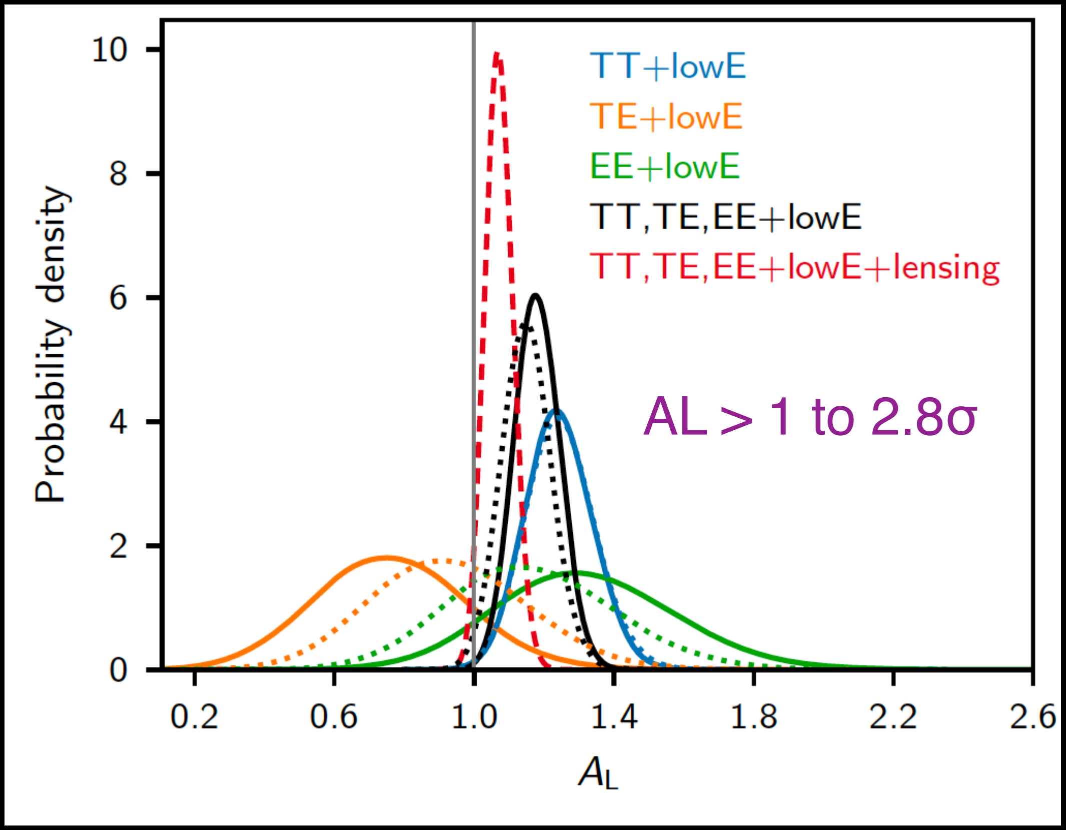
This paper presents an alternative way of analysing Baryon Acoustic Oscillation (BAO) distance measurements via rotations to define new quantities Dperp and Dpar. These quantities allow simple tests of consistency with the Planck LCDM cosmology. The parameter Dperp is determined with negligible uncertainty from Planck under the assumption of LCDM. Comparing with measurements from the Dark Energy Spectroscopic Instrument (DESI), we find that the measurements of Dperp from Data Release 2 (DR2) move into significantly better agreement with the Planck LCDM cosmology compared to DESI Data Release 1 (DR1). The quantity in the orthogonal direction Dpar provides a measure of the physical matter density omega_m in the LCDM cosmology. The DR2 measurements of Dpar\ also come into better agreement with Planck LCDM compared to the earlier DR1 results. From the comparison of Planck and DESI BAO measurements, we find no significant evidence in support of evolving dark energy. We also investigate a rotation in the theory space of the w_0 and w_a parameterization of the dark energy equation-of-state w(z). We show that the combination of DESI BAO measurements and the CMB constrain w(z=0.5) = -0.996 pm 0.046, i.e. very close to the value expected for a cosmological constant. We present a critique of the statistical methodology employed by the DESI collaboration and argue that it gives a misleading impression of the evidence in favour of evolving dark energy. An Appendix shows that the cosmological parameters determined from the Dark Energy Survey 5 Year supernova sample are in tension with those from
DESI DR2 and parameters determined by Planck.

There is a selection bias in our community:
we tend to trust data only when they agree with Planck LCDM.

What about the CMB problems?

Plik PR3 A_L problem

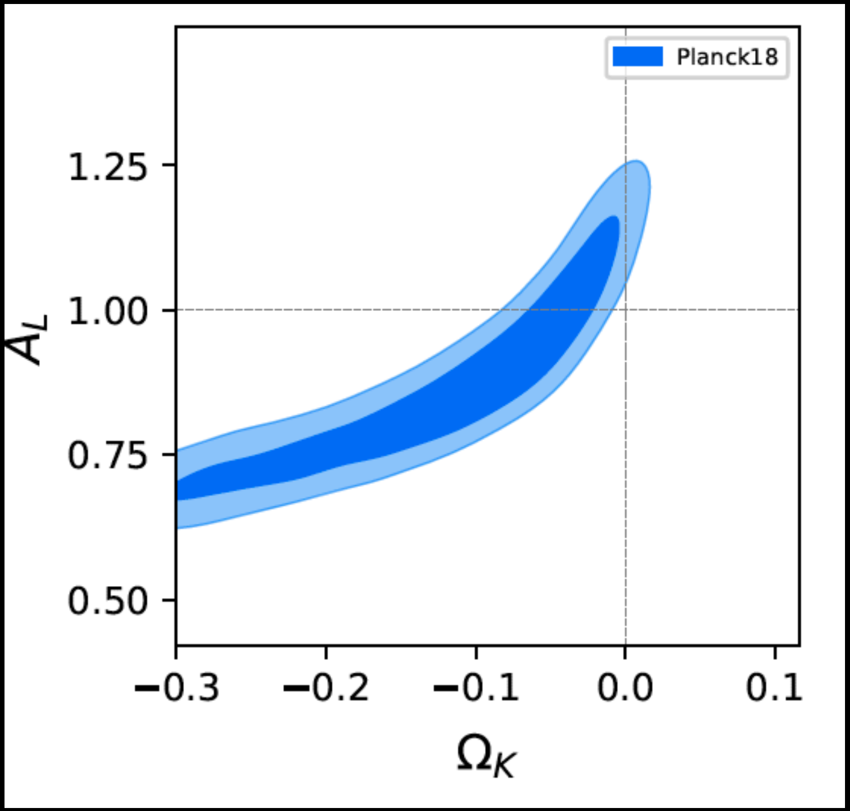
Planck 2018, Astron.Astrophys. 641 (2020) A6

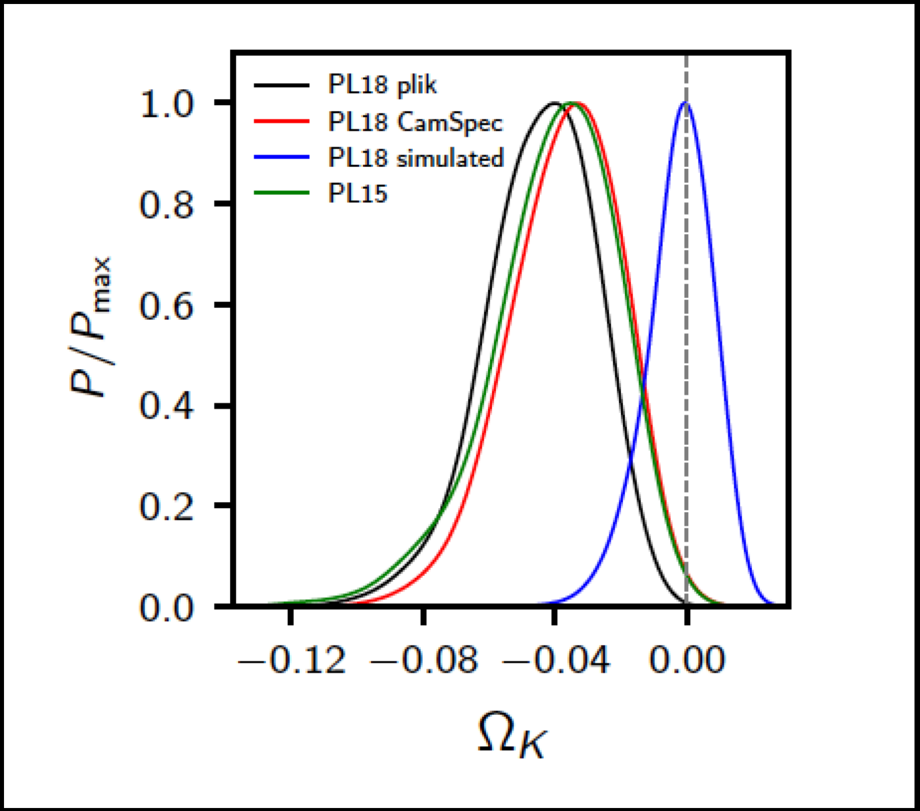


$$A_L = 1.243 \pm 0.096 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT{+}lowE}),$$
$$A_L = 1.180 \pm 0.065 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT{,}TE{,}EE{+}lowE}),$$

The preference for a high AL is not merely a volume effect in the full parameter space; the best fit improves by $\Delta\chi^2 \approx 9$ when adding AL for TT+lowE, and by ≈ 10 for TTTEEE+lowE.

Plik PR3 Ω_K problem





Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203

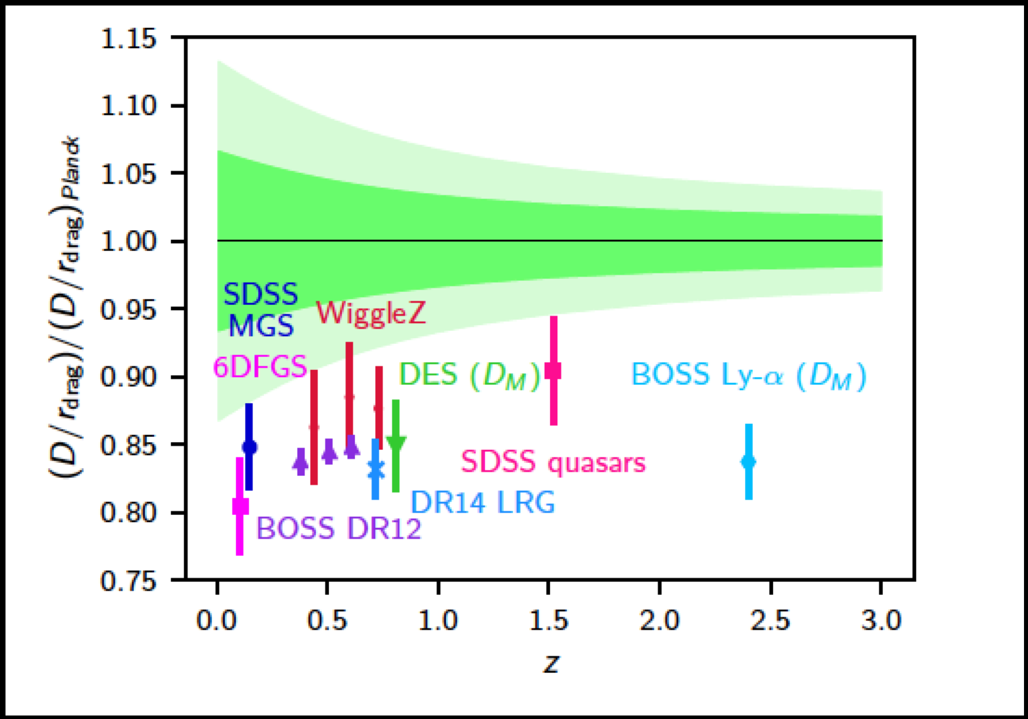
This excess of lensing affects the constraints on the curvature of the universe:

$$\Omega_K = -0.044^{+0.018}_{-0.015} \quad (68\,\%, \textit{Planck}\ \text{TT,TE,EE+lowE}),$$

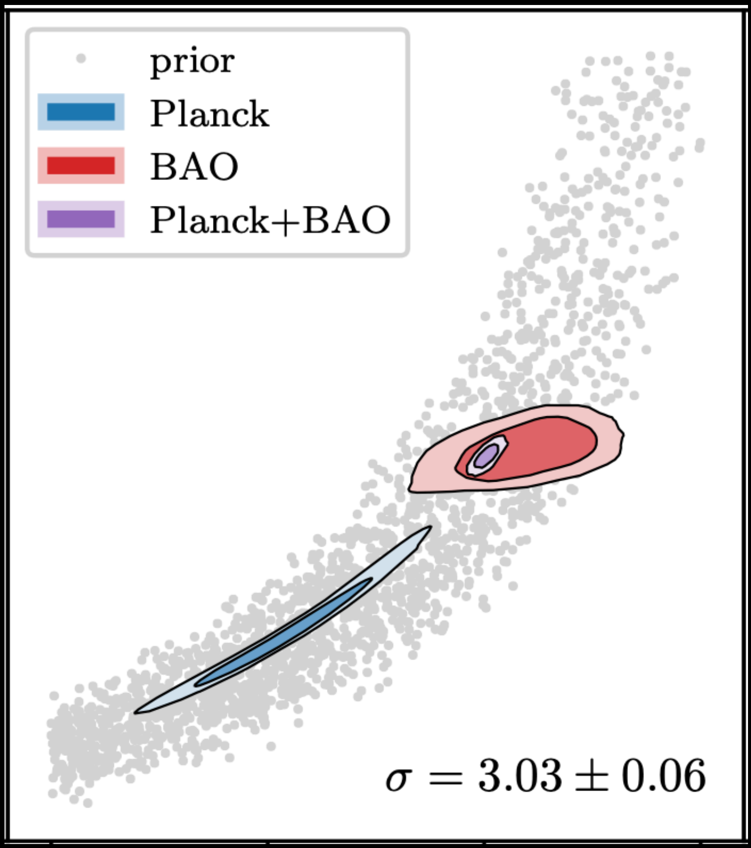
Planck 2018, Astron.Astrophys. 641 (2020) A6

leading to a detection of non-zero curvature,
with a 99% probability region of $-0.095 \leq \Omega_K \leq -0.007$.

Plik PR3 - SDSS tension in kLCDM



Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203



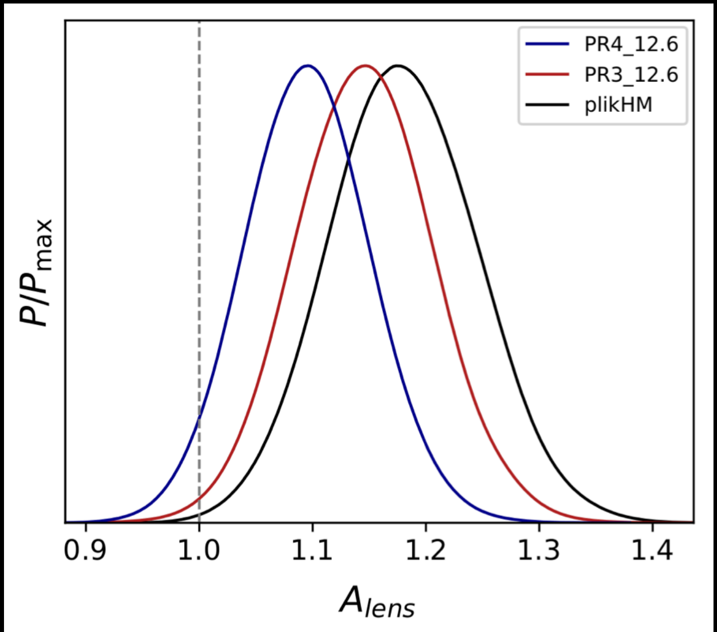
Handley, *Phys.Rev.D* 103 (2021) 4, L041301

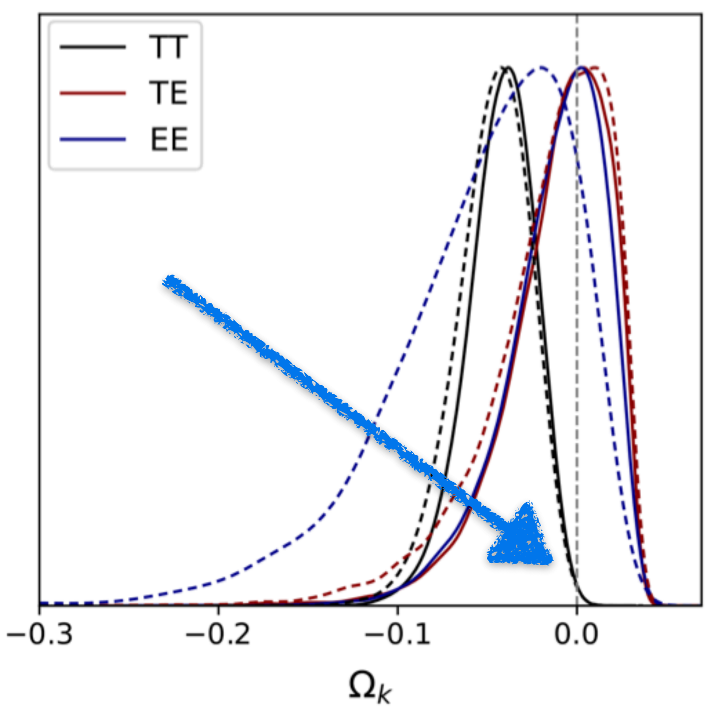
Allowing curvature to vary reveals a significant disagreement between the Planck spectra and BAO data.

CamSpec PR4

PR4_12.6	A_L	Ω_K	$N_{\rm eff}$	m_ν
TTTEEE	1.095 ± 0.056	$-0.025^{+0.013}_{-0.010}$	3.00 ± 0.21	< 0.161
TT	1.198 ± 0.084	$-0.042^{+0.022}_{-0.016}$	$2.98^{+0.28}_{-0.35}$	< 0.278
TE	0.96 ± 0.15	$-0.010^{+0.035}_{-0.015}$	$3.11^{+0.38}_{-0.42}$	< 0.400
EE	0.995 ± 0.15	$-0.012^{+0.034}_{-0.017}$	4.6 ± 1.3	< 2.37
PR3_12.6	A_L	Ω_K	$N_{\rm eff}$	m_ν
TTTEEE	1.146 ± 0.061	$-0.035^{+0.016}_{-0.012}$	$2.94^{+0.20}_{-0.23}$	< 0.143
TT	1.215 ± 0.089	$-0.047^{+0.024}_{-0.017}$	$2.89^{+0.28}_{-0.32}$	< 0.248
TE	0.96 ± 0.17	$-0.015^{+0.043}_{-0.015}$	$2.96^{+0.42}_{-0.49}$	< 0.504
EE	1.15 ± 0.20	$-0.053^{+0.063}_{-0.029}$	$2.46^{+0.94}_{-1.7}$	-

Rosenberg et al., arXiv:2205.10869

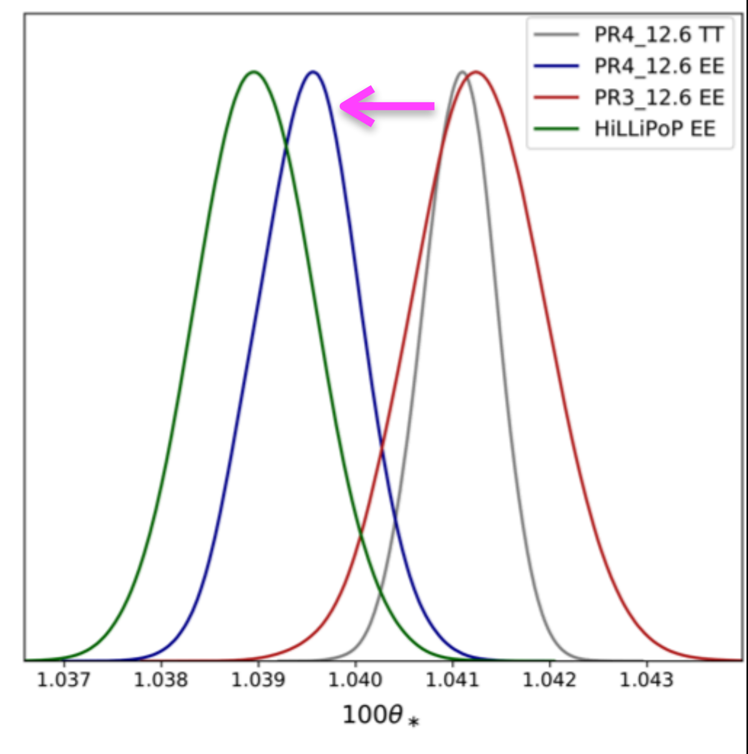




This new likelihood does not truly resolve the problem of AL/ΩK, which originates primarily from the TT power spectrum. Moreover, the constraints from TT remain essentially unchanged between the two releases.

CamSpec PR4

PR4_12.6	A_L	Ω_K	$N_{\rm eff}$	m_ν
TTTEEE	1.095 ± 0.056	$-0.025^{+0.013}_{-0.010}$	3.00 ± 0.21	< 0.161
TT	1.198 ± 0.084	$-0.042^{+0.022}_{-0.016}$	$2.98^{+0.28}_{-0.35}$	< 0.278
TE	0.96 ± 0.15	$-0.010^{+0.035}_{-0.015}$	$3.11^{+0.38}_{-0.42}$	< 0.400
EE	0.995 ± 0.15	$-0.012^{+0.034}_{-0.017}$	4.6 ± 1.3	< 2.37
PR3_12.6	A_L	Ω_K	$N_{\rm eff}$	m_ν
TTTEEE	1.146 ± 0.061	$-0.035^{+0.016}_{-0.012}$	$2.94^{+0.20}_{-0.23}$	< 0.143
TT	1.215 ± 0.089	$-0.047^{+0.024}_{-0.017}$	$2.89^{+0.28}_{-0.32}$	< 0.248
TE	0.96 ± 0.17	$-0.015^{+0.043}_{-0.015}$	$2.96^{+0.42}_{-0.49}$	< 0.504
EE	1.15 ± 0.20	$-0.053^{+0.063}_{-0.029}$	$2.46^{+0.94}_{-1.7}$	-



Rosenberg et al., arXiv:2205.10869

The constraints derived from the EE power spectrum are the ones pulling all parameters toward ΛCDM, thereby alleviating the tensions.

However, this change in EE induces a significant shift in the acoustic scale parameter θ, leading to an internal tension of 2.8σ between TT and EE, which increases to over 3.2-3.3σ when AL/ΩK are allowed to vary.

