Cracks in the Standard Cosmological Model: Anomalies, Tensions, and Hints of New Physics

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Sofia University

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Why Do We Care?

Dark Matter is at the heart of cosmological tensions and ΛCDM's cracks.

The dark sector is no longer just the background of cosmology:
it may be the key to new physics, and the persistent tensions could represent the first indirect hints of new light particles or interactions.

Cosmology now probes couplings and relics beyond the reach of laboratory experiments, but if these tensions stem from systematics or from a wrong assumption about the underlying ΛCDM model,
any particle-physics interpretation must wait.

The ΛCDM model

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

However, despite its incredible success, ΛCDM harbours large areas of phenomenology and ignorance. For example, it still cannot explain key concepts in our understanding of the structure and evolution of the Universe, at the moment based on unknown quantities, that are also its largest components. In addition, their physical evidence comes from cosmological and astrophysical observations only, without strong theoretical motivations.

The ΛCDM model

Three unknown pillars:

- an early stage of accelerated expansion (Inflation) which produces