CamSpec PR4

Efstathiou & Gratton, arXiv:1910.00483

spectrum	ℓ range	N_D	$\hat{\chi}^2$	$(\hat{\chi}^2 - 1)/\sqrt{2/N_D}$
TT coadded	$30 - 2500$	2471	1.01	0.18
TT 100×100	$30 - 1400$	1371	1.04	0.97
TT 143×143	$30 - 2000$	1971	1.02	0.56
TT 143×217	$500 - 2500$	2001	0.98	-0.57
TT 217×217	$500 - 2500$	2001	0.95	-1.58
TT All	$30 - 2500$	7344	0.99	-0.38
TE	$30 - 2000$	1971	1.01	0.32
EE	$30 - 2000$	1971	0.93	-2.12
TEEE	$30 - 2000$	3942	1.02	0.98
TTTEEE	$30 - 2500$	11286	0.97	-2.20

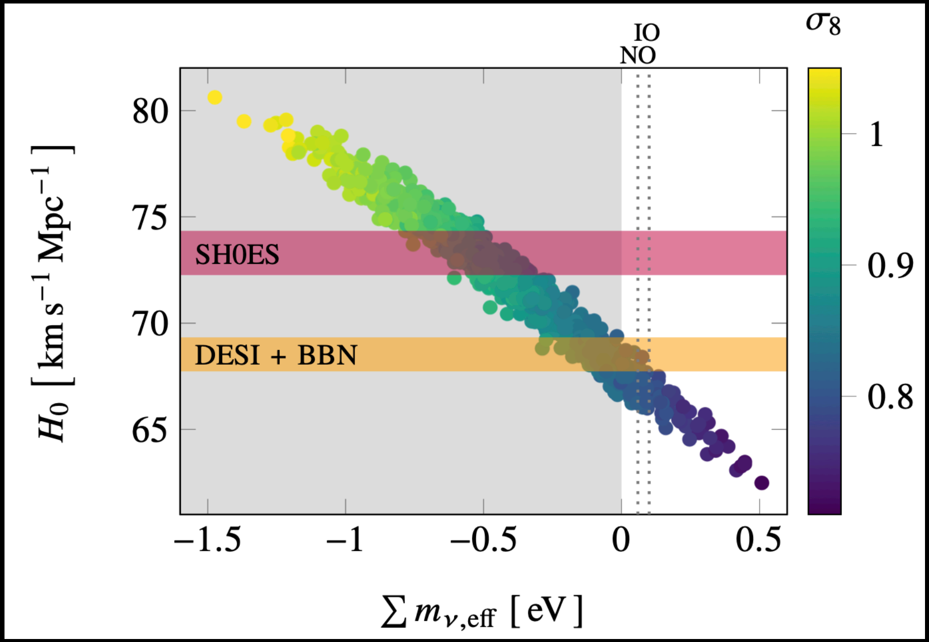
	ℓ range	N_D	$\hat{\chi}^2$	$(\hat{\chi}^2 - 1)/\sqrt{2/N_D}$
TT 143x143	30 – 2000	1971	1.021	0.67
TT 143x217	500 – 2500	2001	0.985	-0.47
TT 217x217	500 – 2500	2001	1.002	0.05
TT All	30 – 2500	5973	1.074	4.07
TE	30 – 2000	1971	1.055	1.73
EE	30 – 2000	1971	1.026	0.82
TEEE	20 – 2000	3942	1.046	2.02
TTTEEE	30 – 2500	9915	1.063	4.46

Table 1. χ^2 of the different components of the PR4_12.6 likelihood with respect to the TTTEEE best-fit model. N_D is the size of the data vector. $\hat{\chi}^2 = \chi^2/N_D$ is the reduced χ^2. The last column gives the number of standard deviations of $\hat{\chi}^2$ from unity.

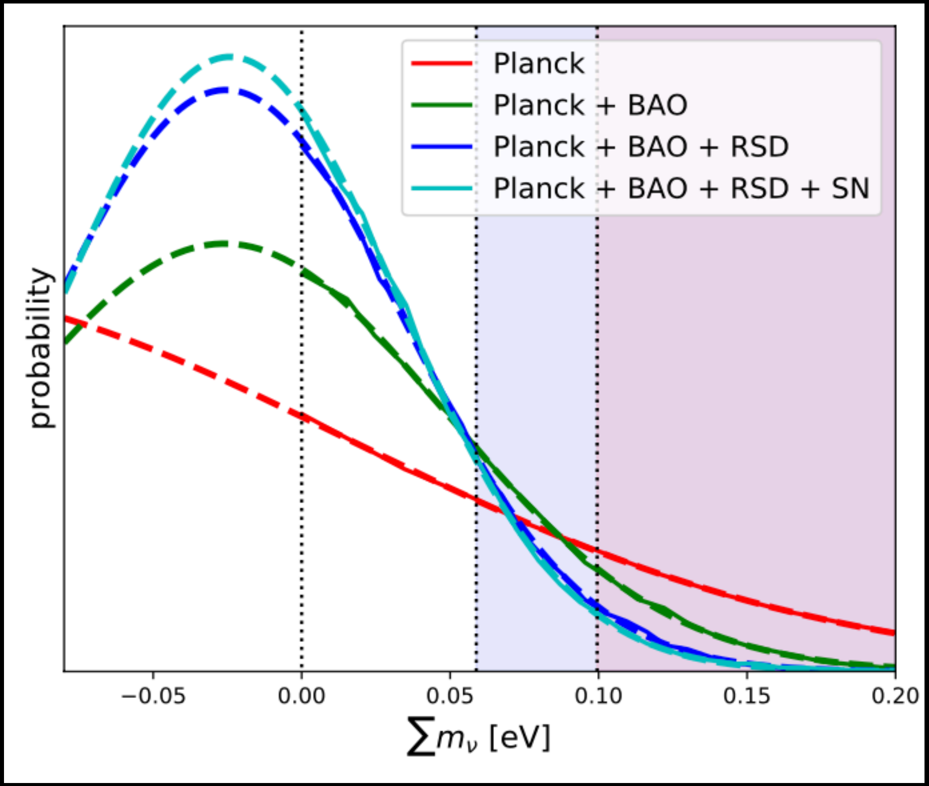
Rosenberg et al., arXiv:2205.10869

Moreover, the reduced χ2 values reveal a >4σ tension between the data and the ΛCDM best-fit from TTTEEE.

Negative total neutrino mass



Elbers et al., arXiv: 2407.10965

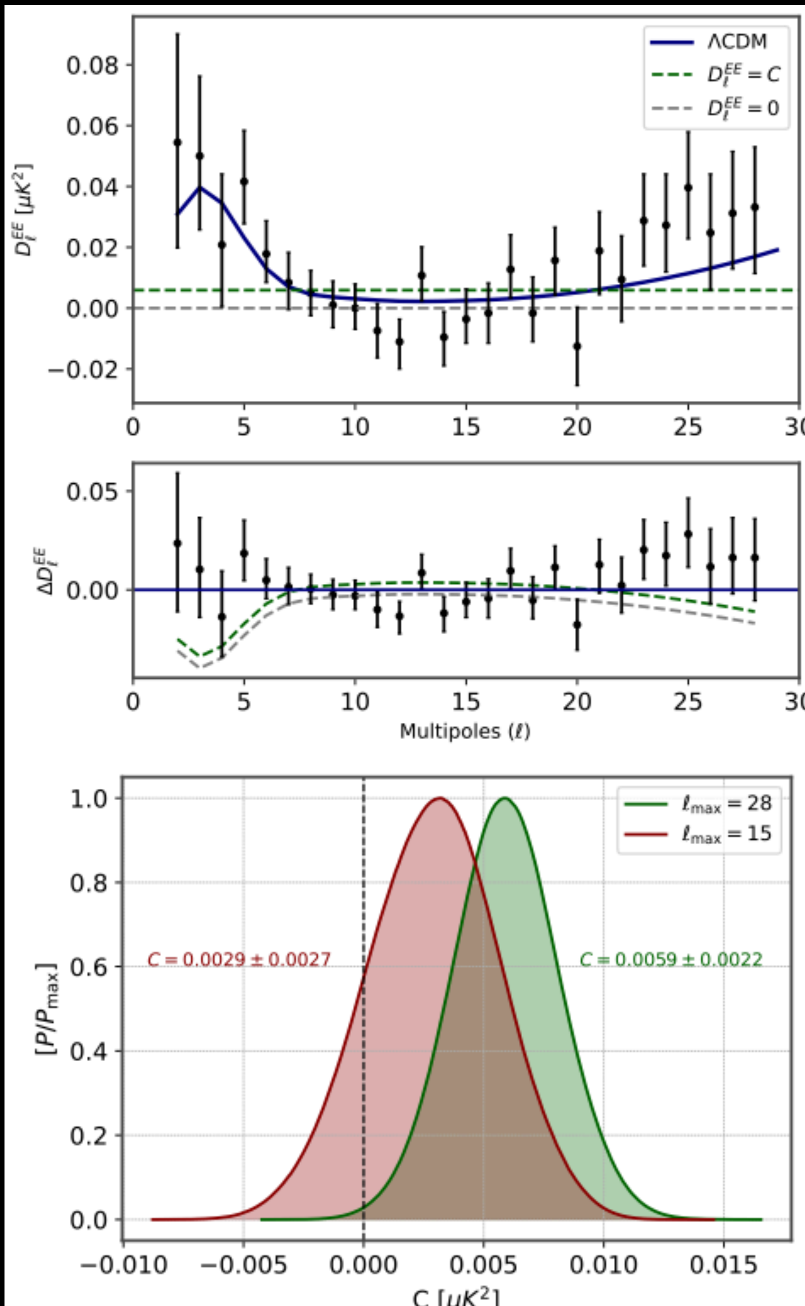


eBOSS collaboration, Alam et al.,
Phys.Rev.D 103 (2021) 8, 083533

The excess of lensing observed in the CMB affects the inferred total neutrino mass:
Planck alone (CamSpec PR4) prefers a negative neutrino mass,
a trend already seen in Plik PR3 combined with SDSS.

The optical depth

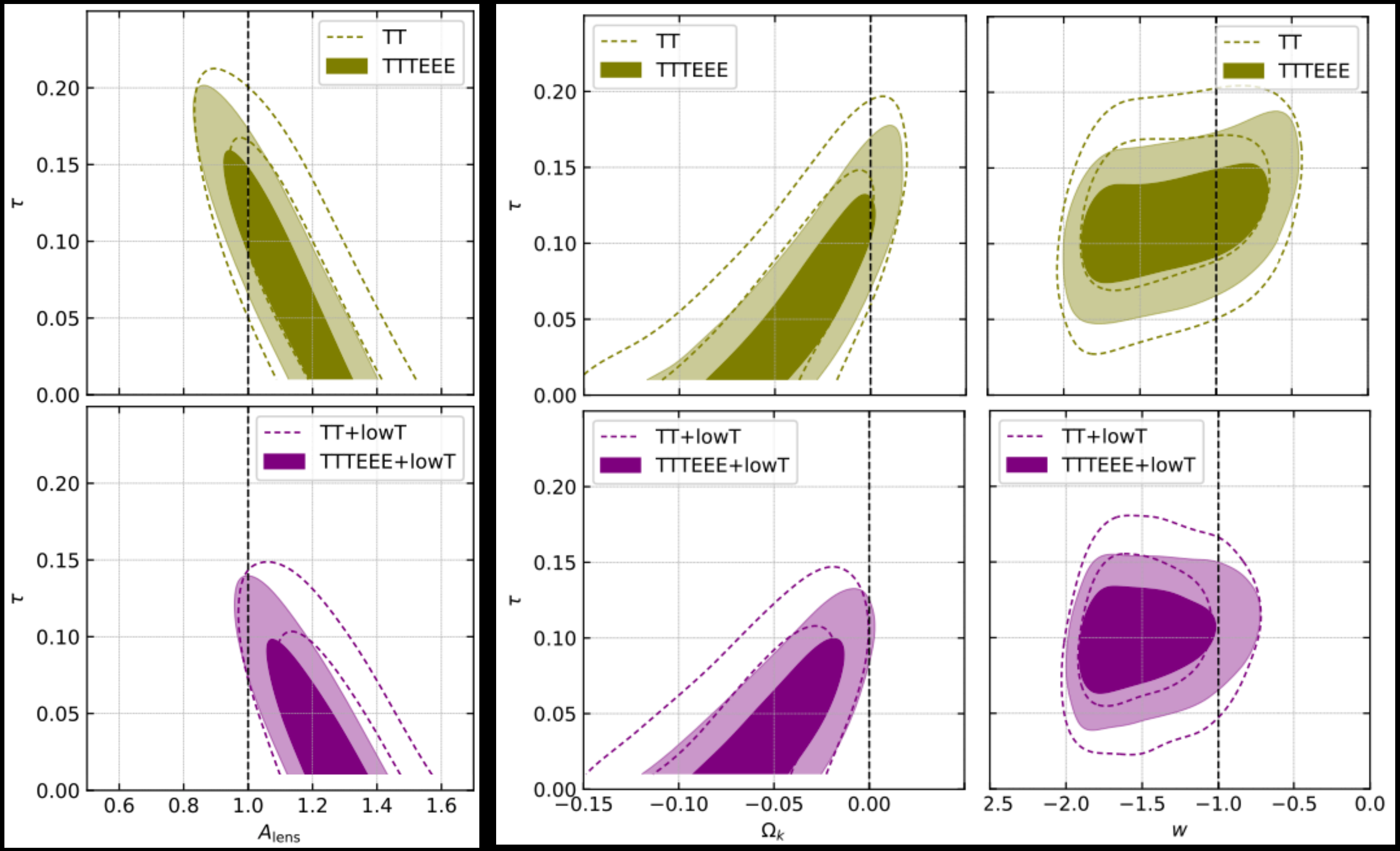
$$C_\ell^{EE} \propto \tau^2/\ell^4$$



Reionization leaves an imprint on the large-scale CMB E-mode polarization (EE) and causes a suppression of temperature anisotropies at smaller scales (proportional to $A_s e^{-2\tau}$). Planck measured $\tau = 0.054 \pm 0.008$ at 68% CL, a significant improvement over the WMAP9 value of $\tau = 0.089 \pm 0.014$. However, the low-ℓ EE signal is extremely weak, in the cosmic variance limited region, and close to the detection threshold.

We tested the EE spectrum: fitting it with a flat line (i.e., no reionization bump) yields a p-value of 0.063. If we focus only on data points at $2 \leq l \leq 15$, the case C=0 (no signal) falls within the 1σ range. This raises concerns that, when dealing with measurements so close to the noise level, any statistical fluctuation or insufficient understanding of foregrounds could significantly affect the measurement of τ.

The role of the optical depth



When the lowE data are excluded, the results become consistent with ΛCDM, and the Planck anomalies disappear.

Giarè, Di Valentino, Melchiorri, Phys.Rev.D 109 (2024) 10, 103519

All the models are wrong, but some are useful

We shouldn't interpret observations through personal, theoretical, or historical priors.
If data agree with our beliefs, we call them "robust."
If they don't, we dismiss them or question their reliability.

I'm not saying we need new physics:
but we've become too precise and not accurate enough.

We're cherry-picking datasets based on convenience:
Plik PR3 or CamSpec? Pantheon+ or DESY5? DESI or SDSS?
Depends on which agrees better with "our" preferred results.

The same is happening with BAO: once considered a gold standard, is now questioned. And we cannot just go back to using older data like SDSS only when it supports our narrative. That's arbitrary and it's undermining scientific objectivity.

And finally we're ignoring the elephant in the room.

All the discussions so far focus on possible signs of new physics in the data, yet none of them can account for the high value of H0.

What is H0?

The Hubble constant H0 describes the expansion rate of the Universe today.

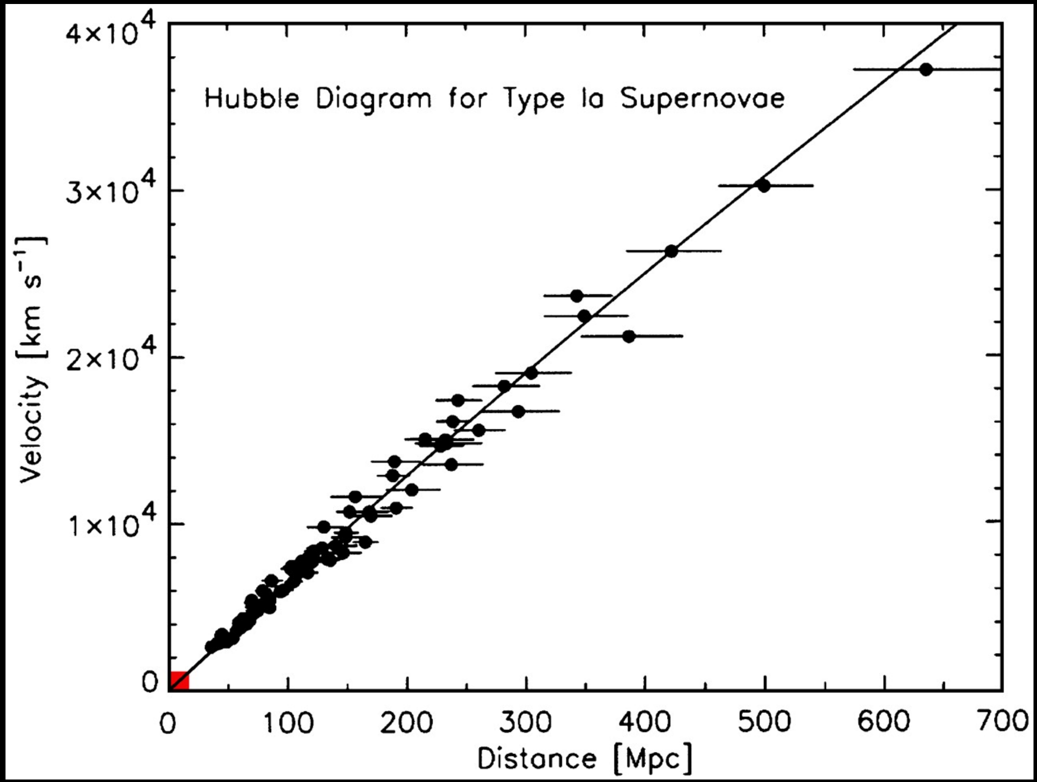
This can be obtained in two ways:

1. measuring the luminosity distance and the recessional velocity of known galaxies, and computing the proportionality factor.

Hubble's Law

$$v = H_0 \, D$$

This approach is model independent and based on geometrical measurements.



Jha, S. (2002) Ph.D. thesis (Harvard Univ., Cambridge, MA).

What is H0?

The Hubble constant H0 describes the expansion rate of the Universe today.

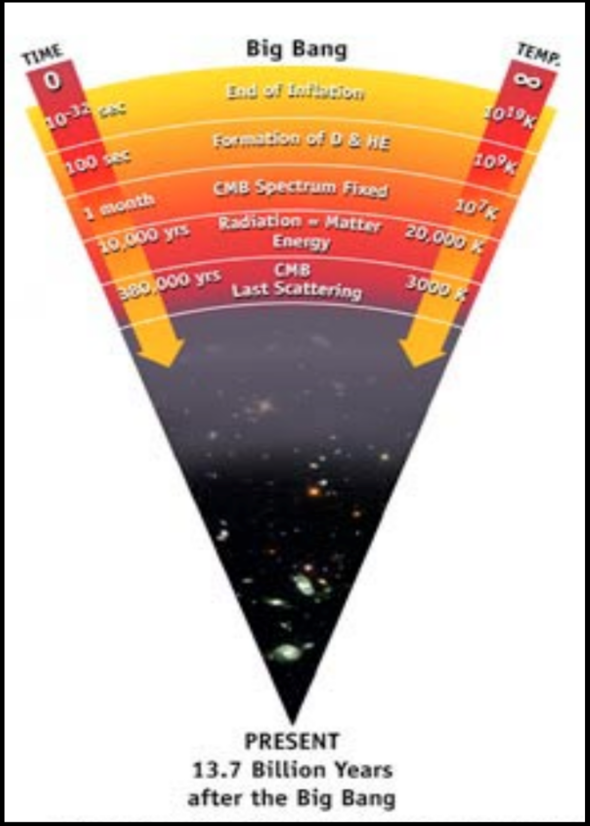
This can be obtained in two ways:

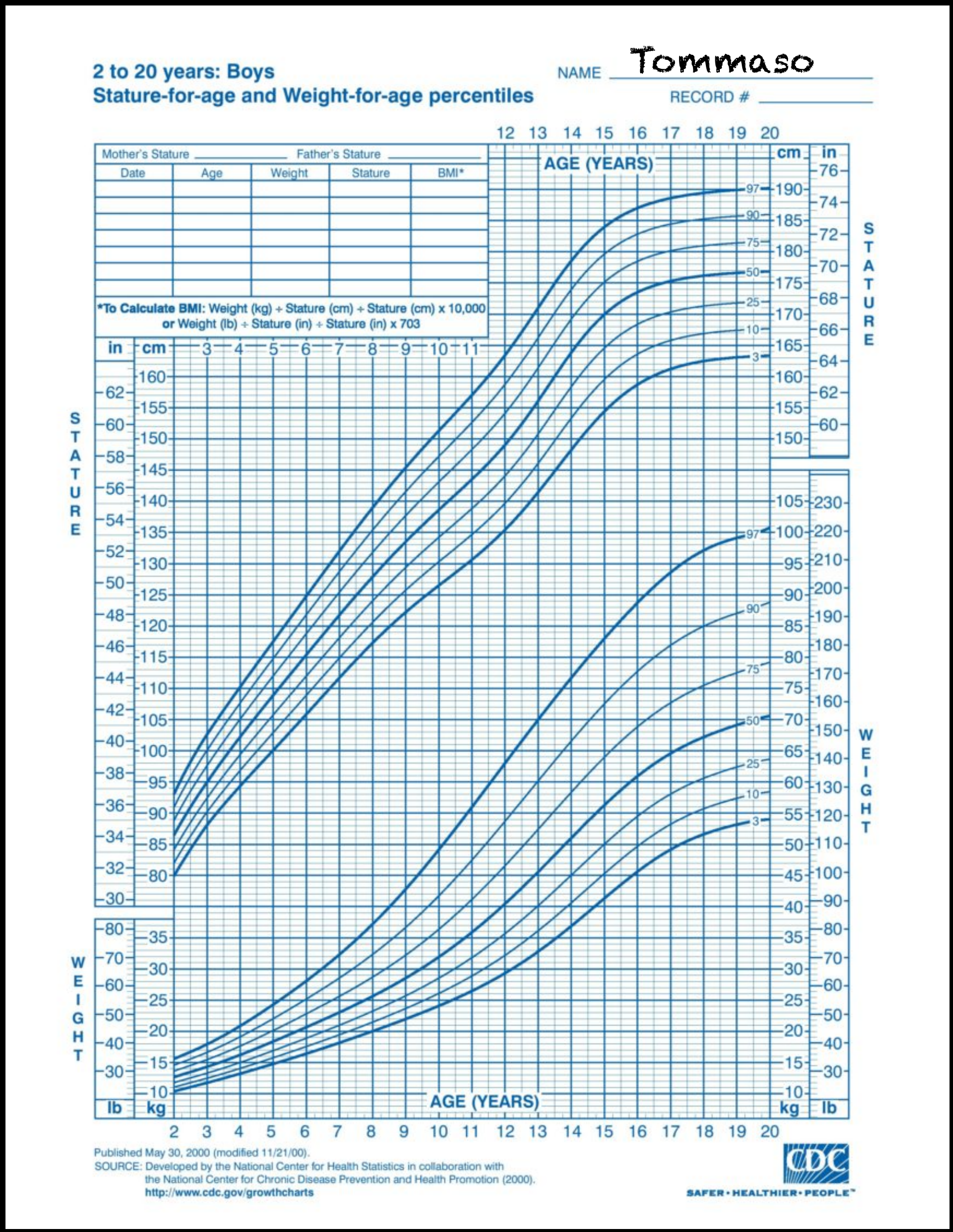
1. measuring the luminosity distance and the recessional velocity of known galaxies, and computing the proportionality factor.
2. considering early universe measurements, and assuming a model for the expansion history of the universe.

For example, we have CMB measurements and we assume the standard model of cosmology, i.e. the ΛCDM scenario.

1st Friedmann equation describes the expansion history of the universe:

$$H^2(z) = H_0^2 \left(\Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda\right) .$$



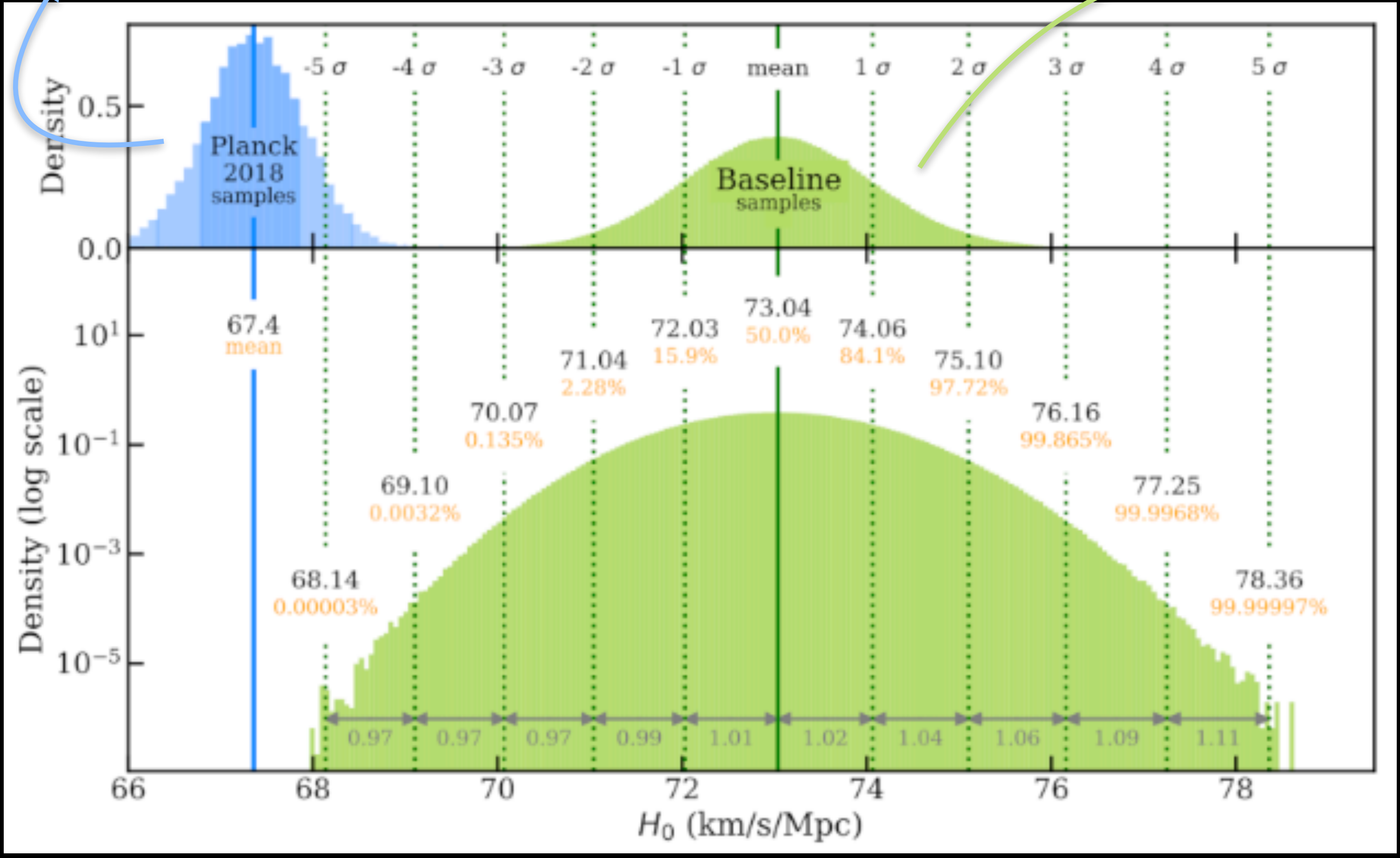

2 to 20 years: Boys
Stature-for-age and Weight-for-age percentiles
NAME Tommaso
RECORD #
Mother's Stature
Father's Stature
Date
Age
Weight
Stature
BMI*
*To Calculate BMI: Weight (kg) ÷ Stature (cm) ÷ Stature (cm) x 10,000
or Weight (lb) ÷ Stature (in) ÷ Stature (in) x 703
AGE (YEARS)
STATURE
WEIGHT
in
cm
lb
kg
Published May 30, 2000 (modified 11/21/00).
SOURCE: Developed by the National Center for Health Statistics in collaboration with
the National Center for Chronic Disease Prevention and Health Promotion (2000).
http://www.cdc.gov/growthcharts
CDC
SAFER • HEALTHIER • PEOPLE™

H0 tension

If we compare the H0 estimates using these 2 methods they disagree.

The Planck estimate assuming a “vanilla" ΛCDM cosmological model:
H0 = 67.36 ± 0.54 km/s/Mpc

Planck 2018, Astron.Astrophys. 641 (2020) A6



The latest local measurements obtained by the SH0ES collaboration

H0 = 73.04 ± 1.04 km/s/Mpc

Riess et al. arXiv:*2112.04510*

5σ = one in 3.5 million implausible to reconcile the two by chance

H0 tension

If we compare the H0 estimates using these 2 methods they disagree.

arXiv > astro-ph > arXiv:2404.08038

Search...

Help | Adv

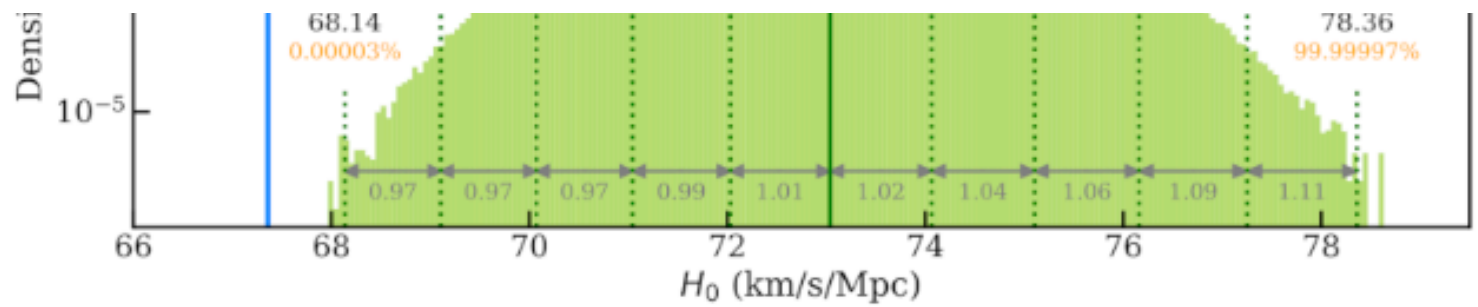
Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 11 Apr 2024]

Small Magellanic Cloud Cepheids Observed with the Hubble Space Telescope Provide a New Anchor for the SH0ES Distance Ladder

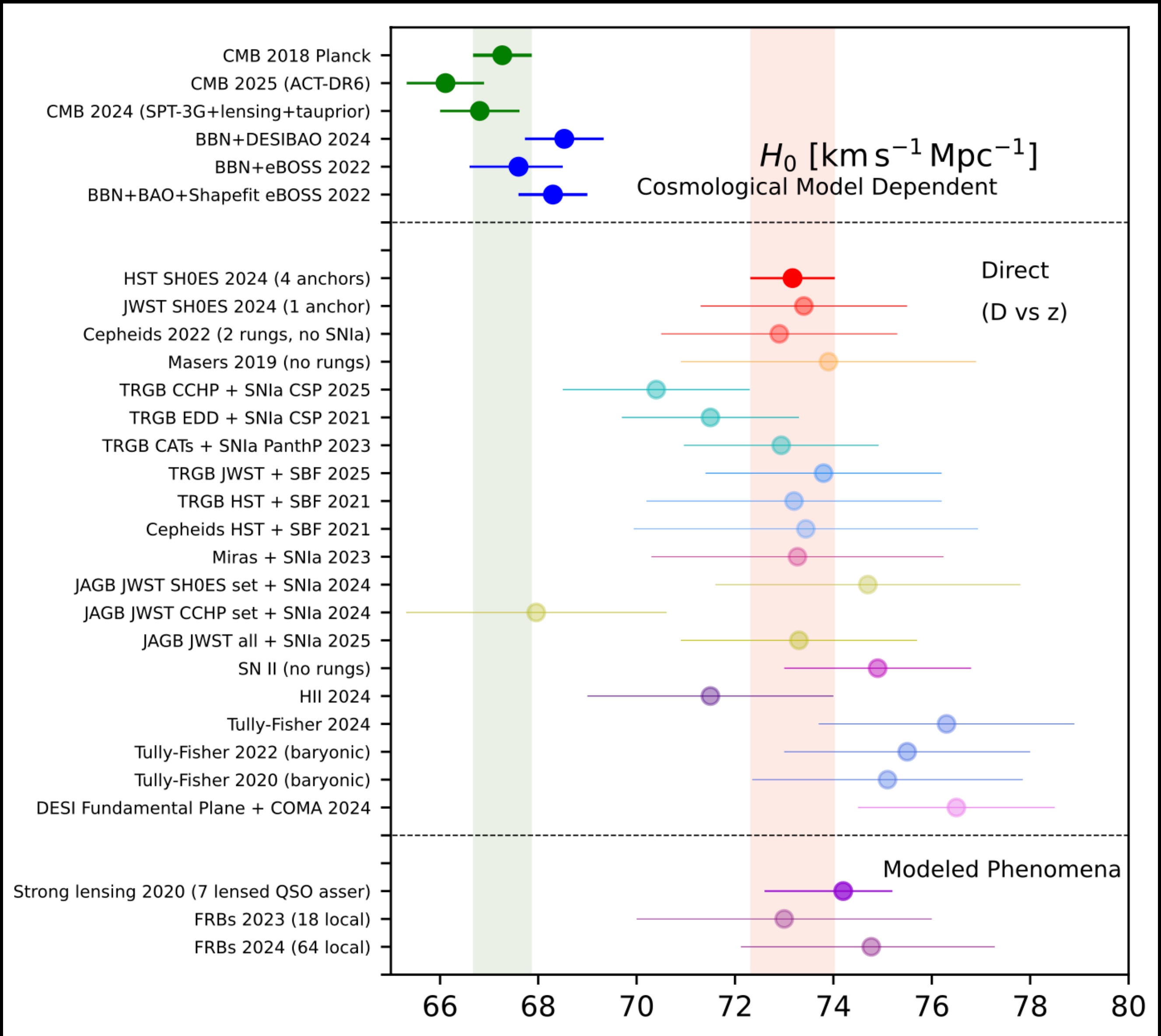
Louise Breuval, Adam G. Riess, Stefano Casertano, Wenlong Yuan, Lucas M. Macri, Martino Romaniello, Yukei S. Murakami, Daniel Scolnic, Gagandeep S. Anand, Igor Soszyński

We present photometric measurements of 88 Cepheid variables in the core of the Small Magellanic Cloud (SMC), the first sample obtained with the Hubble Space Telescope (HST) and Wide Field Camera 3, in the same homogeneous photometric system as past measurements of all Cepheids on the SH0ES distance ladder. We limit the sample to the inner core and model the geometry to reduce errors in prior studies due to the non-trivial depth of this Cloud. Without crowding present in ground-based studies, we obtain an unprecedentedly low dispersion of 0.102 mag for a Period-Luminosity relation in the SMC, approaching the width of the Cepheid instability strip. The new geometric distance to 15 late-type detached eclipsing binaries in the SMC offers a rare opportunity to improve the foundation of the distance ladder, increasing the number of calibrating galaxies from three to four. With the SMC as the only anchor, we find $H_0 = 74.1 \pm 2.1$ km s^{-1} Mpc^{-1}. Combining these four geometric distances with our HST photometry of SMC Cepheids, we obtain $H_0 = 73.17 \pm 0.86$ km s^{-1} Mpc^{-1}. By including the SMC in the distance ladder, we also double the range where the metallicity ([Fe/H]) dependence of the Cepheid Period-Luminosity relation can be calibrated, and we find $\gamma = -0.22 \pm 0.05$ mag dex^{-1}. Our local measurement of H_0 based on Cepheids and Type Ia supernovae shows a 5.8σ tension with the value inferred from the CMB assuming a ΛCDM cosmology, reinforcing the possibility of physics beyond ΛCDM.



implausible to reconcile the two by chance

Latest H0 measurements



Hubble constant measurements made by different astronomical missions and groups over the years.

The red vertical band corresponds to the H0 value from SH0ES Team and the grey vertical band corresponds to the H0 value as reported by Planck 2018 team within a ΛCDM scenario.

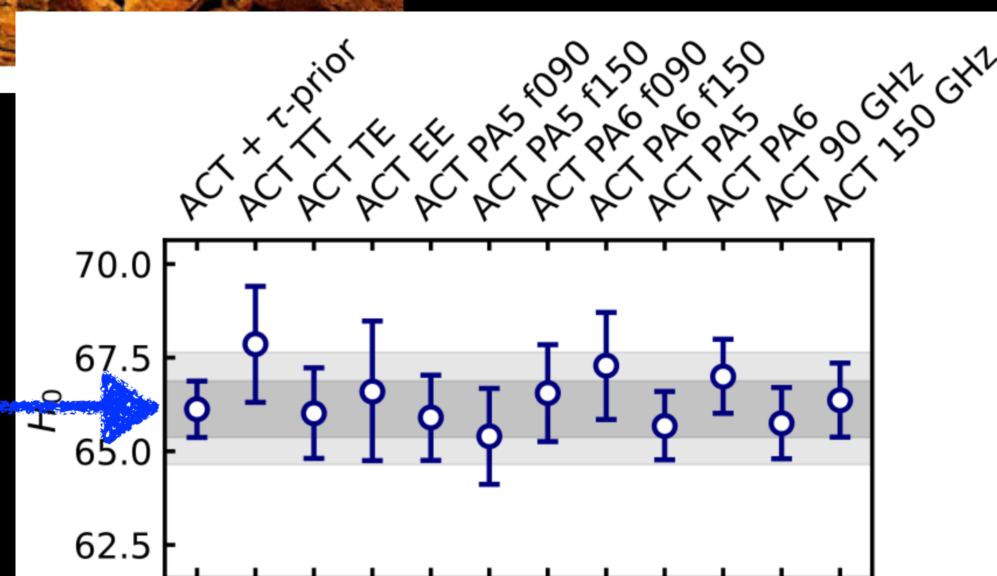
CosmoVerse, Di Valentino et al., arXiv:2504.01669

On the same side of Planck, i.e. preferring smaller values of H_0 we have:

Ground based CMB telescope

ACT-DR6:
H0 = 66.11 ± 0.79 km/s/Mpc in ΛCDM

ACT-DR6 + WMAP:
H0 = 66.78 ± 0.68 km/s/Mpc in ΛCDM

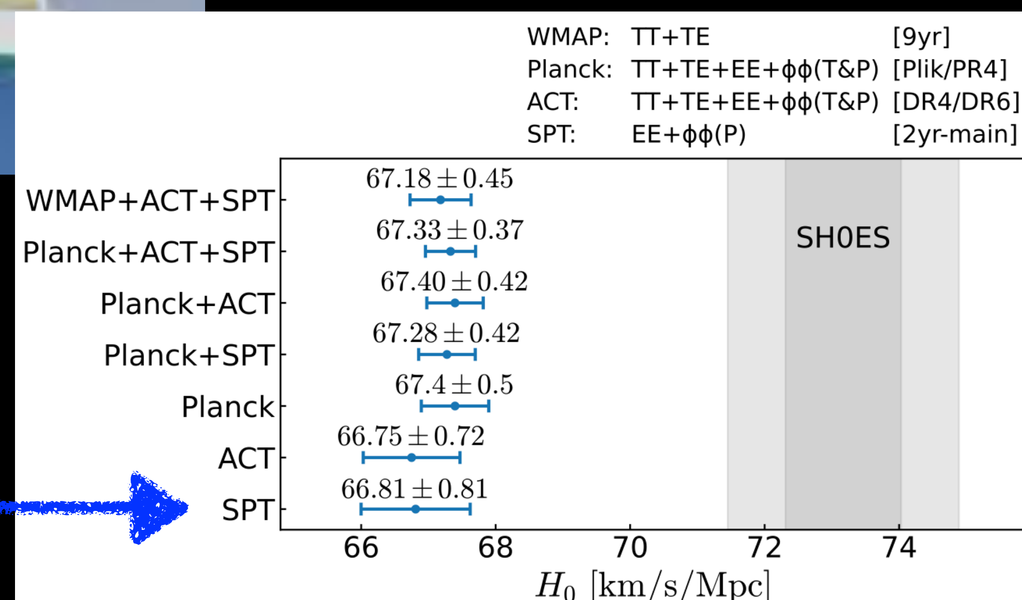


ACT-DR6 2025

ΛCDM - dependent

On the same side of Planck, i.e. preferring smaller values of H_0 we have:

Ground based CMB telescope



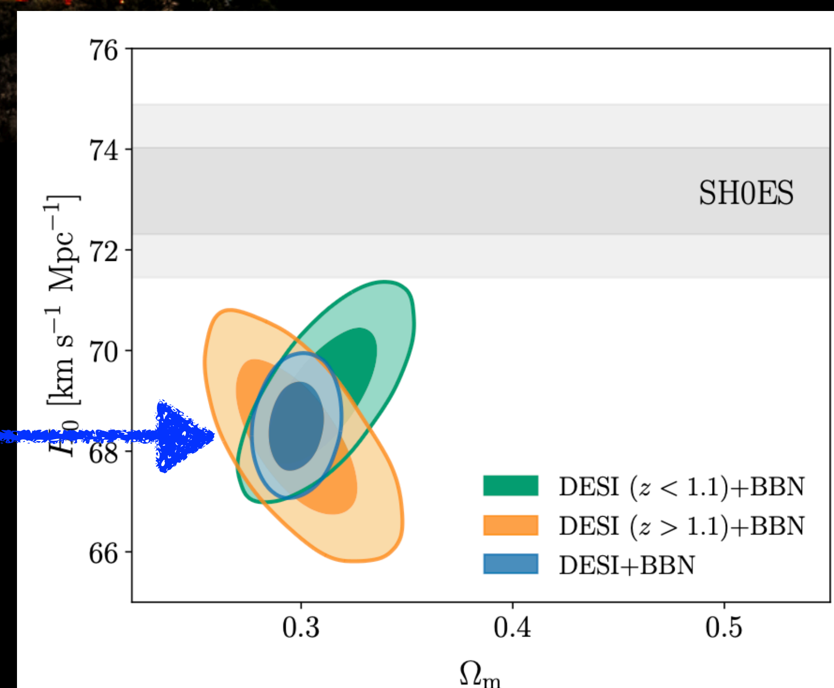
SPT-3G:
$H_0 = 66.81 \pm 0.81$ km/s/Mpc in ΛCDM

SPT-3G collaboration, arXiv:2411.06000

ΛCDM - dependent

On the same side of Planck, i.e. preferring smaller values of H_0 we have:

In ΛCDM the tension between the DESI+BBN and SH0ES H0 results now stands at 4.5σ independent of the CMB

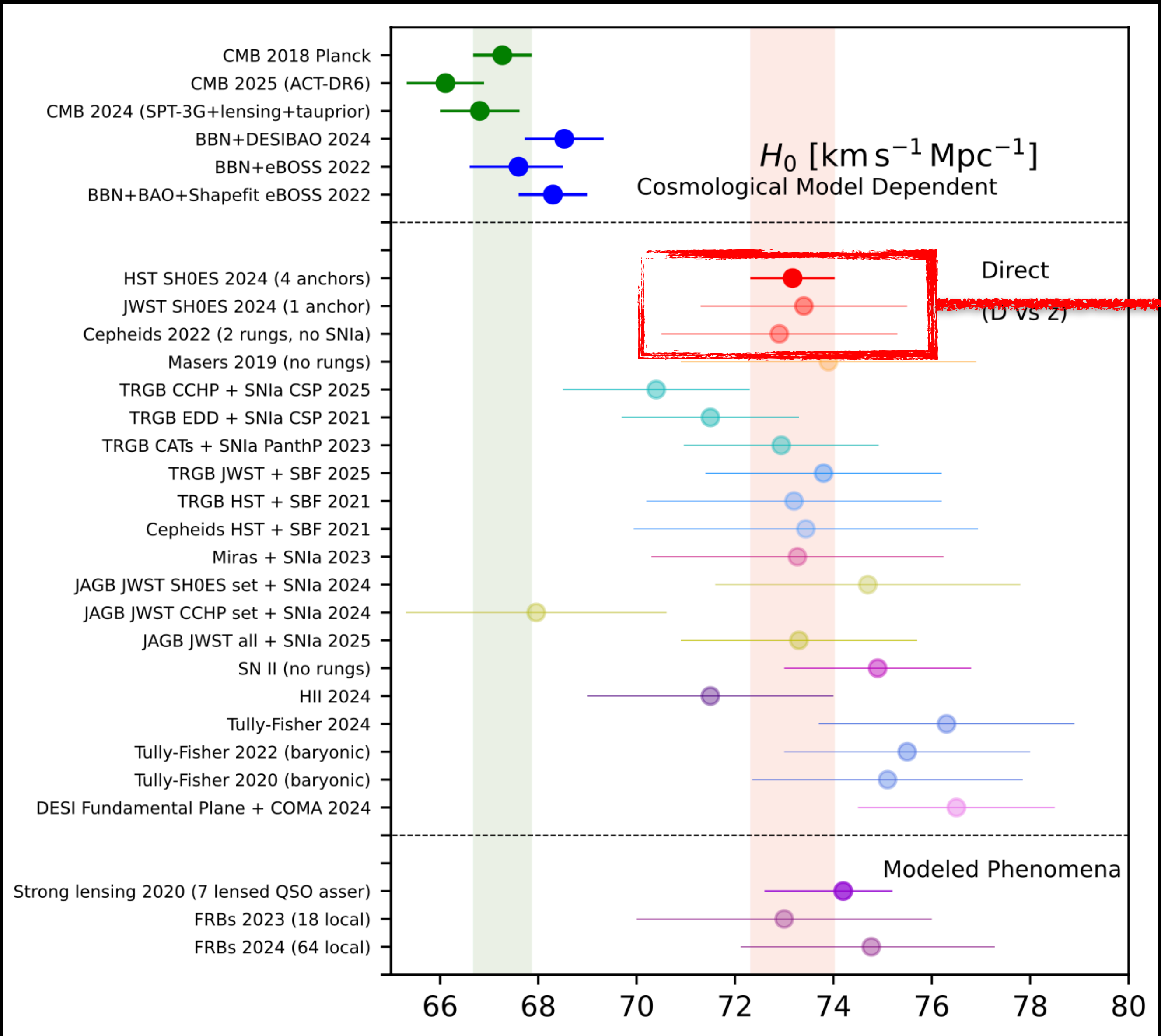


DESI+BBN:
H0 = 68.51 ± 0.58 km/s/Mpc in ΛCDM

ΛCDM - dependent

DESI collaboration, Abdul Karim et al., arXiv:2503.14738

Latest H0 measurements



CosmoVerse, Di Valentino et al., arXiv:2504.01669

Cepheids-SN Ia:

H0 = 73.4 ± 2.1 km/s/Mpc

Riess et al., arXiv: *2408.11770*

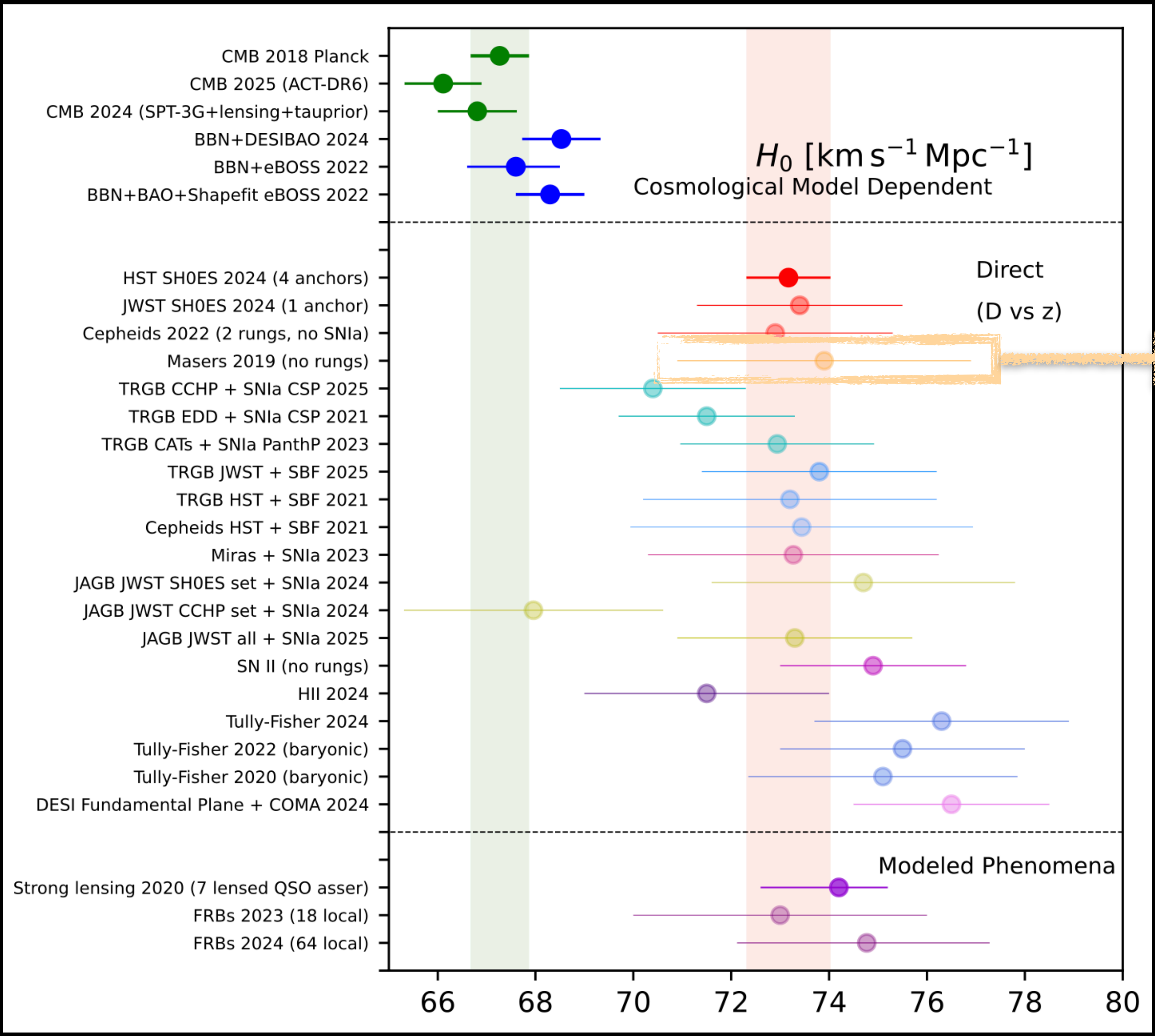
H0 = 73.17 ± 0.86 km/s/Mpc

Breuval et al., arXiv:*2404.08038*

H0 = 72.9 ± 2.4 km/s/Mpc

Kenworthy et al., arXiv:2204.10866

Latest H0 measurements



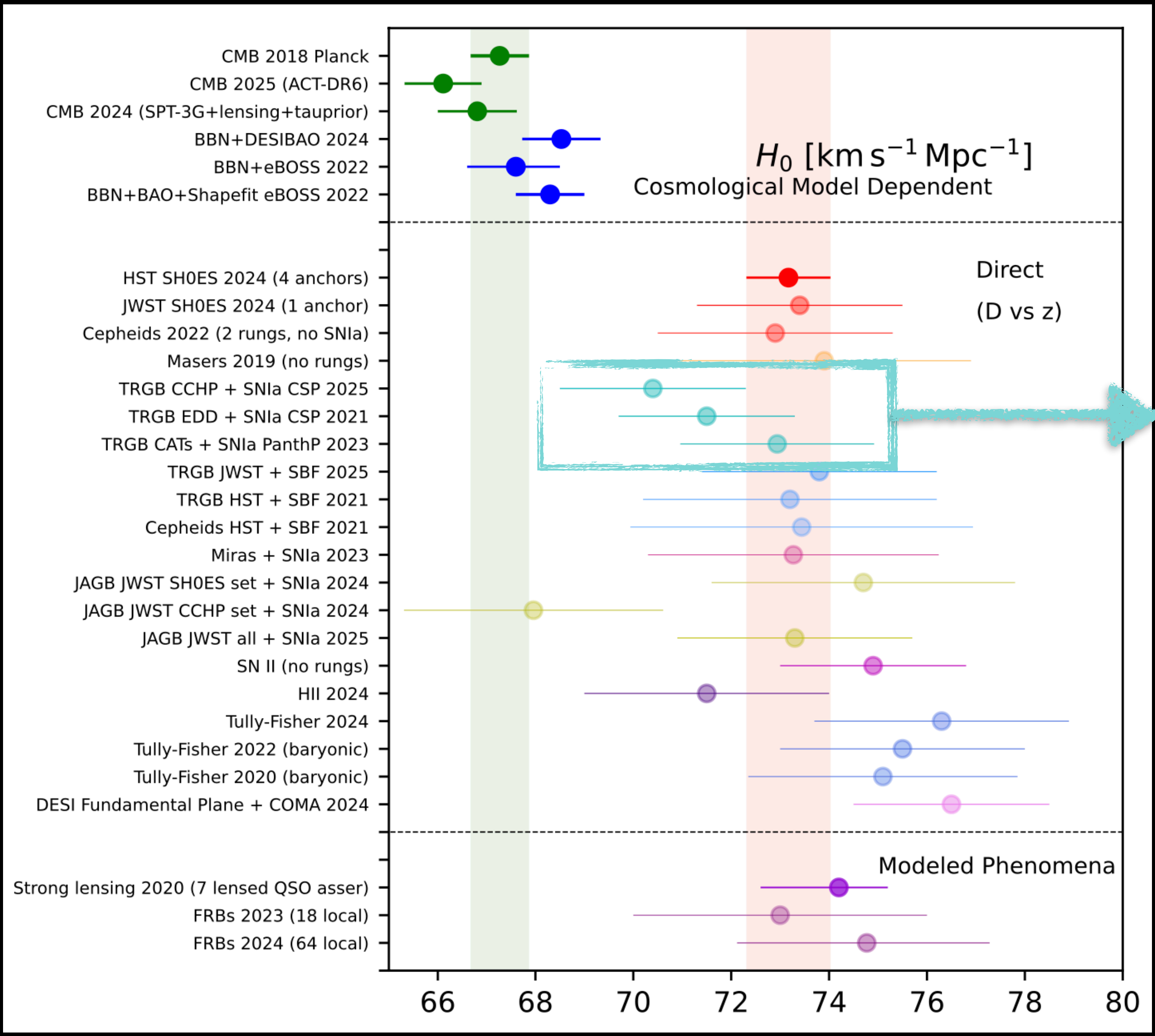
The Megamaser Cosmology Project measures H0 using geometric distance measurements to six Megamaser - hosting galaxies. This approach avoids any distance ladder by providing geometric distance directly into the Hubble flow.

H0 = 73.9 ± 3.0 km/s/Mpc

Pesce et al. arXiv:2001.09213

CosmoVerse, Di Valentino et al., arXiv:2504.01669

Latest H0 measurements



The Tip of the Red Giant Branch (TRGB) is the peak brightness reached by red giant stars after they stop using hydrogen and begin fusing helium in their core.

H0 = 70.39 ± 1.94 km/s/Mpc

Freedman et al., arXiv:*2408.06153*

H0 = 71.5 ± 1.8 km/s/Mpc

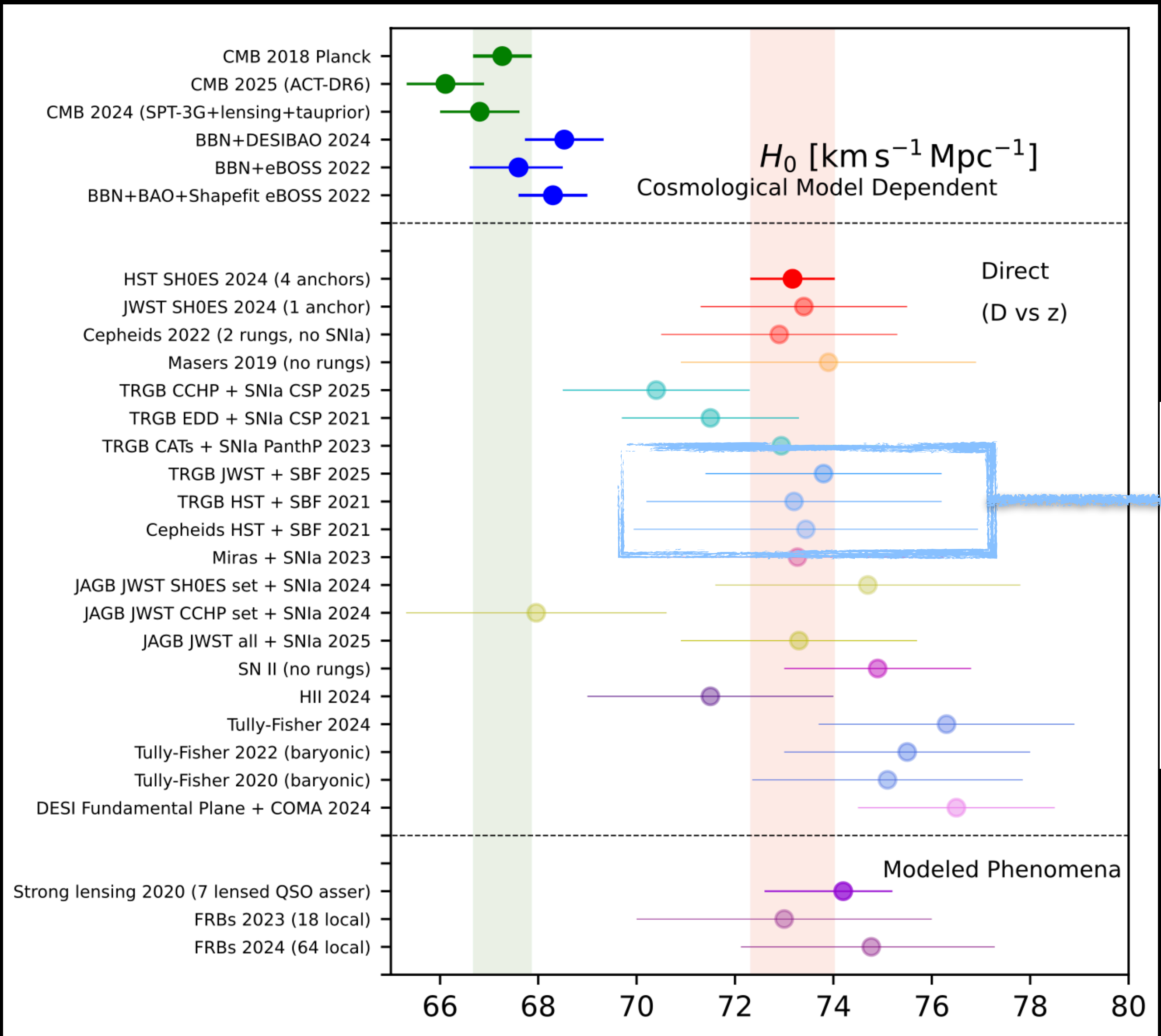
Anand et al., arXiv: *2108.00007*

H0 = 73.22 ± 2.06 km/s/Mpc

Scolnic et al., arXiv:2304.06693

CosmoVerse, Di Valentino et al., arXiv:2504.01669

Latest H0 measurements



H0 = 73.8 ± 2.4 km/s/Mpc

Jensen et al., arXiv:2502.15935

H0 = 73.2 ± 3.5 km/s/Mpc

Blakeslee et al., arXiv:2101.02221

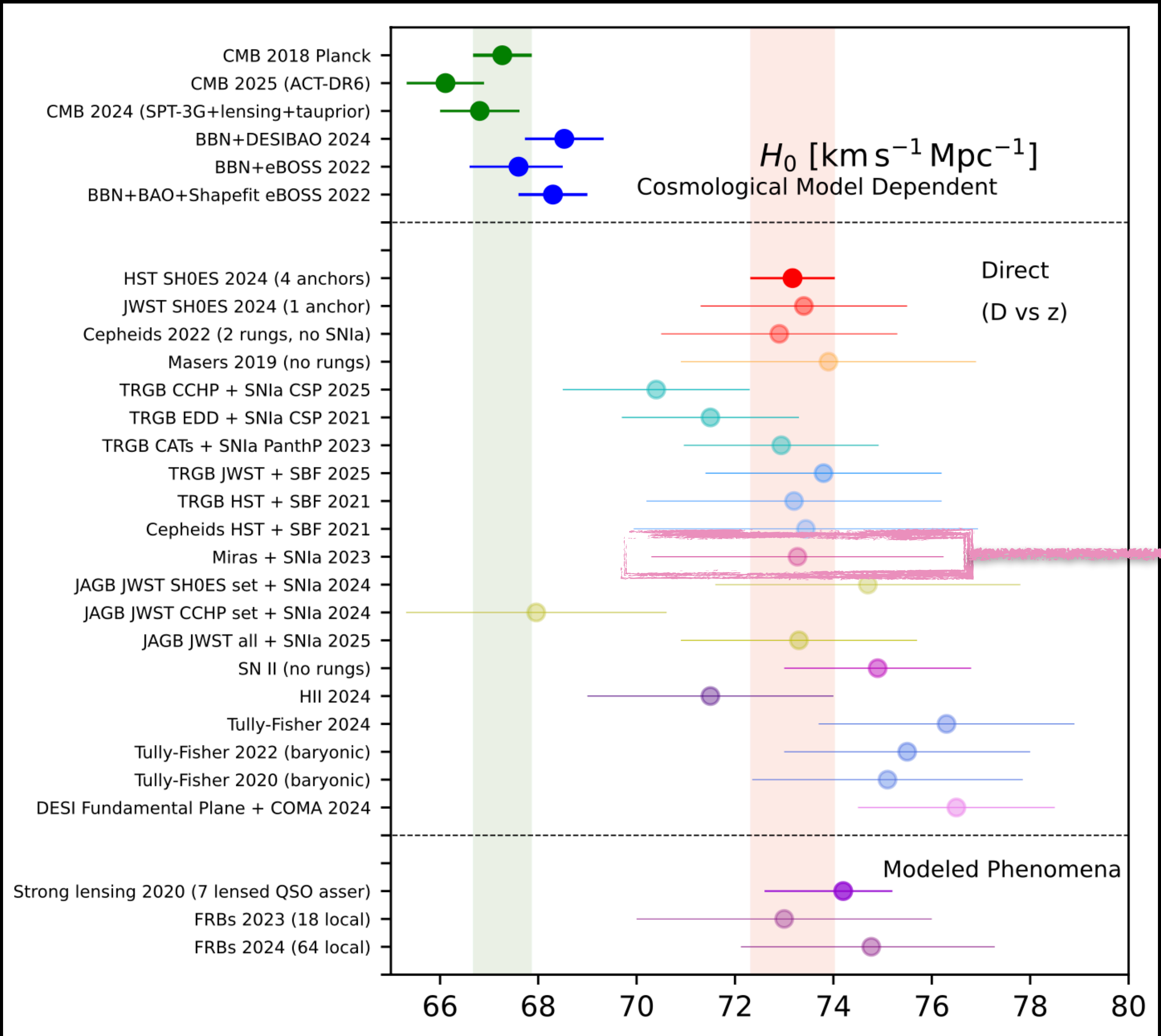
H0 = 73.44 ± 3.0 km/s/Mpc

Blakeslee et al., arXiv:2101.02221

Surface Brightness Fluctuations (substitutive distance ladder for long range indicator, calibrated by both Cepheids and TRGB)

CosmoVerse, Di Valentino et al., arXiv:2504.01669

Latest H0 measurements



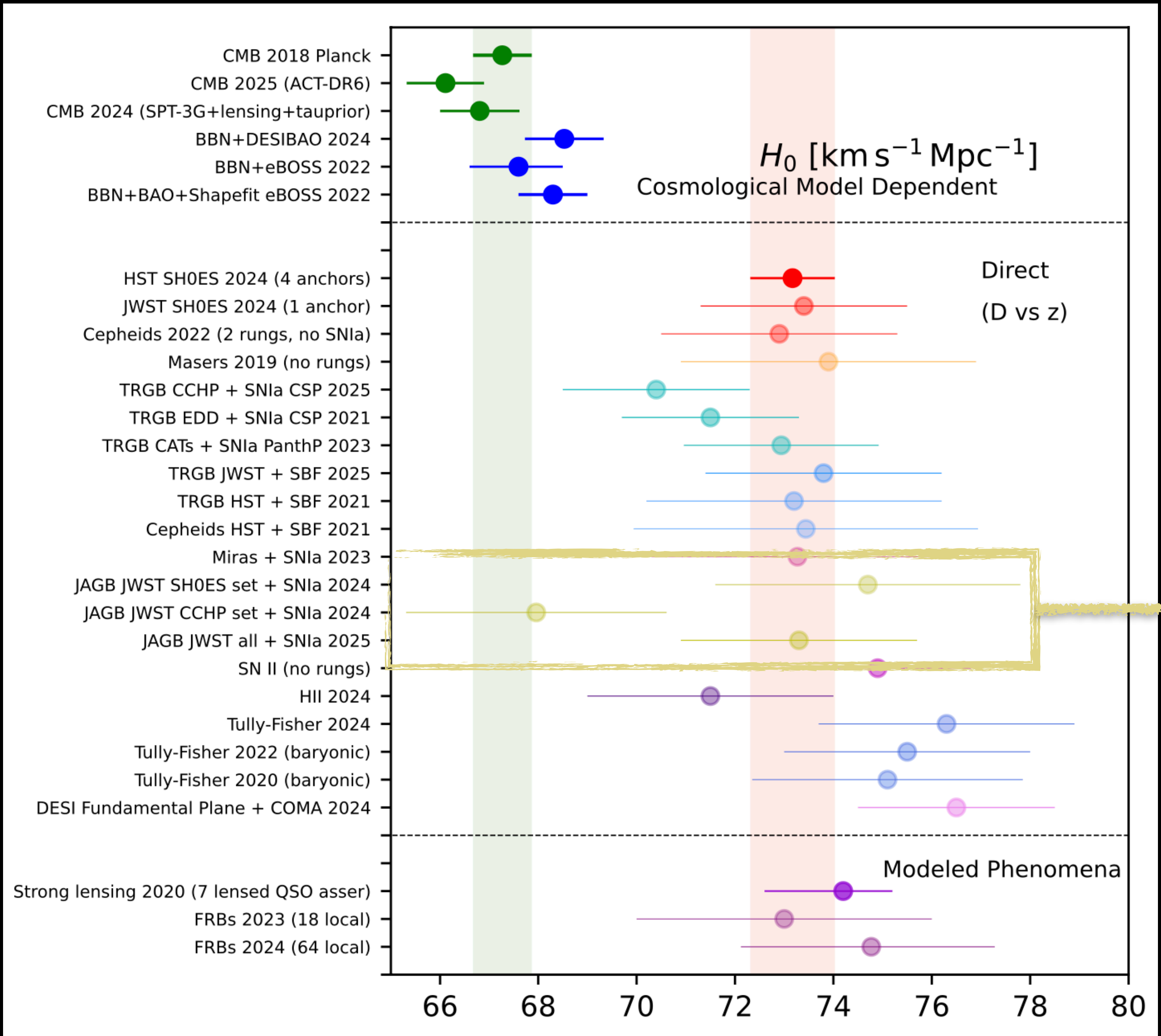
MIRAS
variable red giant stars from older stellar populations

H0 = 72.37 ± 2.97 km/s/Mpc

Huang et al., arXiv:2312.08423]

CosmoVerse, Di Valentino et al., arXiv:2504.01669

Latest H0 measurements



CosmoVerse, Di Valentino et al., arXiv:2504.01669

H0 = 74.7 ± 3.1 km/s/Mpc

Li et al., arXiv: *2401.04777*

H0 = 67.96 ± 2.65 km/s/Mpc

Lee et al., arXiv:2408.03474

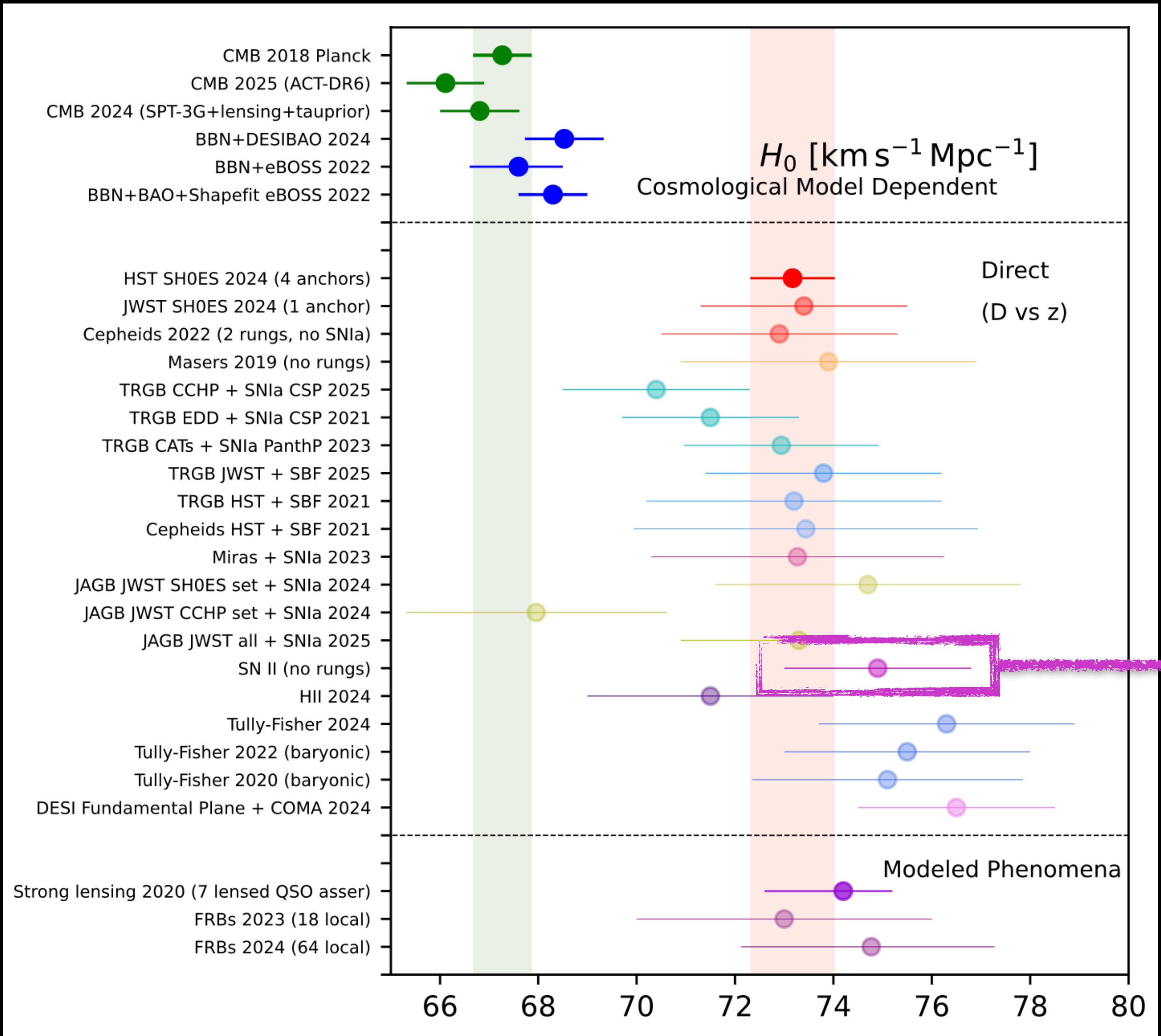
H0 = 73.3 ± 2.4 km/s/Mpc

Li et al., arXiv: *2502.05259*

JAGB

The J-regions of the Asymptotic Giant Branch is expected from stellar theory to be populated by thermally-pulsing carbon-rich dust-producing asymptotic giant branch stars.

Latest H0 measurements



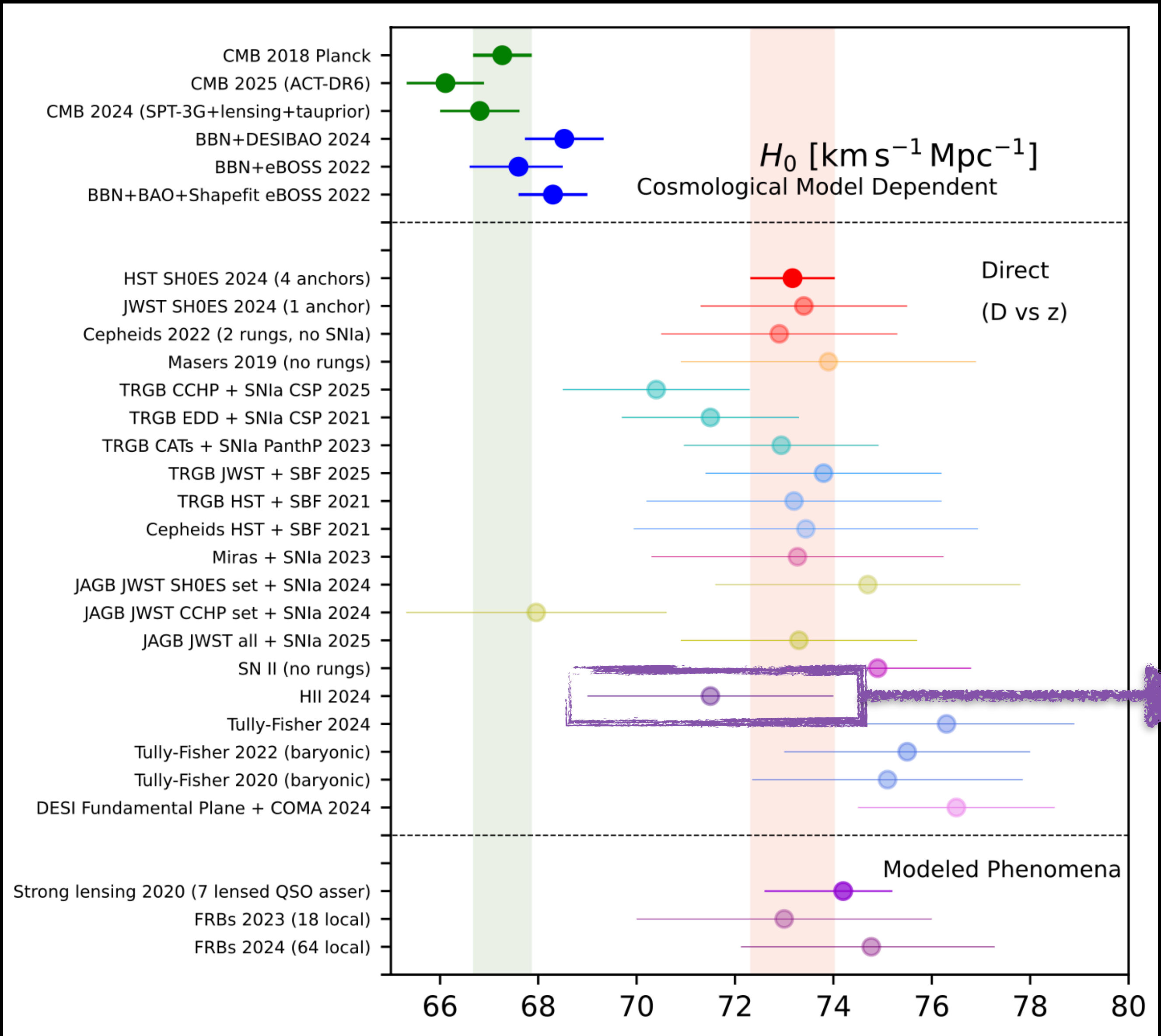
H0 = 74.9 ± 1.9 km/s/Mpc

Vogl et al., arXiv:2411.04968

Spectral modeling-based Type II supernova distances: for each of these supernovae distances were measured through a recent variant of the tailored Expanding Photosphere Method using radiative transfer models.

CosmoVerse, Di Valentino et al., arXiv:2504.01669

Latest H0 measurements



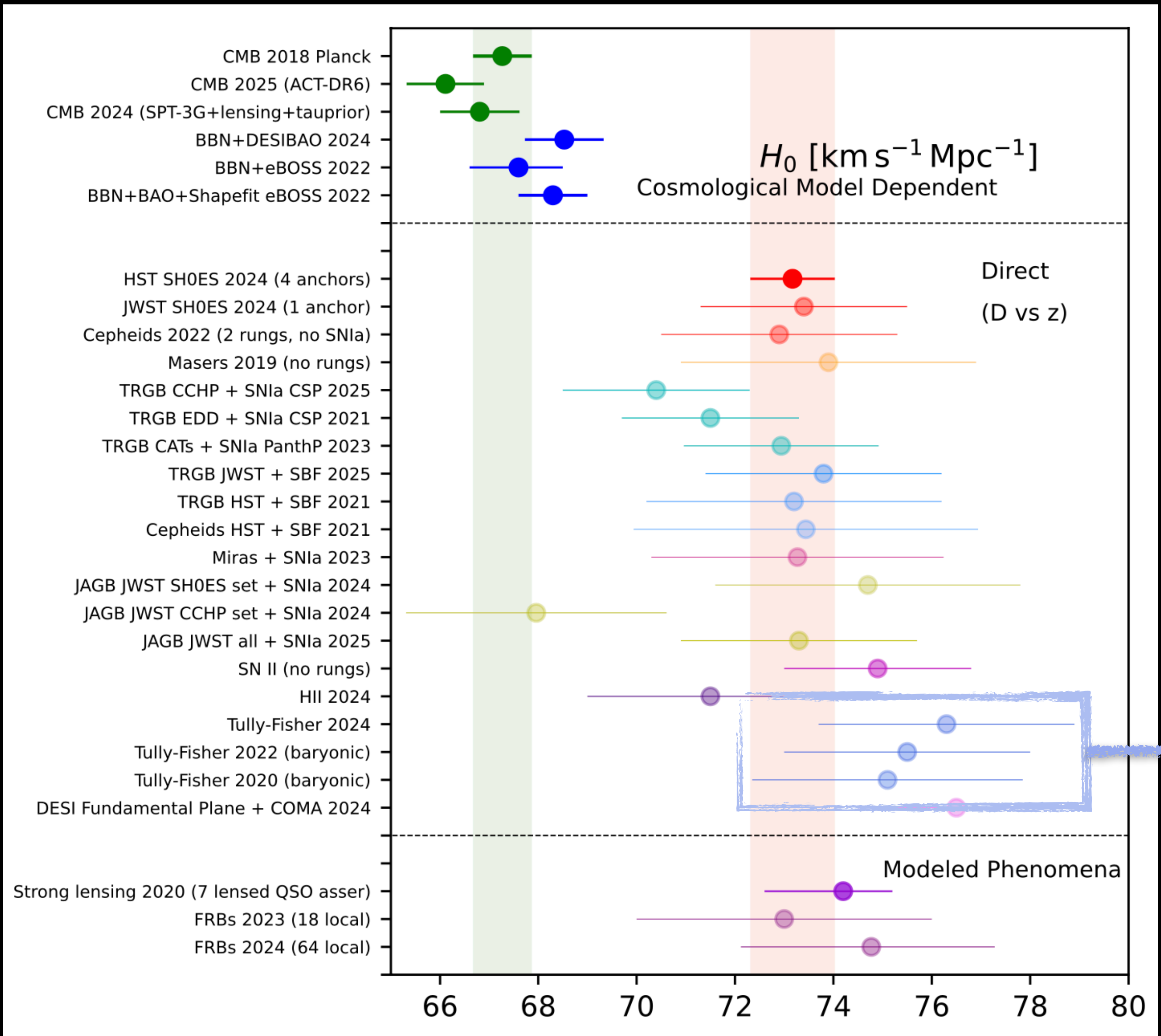
CosmoVerse, Di Valentino et al., arXiv:2504.01669

H0 = 71.5 ± 2.5 km/s/Mpc

Chávez et al., arXiv:2404.16261

HII galaxies calibrated using Giant Extragalactic HII Regions (GEHRs) in local galaxies with Cepheid-based distances.

Latest H0 measurements



CosmoVerse, Di Valentino et al., arXiv:2504.01669

H0 = 76.3 ± 2.6 km/s/Mpc

Scolnic et al. arXiv:2412.08449

H0 = 75.5 ± 2.5 km/s/Mpc

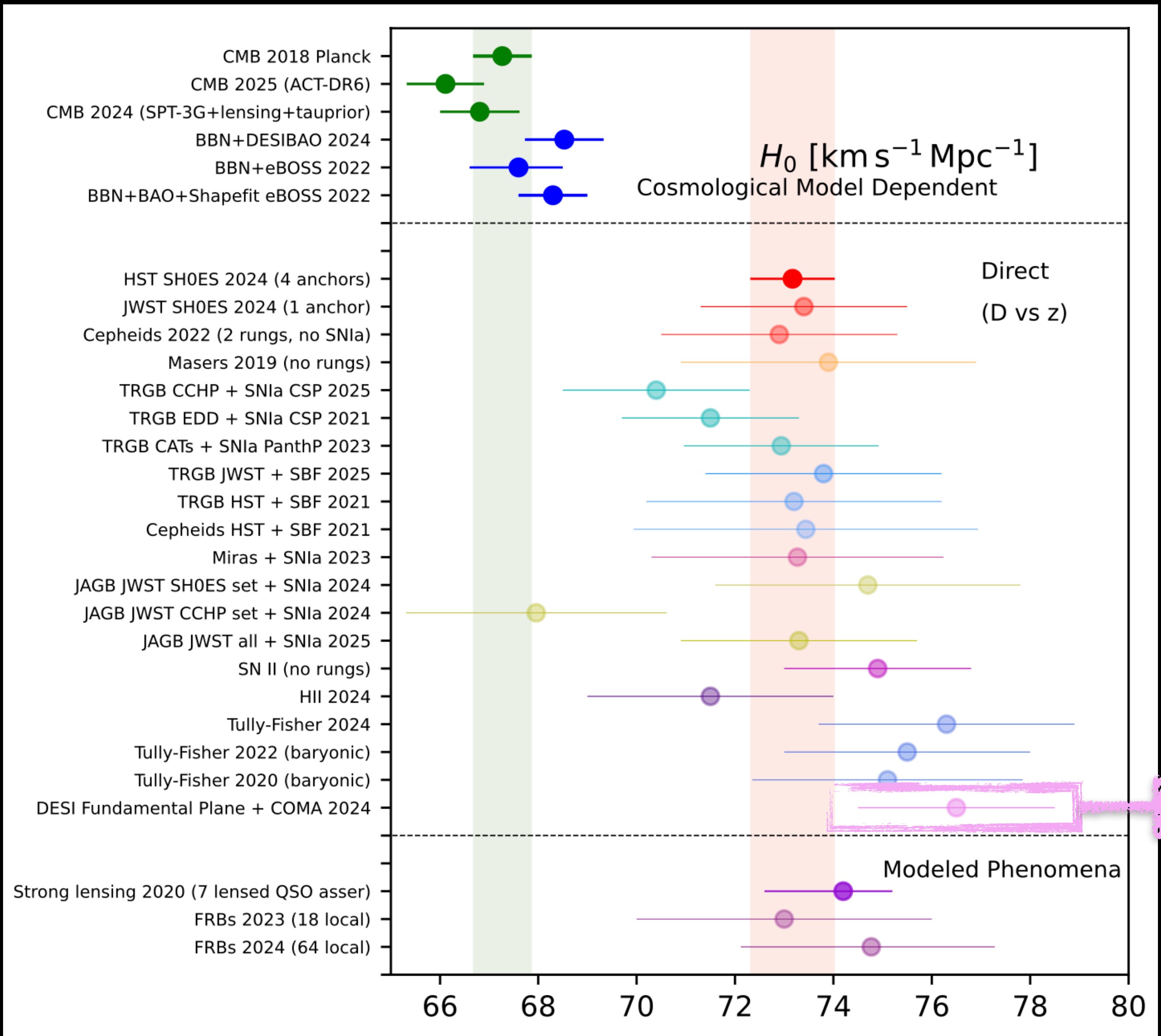
Kourkchi et al. arXiv:2201.13023

H0 = 75.10 ± 2.75 km/s/Mpc

Schombert et al. arXiv:2006.08615

Tully-Fisher Relation (based on the correlation between the rotation rate of spiral galaxies and their absolute luminosity or total baryonic mass, and using as calibrators Cepheids and TRGB)

Latest H0 measurements



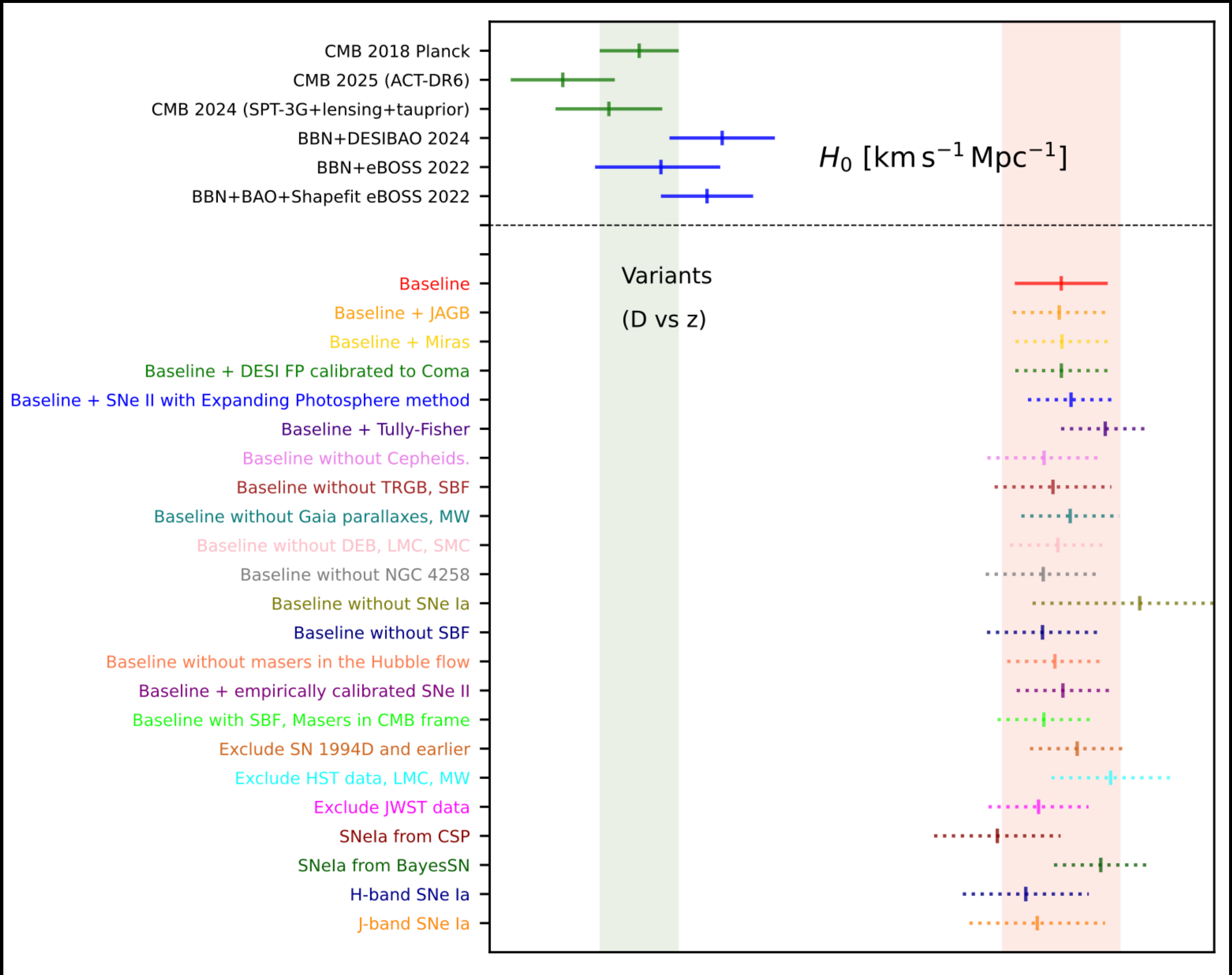
DESI measured relation between H0 and the distance to the Coma cluster using the fundamental plane relation of early-type galaxies.

H0 = 76.5 ± 2.2 km/s/Mpc

Scolnic et al., arXiv: *2409.14546*

CosmoVerse, Di Valentino et al., arXiv:2504.01669

Towards a consensus value on the local expansion rate of the Universe



Casertano et al., in preparation

- We obtained a decorrelated, optimized, multi-method mean.
- The final uncertainty on H0 decreases by 25% compared to SH0ES, reaching 1% precision.
- Excluding Cepheids or some of the distance anchors does not lead to significant changes in the result.
- Replacing Pantheon+ with CSP removes 40% of the SN, causing H0 to decrease by ~0.7 km/s/Mpc.

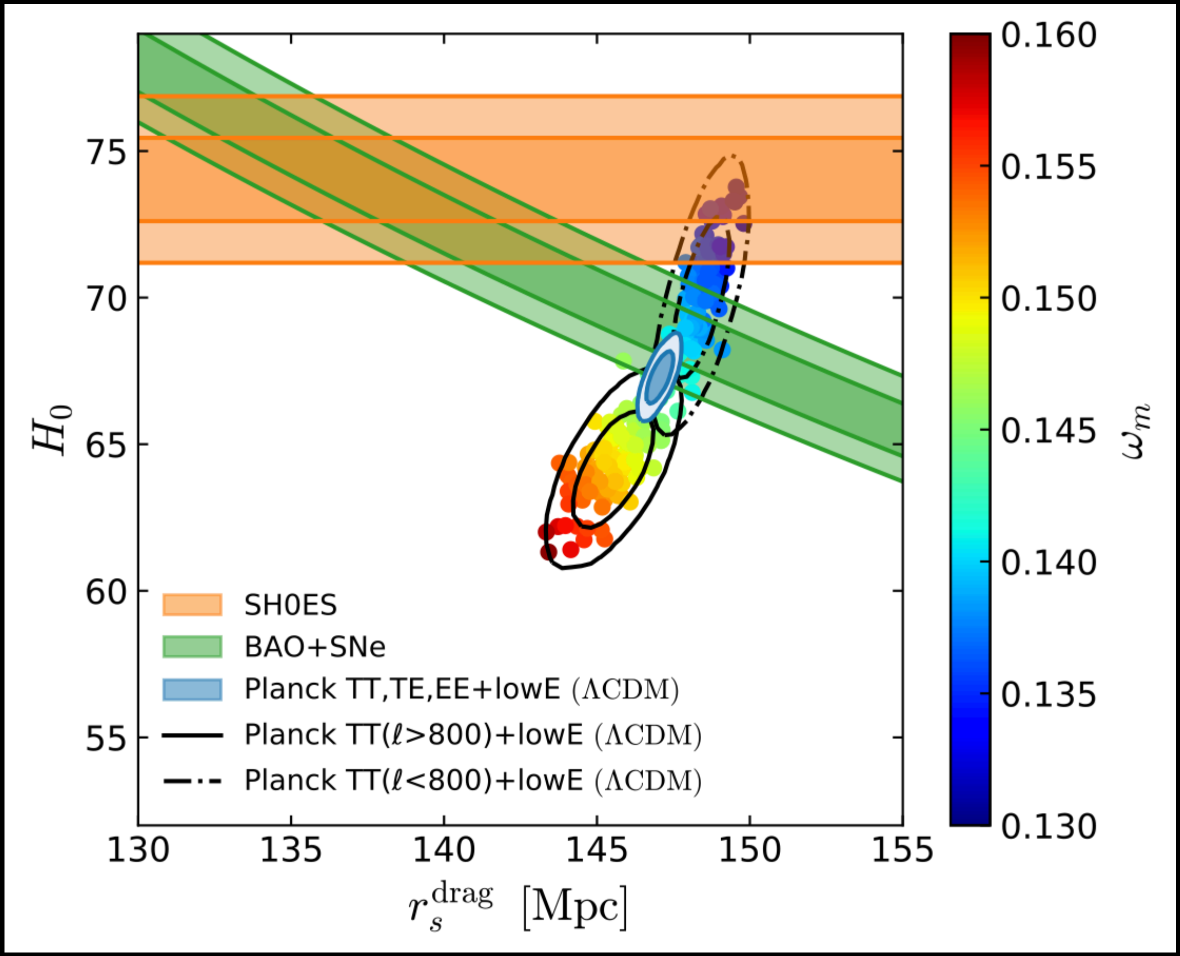
The Hubble tension doesn't depend on any one source!

What about possible solutions?

Before DESI

BAO+Pantheon measurements constrain the product of H0 and the sound horizon r_s.

In order to have a higher H0 value in agreement with SH0ES, we need r_s near 137 Mpc. However, Planck by assuming ΛCDM, prefers r_s near 147 Mpc. Therefore, a cosmological solution that can increase H0 and at the same time can lower the sound horizon inferred from CMB data is the most promising way to put in agreement all the measurements.



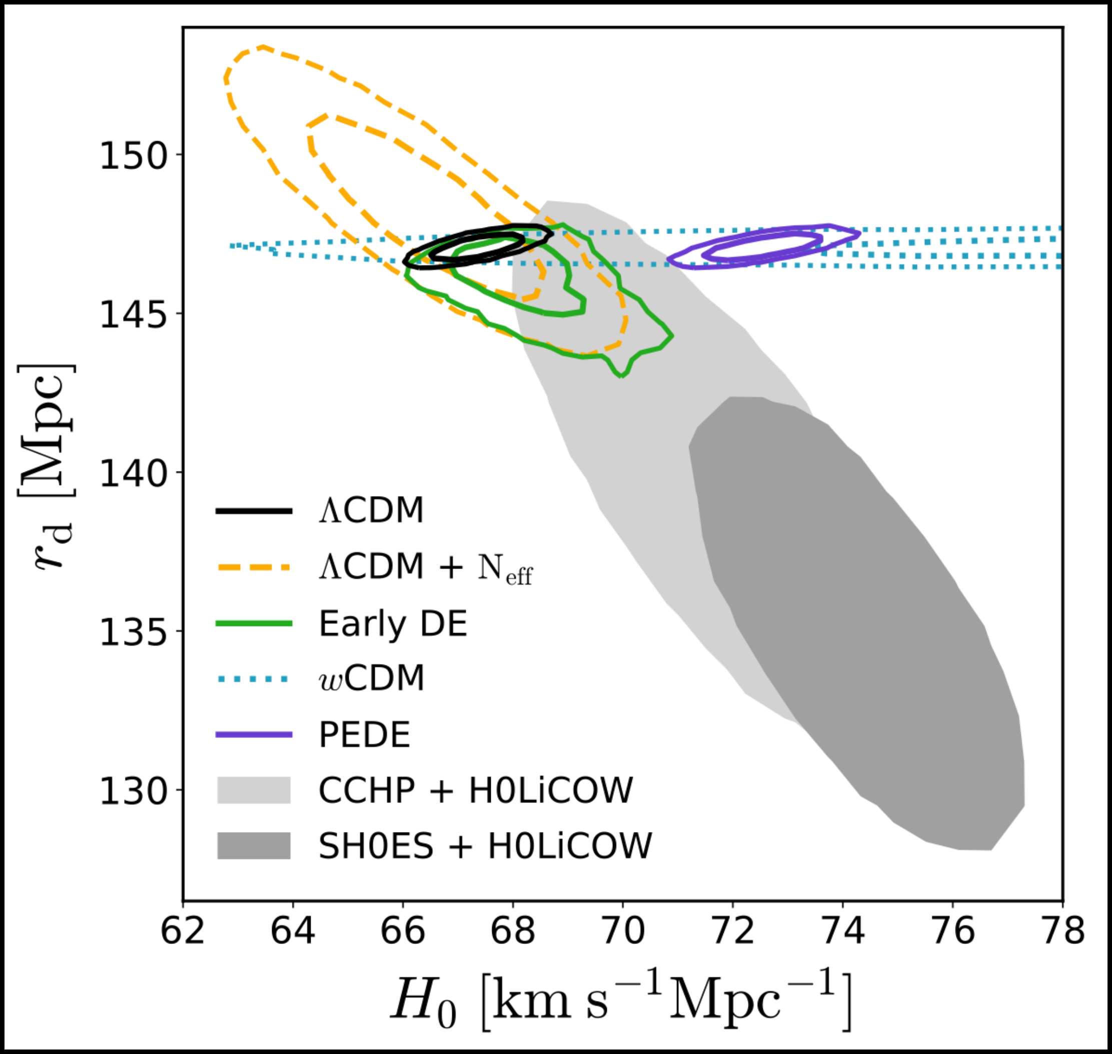
Knox and Millea, *Phys.Rev.D* 101 (2020) 4, 043533

Early vs late time solutions

Here we can see the comparison of the 2σ credibility regions of the CMB constraints and the measurements from late-time observations (SN + BAO + H0LiCOW + SH0ES).

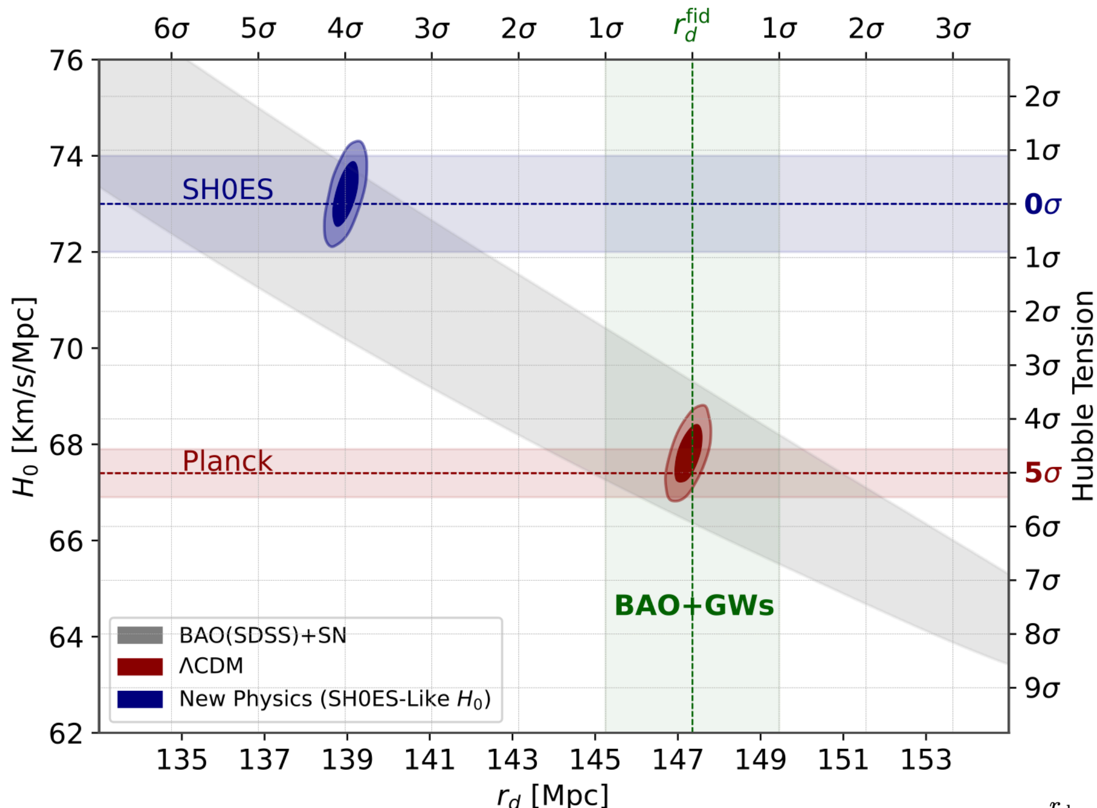
We see that the late time solutions, as wCDM, increase H0 because they decrease the expansion history at intermediate redshift, but leave r_s unaltered.

However, the early time solutions, as Neff or Early Dark Energy, move in the right direction both the parameters, but can't solve completely the H0 tension between Planck and SH0ES.



Arendse et al., Astron.Astrophys. 639 (2020) A57

Sound Horizon from GWSS and 2D BAO



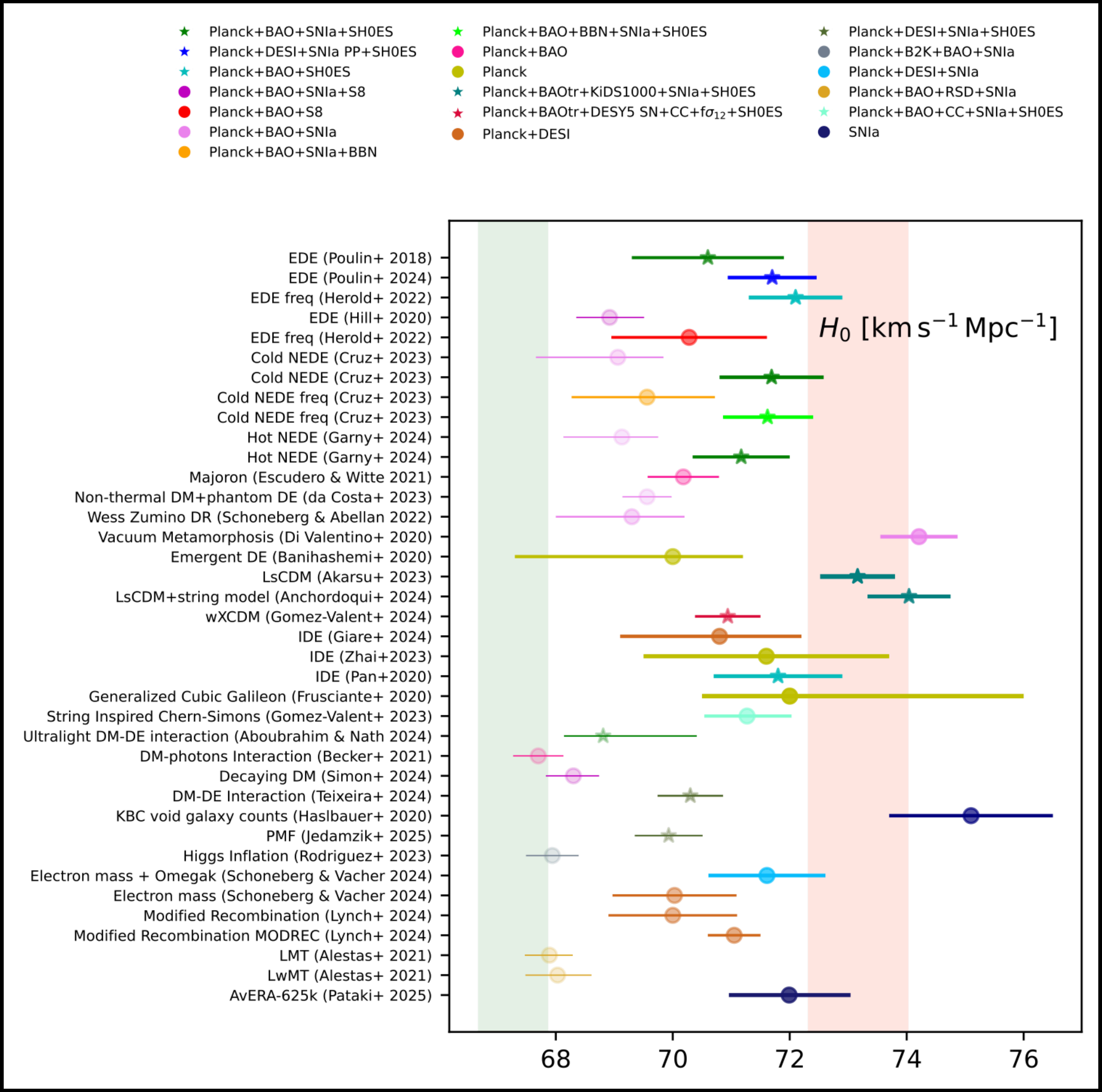
$$\theta_{\mathrm{BAO}}(z) = \frac{r_{\mathrm{d}}}{(1+z)D_{\mathrm{A}}(z)} = \frac{(1+z)\,r_{\mathrm{d}}}{D_{\mathrm{L}}(z)},$$

Figure 1. Illustrative plot in the r_{d} - H_0 plane of the consistency test proposed to assess the possibility of new physics prior to recombination for solving the Hubble constant tension. The red band represents the present value of H_0 measured by the Planck collaboration within a standard ΛCDM model of cosmology, whereas the 2D contours represent the marginalized 68% and 95% CL constraints obtained from the Planck-2018 data. The grey band represents the 95% CL region of the plane identified by analyzing current BAO measurements from the SDSS collaboration and Type Ia supernovae from the Pantheon+ catalogue. The horizontal blue band represents the value of the Hubble constant measured by the SH0ES collaboration. In order to reconcile all the datasets, a potential model of early-time new physics should shift the ΛCDM red contours along the grey band until the grey band overlaps with the SH0ES result. This scenario is depicted by the 2D blue contours obtained under the assumption that the model of new physics does not increase uncertainties on parameters compared to ΛCDM. The green vertical band represents the model-independent value of the sound horizon we are able to extract from combinations of GW data from LISA and BAO measurements (either from DESI-like or Euclid-like experiments) assuming a fiducial ΛCDM baseline cosmology. As is clear from the top x-axis, this value would be able to confirm or rule out the possibility of new physics at about 4σ.

We forecast a relative precision of $\sigma_{rd}/r_d \sim 1.5\%$ within the redshift range $z \lesssim 1$. These measurements can serve as a consistency test for ΛCDM, potentially clarifying the nature of the Hubble tension and confirming or ruling out new physics prior to recombination with a statistical significance of $\sim 4\sigma$.

Giarè, Betts, van de Bruck, and Di Valentino, arXiv:2406.07493

Successful models?



CosmoVerse, Di Valentino et al., arXiv:2504.01669

After DESI

What about the interacting DM-DE models?

The IDE case

In the standard cosmological framework, DM and DE are described as separate fluids not sharing interactions beyond gravitational ones.
At the background level, the conservation equations for the pressureless DM and DE components can be decoupled into two separate equations with an inclusion of an arbitrary function, Q, known as the coupling or interacting function:

$$\begin{aligned} \dot{\rho}_c + 3\mathcal{H}\rho_c &= Q\,, \\ \dot{\rho}_x + 3\mathcal{H}(1+w)\rho_x &= -Q\,, \end{aligned}$$

and we assume the phenomenological form for the interaction rate:

$$Q = \xi \mathcal{H} \rho_x$$

proportional to the dark energy density ρ_x and the conformal Hubble rate $\mathcal{H}$, via a negative dimensionless parameter ξ quantifying the strength of the coupling, to avoid early-time instabilities.

Gavela et al. J. Cosmol. Astropart. Phys. 07 (2009) 034

The IDE case

In this scenario of IDE the tension on H0 between the Planck satellite and SH0ES is completely solved. The coupling could affect the value of the present matter energy density Ω_m. Therefore, if within an interacting model Ω_m is smaller (because for negative ξ the dark matter density will decay into the dark energy one), a larger value of H0 would be required in order to satisfy the peaks structure of CMB observations, which accurately determine the value of $\Omega_m h^2$.

Parameter	*Planck*	*Planck+R19*
$\Omega_b h^2$	0.02239 ± 0.00015	0.02239 ± 0.00015
$\Omega_c h^2$	< 0.105	< 0.0615
n_s	0.9655 ± 0.0043	0.9656 ± 0.0044
$100\theta_s$	$1.0458^{+0.0033}_{-0.0021}$	1.0470 ± 0.0015
τ	0.0541 ± 0.0076	0.0534 ± 0.0080
ξ	$-0.54^{+0.12}_{-0.28}$	$-0.66^{+0.09}_{-0.13}$
H_0 [km s^{-1} Mpc^{-1}]	$72.8^{+3.0}_{-1.5}$	$74.0^{+1.2}_{-1.0}$

TABLE I. Mean values with their 68% C.L. errors on selected cosmological parameters within the $\xi\Lambda$CDM model, considering either the *Planck* 2018 legacy dataset alone, or the same dataset in combination with the *R19* Gaussian prior on H_0 based on the latest local distance measurement from *HST*. The quantity quoted in the case of $\Omega_c h^2$ is the 95% C.L. upper limit.

Di Valentino et al., Phys.Dark Univ. 30 (2020) 100666

The IDE case

Constraints at 68% cl.

Parameter	$CMB+BAO$	$CMB+FS$	$CMB+BAO+FS$
ω_c	$0.094^{+0.022}_{-0.010}$	$0.101^{+0.015}_{-0.009}$	$0.115^{+0.005}_{-0.001}$
ξ	$-0.22^{+0.18}_{-0.09}[> -0.48]$	> -0.35	> -0.12
H_0 [km/s/Mpc]	$69.55^{+0.98}_{-1.60}$	$69.04^{+0.84}_{-1.10}$	$68.02^{+0.49}_{-0.60}$
Ω_m	$0.243^{+0.054}_{-0.030}$	$0.261^{+0.038}_{-0.025}$	$0.299^{+0.015}_{-0.007}$

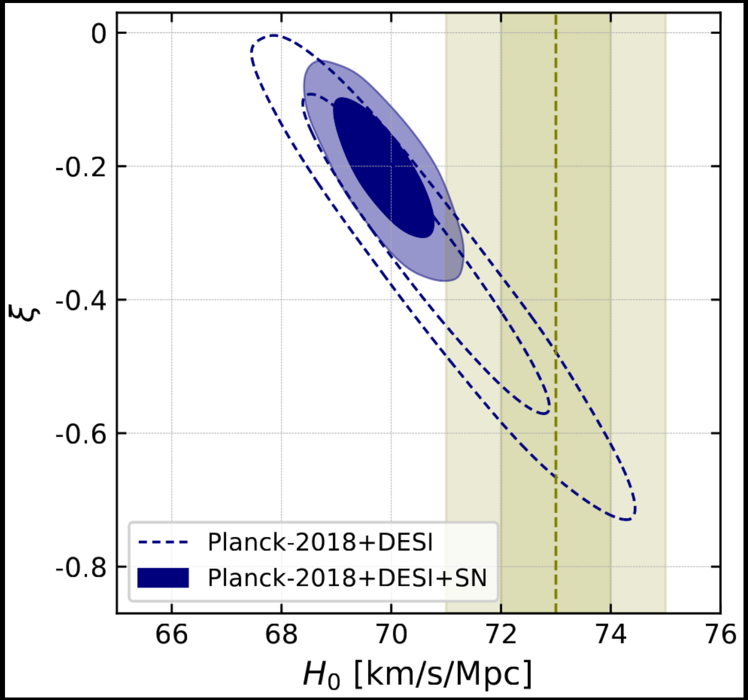
Nunes, Vagnozzi, Kumar, Di Valentino, and Mena, *Phys.Rev.D* 105 (2022) 12, 123506

The addition of low-redshift measurements, as BAO data, still hints to the presence of a coupling, albeit at a lower statistical significance. Also for this data sets the Hubble constant value is larger than that obtained in the case of a pure ΛCDM scenario, enough to bring the H0 tension at 2.1σ with SH0ES.

Constraints at 68% cl.

The IDE case

Parameter	Planck-2018+DESI	Planck-2018+DESI+SN
$\Omega_b h^2$	$0.02243 \pm 0.00014\,(0.02243^{+0.00028}_{-0.00026})$	$0.02254 \pm 0.00013\,(0.02254^{+0.00026}_{-0.00027})$
$\Omega_c h^2$	$0.079^{+0.025}_{-0.016}\,(0.079^{+0.037}_{-0.042})$	$0.0962^{+0.0085}_{-0.0074}\,(0.096^{+0.015}_{-0.015})$
$100\theta_s$	$1.04198 \pm 0.00029\,(1.04198^{+0.00056}_{-0.00056})$	$1.04211 \pm 0.00028\,(1.04211^{+0.00055}_{-0.00057})$
τ_{reio}	$0.0555 \pm 0.0074\,(0.055^{+0.015}_{-0.014})$	$0.0592^{+0.0069}_{-0.0079}\,(0.059^{+0.016}_{-0.014})$
n_s	$0.9672 \pm 0.0037\,(0.9672^{+0.0073}_{-0.0072})$	$0.9696 \pm 0.0038\,(0.9696^{+0.0075}_{-0.0073})$
$\log(10^{10}A_s)$	$3.045 \pm 0.014\,(3.045^{+0.029}_{-0.028})$	$3.051 \pm 0.015\,(3.051^{+0.031}_{-0.028})$
ξ	$-0.32^{+0.18}_{-0.14}\,(-0.32^{+0.30}_{-0.29})$	$-0.186 \pm 0.068\,(-0.19^{+0.13}_{-0.14})$
H_0 [km/s/Mpc]	$70.8^{+1.4}_{-1.7}\,(70.8^{+2.8}_{-2.7})$	$69.87 \pm 0.60\,(69.9^{+1.2}_{-1.2})$
Ω_m	$0.206^{+0.056}_{-0.044}\,(0.206^{+0.090}_{-0.096})$	$0.245 \pm 0.020\,(0.245^{+0.037}_{-0.039})$
σ_8	$1.23^{+0.14}_{-0.36}\,(1.23^{+0.74}_{-0.52})$	$0.974^{+0.059}_{-0.088}\,(0.97^{+0.15}_{-0.14})$
r_{drag} [Mpc]	$147.28 \pm 0.23\,(147.28^{+0.45}_{-0.45})$	$147.42 \pm 0.23\,(147.42^{+0.44}_{-0.46})$
$\Delta\chi^2$	-1.02	-2.27
$\ln \mathcal{B}_{ij}$	-0.10	-0.32



Giarè, Sabogal, Nunes, Di Valentino, *Phys.Rev.Lett.* 133 (2024) 25, 251003

By combining Planck-2018 and DESI data, we observe a preference for interactions exceeding the 95% CL, yielding a present-day expansion rate $H0 = 70.8^{+1.4}_{-1.7}$ km/s/Mpc, in agreement with SH0ES at less than 1.3σ. This preference remains robust when including Type-Ia Supernovae sourced from the Pantheon-plus catalog using the SH0ES Cepheid host distances as calibrators.

After DESI

Redeeming the late time DE proposals…

Omnipotent DE

Density	EoS	Scaling in z	Scaling in a	Naming
$\rho > 0$	$w > -1$	$\mathrm{d}\rho\,/\,\mathrm{d}z > 0$	$\mathrm{d}\rho\,/\,\mathrm{d}a < 0$	p-quintessence
	$w = -1$	$\mathrm{d}\rho\,/\,\mathrm{d}z = 0$	$\mathrm{d}\rho\,/\,\mathrm{d}a = 0$	positive-CC
	$w < -1$	$\mathrm{d}\rho\,/\,\mathrm{d}z < 0$	$\mathrm{d}\rho\,/\,\mathrm{d}a > 0$	p-phantom
$\rho < 0$	$w > -1$	$\mathrm{d}\rho\,/\,\mathrm{d}z < 0$	$\mathrm{d}\rho\,/\,\mathrm{d}a > 0$	n-quintessence
	$w = -1$	$\mathrm{d}\rho\,/\,\mathrm{d}z = 0$	$\mathrm{d}\rho\,/\,\mathrm{d}a = 0$	negative-CC
	$w < -1$	$\mathrm{d}\rho\,/\,\mathrm{d}z > 0$	$\mathrm{d}\rho\,/\,\mathrm{d}a < 0$	n-phantom

Adil, Akarsu, Di Valentino, Nunes, Ozulker, Sen, & Specogna,
Phys.Rev.D 109 (2024) 2, 023527

We named "Omnipotent DE" a class of phenomenologically DE models that are capable of incorporating all six combinations of negative and positive DE density ($\rho_{DE}<0$ and $\rho_{DE}>0$) with different equation of states $w_{DE}<-1$, $w_{DE}=-1$, and $w_{DE}>-1$ into a single expansion scenario for at least one point in its parameter space. This class of DE models incorporates oscillatory/non-monotonic evolution, and the equation of states can have singularities and phantom divide line crossing.

Omnipotent DE

A particular Omnipotent DE model is the one that introduces a transition in the dark energy density ρ_{DE} assuming that there is an extrema at a scale factor a_m.
If we take a Taylor series expansion of ρ_{DE} around a_m, we have:

$$\begin{aligned}\rho_{DE}(a) &= \rho_0 + \rho_2(a-a_m)^2 + \rho_3(a-a_m)^3 \\ &= \rho_0[1+\alpha(a-a_m)^2+\beta(a-a_m)^3].\end{aligned}$$

So the expansion rate of the Universe will be:

$$\begin{aligned}H^2(a)/H_0^2 = \Omega_{m0}a^{-3} + \Omega_{k0}a^{-2} + \Omega_{\gamma 0}a^{-4} \\ + \left(\frac{1-\Omega_{m0}-\Omega_{k0}-\Omega_{\gamma 0}}{1+\alpha(1-a_m)^2+\beta(1-a_m)^3}\right) \\ \left[1+\alpha(a-a_m)^2+\beta(a-a_m)^3\right],\end{aligned}$$

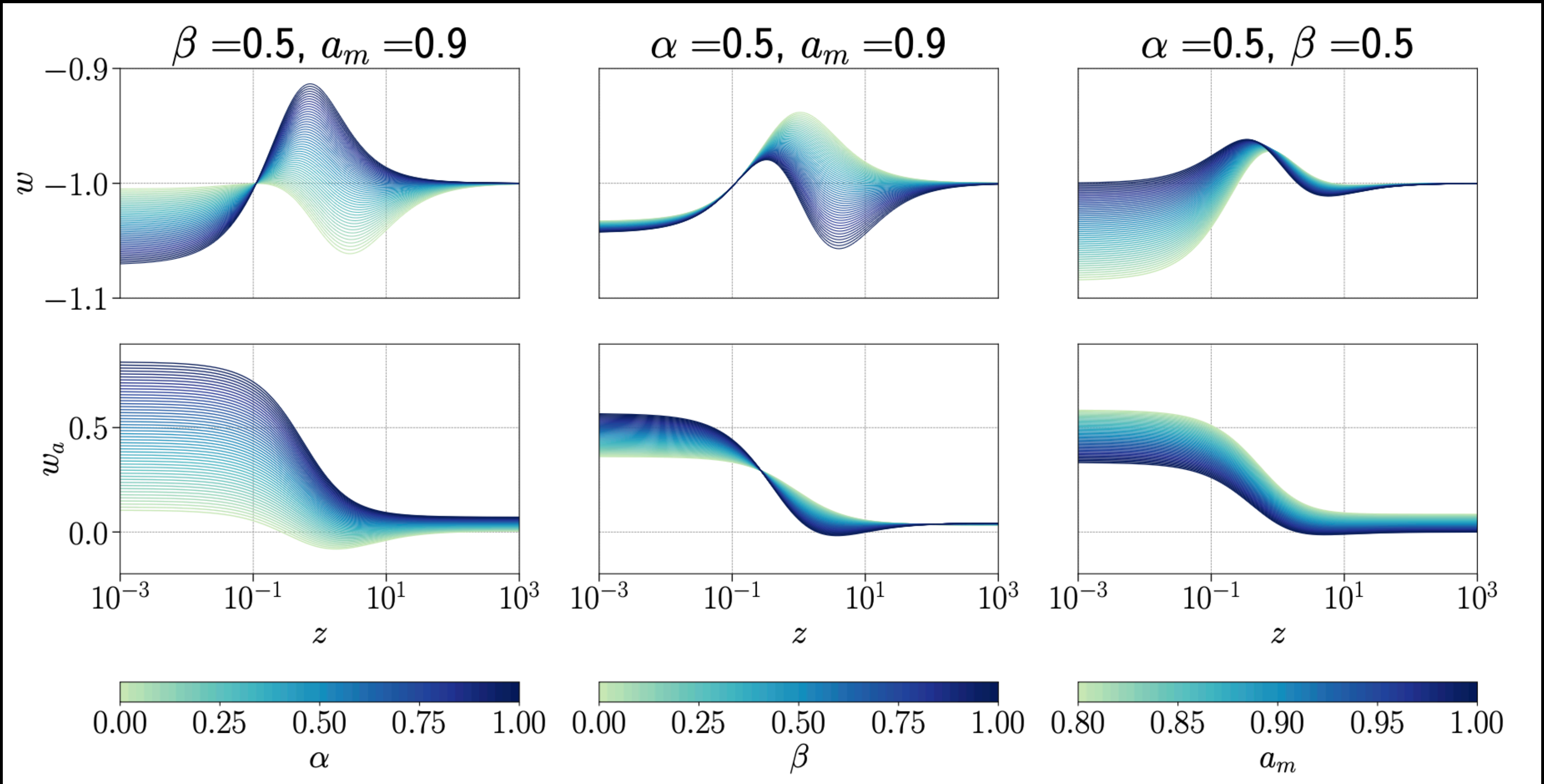
And the dark energy equation of state:

$$w_{DE}(a) = -1 - \frac{a[2\alpha(a-a_m)+3\beta(a-a_m)^2]}{3[1+\alpha(a-a_m)^2+\beta(a-a_m)^3]}.$$

If $a_m < 1$, this crossing happens before the present day.

Di Valentino et al., *Entropy* 23 (2021) 4, 404

Omnipotent DE



Specogna, Adil, Ozulker, Di Valentino, Nunes, Akarsu, & Sen, *arXiv: 2504.17859*

This EoS cannot be cast/remapped to the CPL parametrization.

Constraints at 68% cl.

Omnipotent DE

Parameters	CMB+lensing	CMB+R19	CMB+BAO	CMB+Pantheon	CMB+all
a_m	< 0.276	> 0.830	0.859 ± 0.064	$0.917^{+0.054}_{-0.029}$	$0.851^{+0.048}_{-0.031}$
α	< 17.7	< 8.62	7.3 ± 3.9	< 5.10	< 3.32
β	< 16.7	16.0 ± 7.5	16.1 ± 7.8	$10.6^{+4.4}_{-7.9}$	$7.7^{+2.2}_{-4.7}$
$\Omega_c h^2$	0.1194 ± 0.0014	0.1196 ± 0.0014	0.1201 ± 0.0013	0.1198 ± 0.0014	0.1198 ± 0.0011
$\Omega_b h^2$	0.02243 ± 0.00014	0.02243 ± 0.00016	0.02238 ± 0.00014	0.02240 ± 0.00015	0.02240 ± 0.00014
$100\theta_{MC}$	1.04097 ± 0.00031	1.04096 ± 0.00032	1.04092 ± 0.00030	1.04095 ± 0.00032	1.04093 ± 0.00030
τ	0.0521 ± 0.0076	0.0532 ± 0.0080	$0.0539^{+0.0070}_{-0.0080}$	0.0529 ± 0.0076	0.0521 ± 0.0075
n_s	0.9667 ± 0.0042	0.9665 ± 0.0045	0.9652 ± 0.0043	0.9659 ± 0.0045	0.9655 ± 0.0038
$\ln(10^{10} A_s)$	3.038 ± 0.015	3.041 ± 0.016	3.044 ± 0.016	3.041 ± 0.016	3.039 ± 0.015
H_0[km/s/Mpc]	> 92.8	74.2 ± 1.4	$71.0^{+2.9}_{-3.8}$	$71.7^{+2.2}_{-3.1}$	70.25 ± 0.78
σ_8	$1.012^{+0.051}_{-0.009}$	0.881 ± 0.018	$0.848^{+0.027}_{-0.034}$	$0.860^{+0.026}_{-0.033}$	0.838 ± 0.011
S_8	$0.752^{+0.009}_{-0.025}$	0.818 ± 0.016	0.826 ± 0.019	0.828 ± 0.016	0.823 ± 0.011

We find that the combination of all the observational data including Planck, in agreement one with each other for this model, is indeed consistent with $a_m < 1$ at more than 2σ.

Moreover this model also helps to alleviate the H0 tension between low and high redshift observations below 2σ, even for the full datasets combination, redeeming the possibility of a late time solution, if the DE is not monotonic and can be negative.

Di Valentino et al., *Entropy* 23 (2021) 4, 404

Constraints at 68% cl.

Omnipotent DE: DESI

	SPT+WMAP +DESI	SPT+WMAP +DESI+PP	PL18+DESI	PL18+DESI+PP
$\boldsymbol{\Omega_b h^2}$	0.02244 ± 0.00020	0.02244 ± 0.00019	0.02248 ± 0.00014	0.02247 ± 0.00014
$\boldsymbol{\Omega_c h^2}$	$0.1157^{+0.0016}_{-0.0014}$	0.1157 ± 0.0016	0.11860 ± 0.00093	0.11883 ± 0.00098
$\boldsymbol{100\theta_{MC}}$	1.04028 ± 0.00062	1.04029 ± 0.00064	1.04113 ± 0.00028	$1.04107^{+0.00030}_{-0.00026}$
$\boldsymbol{\tau}$	0.0538 ± 0.0070	0.0537 ± 0.0070	0.0574 ± 0.0076	0.0571 ± 0.0077
$\boldsymbol{\ln(10^{10} A_s)}$	3.030 ± 0.015	3.030 ± 0.015	3.048 ± 0.015	3.048 ± 0.015
$\boldsymbol{n_s}$	0.9690 ± 0.0055	0.9691 ± 0.0055	0.9688 ± 0.0038	0.9683 ± 0.0038
α	< 1.80	$1.40^{+0.65}_{-0.84}$	< 1.02	< 1.01
β	< 2.98	$1.88^{+0.95}_{-1.2}$	< 2.84	1.66 ± 0.72
a_m	$0.74^{+0.16}_{-0.12}$	> 0.930	$0.66^{+0.26}_{-0.13}$	> 0.913
Ω_m	$0.276^{+0.025}_{-0.016}$	0.3030 ± 0.0069	$0.277^{+0.030}_{-0.019}$	$0.3071^{+0.0058}_{-0.0067}$
H_0 [km/s/Mpc]	$71.0^{+1.8}_{-3.2}$	67.68 ± 0.71	$71.7^{+2.3}_{-3.9}$	$67.99^{+0.68}_{-0.56}$
S_8	$0.775^{+0.020}_{-0.017}$	0.786 ± 0.018	$0.806^{+0.015}_{-0.013}$	0.821 ± 0.010
$r_{\rm drag}$ [Mpc]	148.16 ± 0.44	148.18 ± 0.45	147.35 ± 0.23	147.31 ± 0.24
$\Delta\chi^2_{\rm min}$	1.8	-1.4	-0.75	-4.5

surements from the DESI and SDSS surveys. We find that certain data combinations, such as SPT+WMAP+BAO and PL18+BAO, can reduce the significance of the H_0 tension below 1σ, but with considerably large uncertainties. However, the inclusion of PP data restores the tension in H_0. To provide a comprehensive view of the ODE phenomenology, we also investigate the evolution

Specogna, Adil, Ozulker, Di Valentino, Nunes, Akarsu, & Sen, *arXiv: 2504.17859*

Summary – Where Do We Stand?

ΛCDM remains an excellent fit to individual datasets, but fails to jointly explain key cosmological observations. ΛCDM is a remarkably successful fitting model, but it was never meant to be untouchable. It's built on ingredients (dark matter, a cosmological constant, and inflation) none of which have a fundamental theoretical explanation or direct detection. We use them because they work phenomenologically, not because we understand what they are.

We now face persistent tensions and anomalies in the data:

- The H0 tension $>5\sigma$ remains across multiple independent methods.
- The CMB lensing anomaly (AL > 1), the curvature hints ($\Omega_k \neq 0$), and the very strong and low value of the optical depth τ, challenge internal consistency.
- Neutrino mass bounds from cosmology increasingly disagree with terrestrial measurements.
- Hints of new physics are emerging from BAO and SN, such as Dynamical Dark Energy.

Clinging to ΛCDM as the final word in cosmology risks mistaking convenience for truth, and turning precision cosmology into confirmation bias dressed as science.

We must stay open to what the data are really telling us,
and be ready for a reassessment of both our methods and assumptions.

Thank you!

e.divalentino@sheffield.ac.uk

COSMOVERSE • COST ACTION CA21136

Addressing observational tensions in cosmology with systematics and fundamental physics

https://cosmoversetensions.eu/

WG1 – Observational Cosmology and systematics

Unveiling the nature of the existing cosmological tensions and other possible anomalies discovered in the future will require a multi-path approach involving a wide range of cosmological probes, various multiwavelength observations and diverse strategies for data analysis.

READ MORE

WG2 – Data Analysis in Cosmology

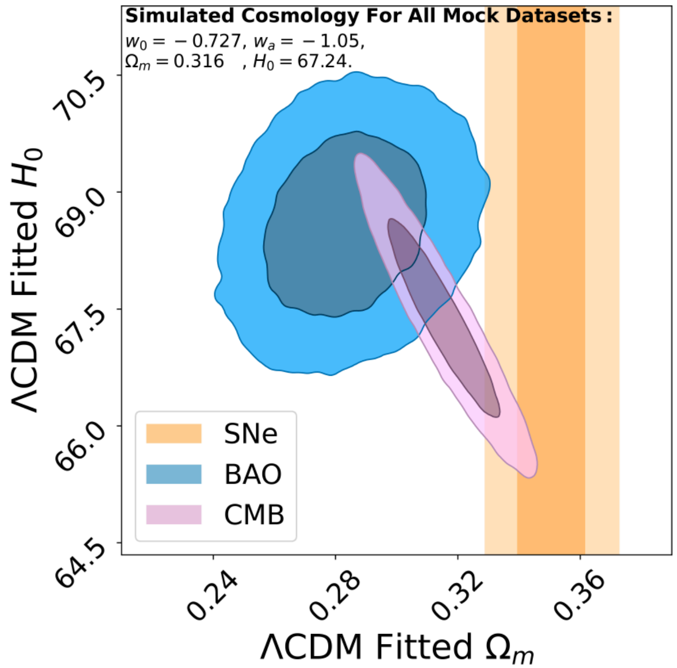
Presently, cosmological models are largely tested by using well-established methods, such as Bayesian approaches, that are usually combined with Monte Carlo Markov Chain (MCMC) methods as a standard tool to provide parameter constraints.

READ MORE

WG3 – Fundamental Physics

Given the observational tensions among different data sets, and the unknown quantities on which the model is based, alternative scenarios should be considered.

READ MORE



Tang et al., arXiv:2412.04430

Data/Mock	ΛCDM Fit	Ω_m Agreement Between Probes (See Section III.1)
Real Data (DESI Y1 VI BAO, DES-SN5YR, Planck18 CMB)	BAO: $\Omega_m = 0.295{\pm}0.015$, $H_0 = 68.5 \pm 0.8$ SNe : $\Omega_m = 0.353{\pm}0.017$ CMB: $\Omega_m = 0.315{\pm}0.007$, $H_0 = 67.3 \pm 0.6$	p-value $= 0.035$
Mock simulated in DESI+CMB Best-Fit ΛCDM $\Omega_m = 0.31$, $H_0 = 68$	BAO: $\Omega_m = 0.311 \pm 0.019$, $H_0 = 68.0 \pm 0.8$ SNe : $\Omega_m = 0.310 \pm 0.011$ CMB: $\Omega_m = 0.310 \pm 0.012$, $H_0 = 68.0 \pm 0.8$	p-value $= 0.999$
Mock simulated in DESI+CMB+DESY5SN Best-Fit w_0w_aCDM $\Omega_m = 0.316$, $w_0 = -0.727$, $w_a = -1.05$, $H_0 = 67.24$	BAO: $\Omega_m = 0.281^{+0.019}_{-0.016}$, $H_0 = 68.6 \pm 0.8$ SNe : $\Omega_m = 0.350 \pm 0.011$ CMB: $\Omega_m = 0.315 \pm 0.012$, $H_0 = 67.4 \pm 0.8$	p-value $= 0.003$

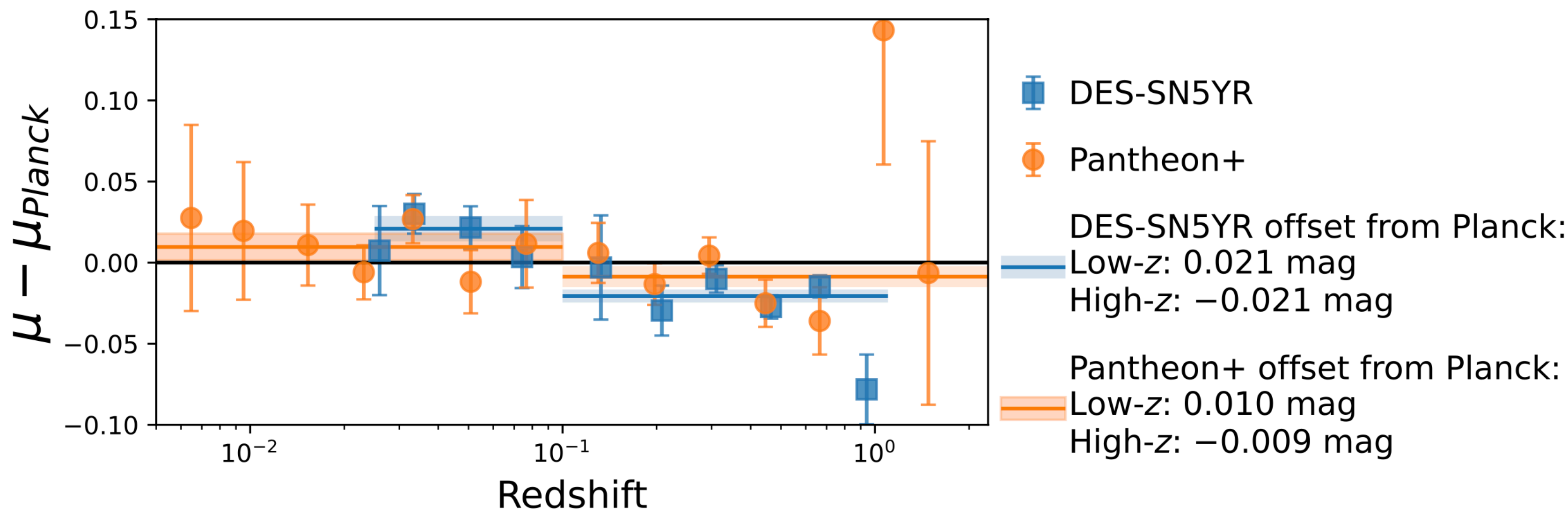


Figure 1. Pantheon+ and DES-SN5YR binned Hubble residuals calculated w.r.t. a FlatΛCDM cosmology assuming $\Omega_M = 0.315$ from *Planck*. In each redshift bin we show the weighted mean of the Hubble residual and statistical-only uncertainties. The horizontal bands show the weighted mean of the Hubble residuals (and associated uncertainties) above and below redshift 0.1 for both Pantheon+ and DES-SN5YR.

6 CONCLUSION

Efstathiou (2024) noted a 0.04 mag low-vs-high redshift distance offset (Eq. 1) between overlapping Pantheon+ and DES-SN5YR events. We have investigated this offset and find that it is explained as follow.

- **Two analysis improvements since Pantheon+**: These improvements are related to the intrinsic scatter model and host stellar mass estimates, and account for 0.018 mag discrepancy between Pantheon+ and DES-SN5YR (from −0.042 to −0.024, see Table 1);
- **Selection differences between Pantheon+ and DES-SN5YR:** Larger distance bias corrections are required for the more heavily biased Pantheon+ sample of spectroscopically identified events, compared to smaller bias corrections for the more complete sample of photometrically classified events in DES-SN5YR (Fig. 4). This difference in selection functions does not affect cosmology results, but leads to misleading conclusions in an object-to-object comparison like the one presented by Efstathiou (2024), where only 20% of the brightest SNe are selected from both analyses. This effect account for an additional 0.016 mag discrepancy between Pantheon+ and DES-SN5YR (from −0.024 to −0.008, see Table 1). This biased comparison can be avoided by comparing the binned Pantheon+ and DES-SN5YR Hubble diagrams as shown in Fig. 1.

Vincenzi et al., arXiv:2501.06664

Analysis changes applied to DES-SN5YR	Contribution to $\Delta\mu_{\rm offset}$ [mag]	Remaining $\Delta\mu_{\rm offset}$ [mag]
None		**−0.042**
Revert to Pantheon+ intrinsic scatter model (∗)	**0.008**	**−0.034**
Revert to Pantheon+ host stellar mass estimations	**0.010**	**−0.024**
Remove offset due to different selection functions (‡)	**0.016**	**−0.008**

Approach used to build the Hubble diagram ↓	**Spectroscopic SN Ia sample (~same data)**	**Photometric SN Ia sample**
Simulation-based method	**Pantheon+**	**DES-5YR**
Bayesian Hierarchical method ("UNITY")	**Union3**	

BAO measurements

To simplify let's consider an ensemble of galaxy pairs at a specific redshift z.

When the pairs are oriented across the line-of-sight, a preferred angular separation of galaxies Δθ can be observed. This allows us to measure the comoving distance DM(z) = rd/Δθ to this redshift, which is an integrated quantity of the expansion rate of the universe.

$$D_{\mathrm{M}}(z) = \frac{c}{H_0} \int_0^z \mathrm{d}z' \frac{H_0}{H(z')}$$

The angular diameter distance will be DA(z) = DM(z)/(1 + z).

Conversely, when the pairs are aligned along the line-of-sight, a preferred redshift separation Δz can be observed. This measures a comoving distance interval that, for small values, provides a redshift dependent measurement of the Hubble parameter, represented by the equivalent distance variable DH(z) = c/H(z) = rd/Δz.

Hence BAO measurements constrain the quantities DM(z)/rd and DH(z)/rd. This interpretation holds under standard assumptions and models similar to ΛCDM. For measurements in redshift bins with low signal-to-noise ratios, the angle-averaged quantity DV(z)/rd can be constrained, where DV(z) is the angle-average distance that represents the average of the distances measured along and perpendicular to the line-of-sight.

$$D_{\mathrm{V}}(z) = \left(z D_{\mathrm{M}}(z)^2 D_H(z)\right)^{1/3}$$

DESI collaboration, arXiv:2404.03002

Bayes factor

Anyway it is clearly interesting to quantify the better accordance of a model with the data respect to another by using the marginal likelihood also known as the Bayesian evidence.

The Bayesian evidence weights the simplicity of the model with the improvement of the fit of the data. In other words, because of the Occam's razor principle, models with additional parameters are penalised, if don't improve significantly the fit.

Given two competing models M_0 and M_1 it is useful to consider the ratio of the likelihood probability (the Bayes factor):

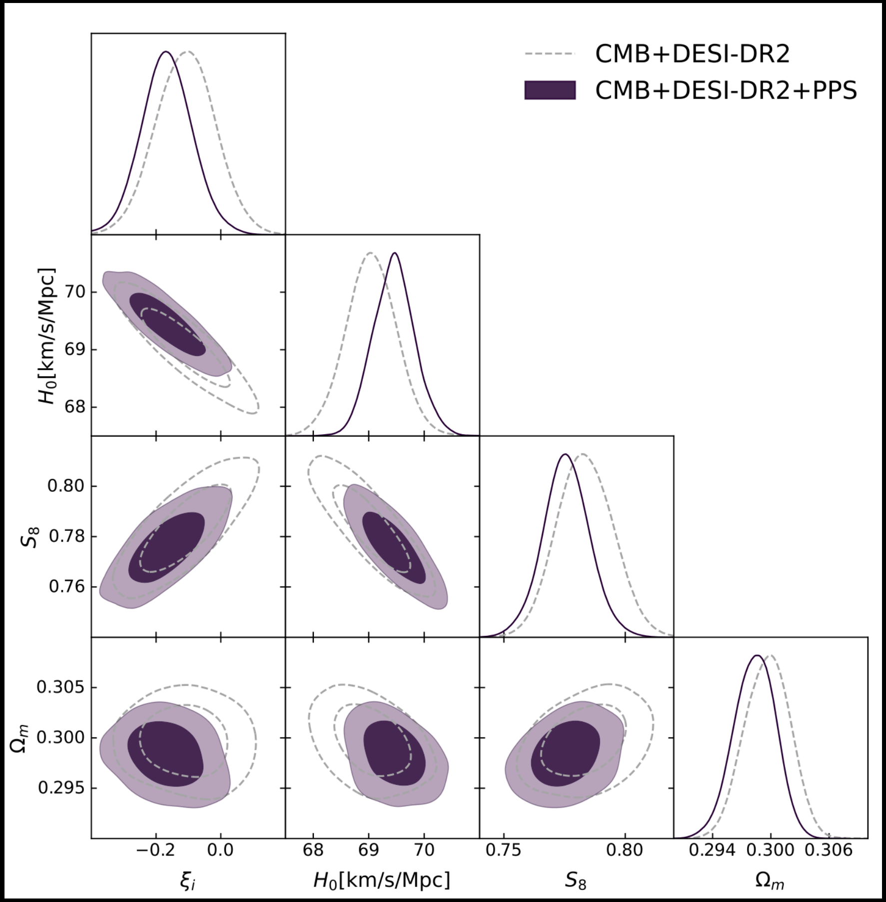
$$ln\mathcal{B} = p(\boldsymbol{x}|M_0)/p(\boldsymbol{x}|M_1)$$

According to the revised Jeffrey's scale by Kass and Raftery 1995, the evidence for M_0 (against M_1) is considered as "weak" if $|\ln B| > 1.0$, "moderate" if $|\ln B| > 2.5$, and "strong" if $|\ln B| > 5.0$.

Constraints at 68% cl.

The IDE case

Parameter	CMB+DESI-DR2	CMB+DESI-DR2+PPS
$10^2\Omega_b h^2$	2.253 ± 0.012	2.259 ± 0.012
$\Omega_c h^2$	$0.1028^{+0.0097}_{-0.0069}$	$0.1045^{+0.0068}_{-0.0054}$
$100\theta_s$	1.04210 ± 0.00027	1.04214 ± 0.00028
$\ln(10^{10}A_s)$	3.051 ± 0.014	3.052 ± 0.015
n_s	0.9703 ± 0.0032	0.9713 ± 0.0033
$\tau_{\rm reio}$	0.0591 ± 0.0070	$0.0597^{+0.0066}_{-0.0076}$
ξ	$-0.132^{+0.087}_{-0.064}$	$-0.116^{+0.060}_{-0.050}$
H_0 [km/s/Mpc]	$69.61^{+0.54}_{-0.67}$	69.61 ± 0.44
Ω_m	$0.260^{+0.025}_{-0.019}$	$0.264^{+0.017}_{-0.015}$
S_8	$0.860^{+0.024}_{-0.040}$	$0.850^{+0.020}_{-0.028}$
$\Delta\chi^2_{\rm min}$	1.1	−2.20
ΔAIC	3.1	−0.20



Silva, Sabogal, Souza, Nunes, Di Valentino & Kumar, arXiv:*2503.23225*

It can alleviate the H0 tension to approximately 2.7σ.

The optical depth

During the cosmic reionization, CMB photons undergo Thomson scattering off free electrons at scales smaller than the horizon size.
As a result, they deviate from their original trajectories, reaching us from a direction different from the one set during recombination.
Similarly to recombination, this introduces a novel ’last scattering’ surface at later times and produces distinctive imprints in the angular power spectra of temperature and polarization anisotropies.
A well-known effect of reionization is an enhancement of the spectrum of CMB polarization at large angular scales alongside a suppression of temperature anisotropies occurring at smaller scales ($A_s e^{-2\tau}$).
The distinctive polarization bump produced by reionization on large scales dominates the signal in the EE spectrum whose amplitude strongly depends on the total integrated optical depth to reionization:

$$\tau = \sigma_{\rm T} \int_0^{z_{\rm rec}} dz\, \bar{n}_e(z)\, \frac{dr}{dz},$$

where σ_T is the Thomson scattering cross-section, $\bar{n}_e(z)$ is the free electron proper number density at redshift z, and dr/dz is the line-of-sight proper distance per unit redshift.
For this reason, precise observations of E-mode polarization on large scales are crucial.

Giarè, Di Valentino, Melchiorri, Phys.Rev.D 109 (2024) 10, 103519

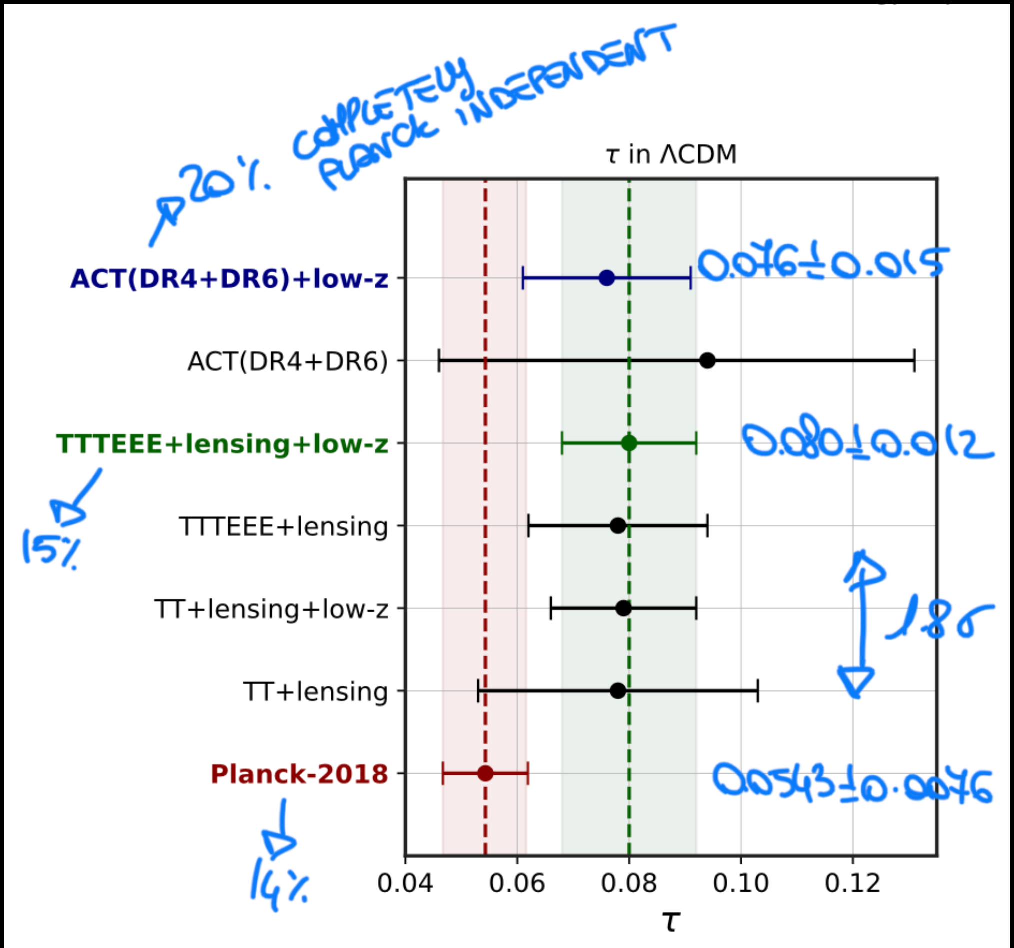
The optical depth

Thanks to large-scale polarization measurements released by the Planck satellite, we have achieved an unprecedented level of accuracy, constraining the optical depth at reionization down to $\tau = 0.054 \pm 0.008$ at 68% CL, from the WMAP9 value of $\tau = 0.089 \pm 0.014$. Measuring τ to such a level of precision holds implications that extend beyond reionization models. For example, the constraints on the Hubble parameter H_0 and the scalar spectral index n_s both improve by approximately 22% when incorporating Planck large-scale polarization data in the analysis. However, as often happens when dealing with high-precision measurements at low multipoles, there are certain aspects that remain less than entirely clear:

- The detected signal in the EE spectrum is extremely small, on scales where cosmic variance sets itself a natural limit on the maximum precision achievable, and even minor undetected systematic errors could have a substantial impact on the results.
- Small, undetected foreground effects could play a role in determining polarization measurements.
- Measurements of temperature and polarization anisotropies at large angular scales exhibit a series of anomalies. For example, the TE spectrum at low multipoles shows an excess variance compared to simulations, for reasons that are not understood, and is commonly disregarded for cosmological data analyses.

Giarè, Di Valentino, Melchiorri, Phys.Rev.D 109 (2024) 10, 103519

lowE independent optical depth



By using different combinations of Planck temperature and polarization data at l > 30, ACT and Planck reconstructions of the lensing potential, BAO measurements from BOSS and eBOSS surveys, and Type-Ia supernova data from the Pantheon-Plus sample, we can constrain τ independently.

The most constraining limit $\tau = 0.080 \pm 0.012$ comes from TTTEEE+lensing+low-z.

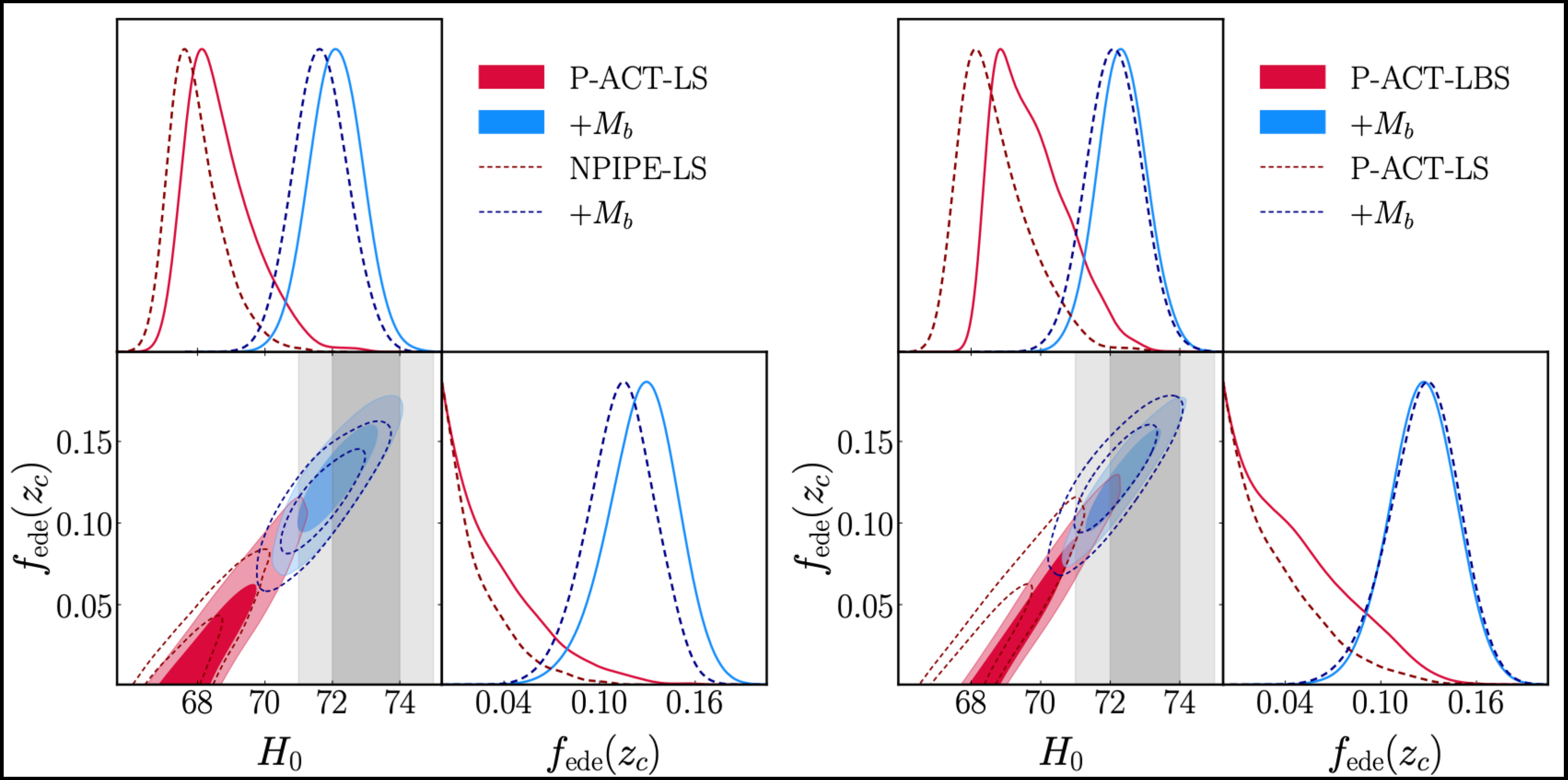
Using only ACT- based temperature, polarization, and lensing data, from ACT(DR4+DR6)+low-z we got $\tau = 0.076 \pm 0.015$ which is entirely independent of Planck.

Giarè, Di Valentino, Melchiorri, Phys.Rev.D 109 (2024) 10, 103519

Early Dark Energy

Constraints at 68% cl.

	NPIPE-LS		P-ACT-LS		P-ACT-LBS	
SH0ES prior?	no	yes	no	yes	no	yes
$100h$	$67.96(68.45)^{+0.51}_{-0.93}$	$71.65(71.96) \pm 0.81$	$68.68(69.76)^{+0.62}_{-1.2}$	$72.11(72.12) \pm 0.79$	$69.71(70.98)^{+0.64}_{-1.3}$	$72.34(72.49) \pm 0.72$
$f_{\rm ede}(z_c)$	$< 0.065(0.043)$	$0.113(0.122) \pm 0.022$	$< 0.092(0.075)$	$0.127(0.134)^{+0.024}_{-0.020}$	$< 0.109(0.0902)$	$0.126(0.133) \pm 0.021$



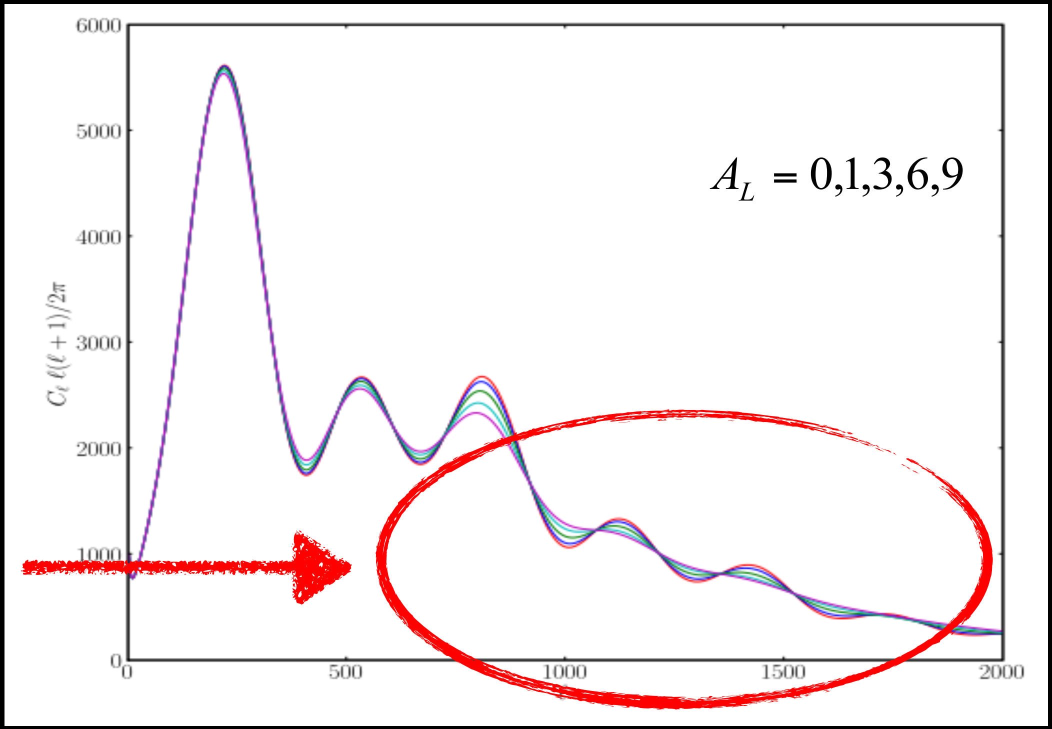
Poulin et al., *arXiv:2505.08051*

A_L internal anomaly

Its effect on the power spectrum is the smoothing of the acoustic peaks, increasing AL.

Interesting consistency checks is if the amplitude of the smoothing effect in the CMB power spectra matches the theoretical expectation AL = 1 and whether the amplitude of the smoothing is consistent with that measured by the lensing reconstruction.

If AL =1 then the theory is correct, otherwise we have a new physics or systematics.



Calabrese et al., Phys. Rev. D, 77, 123531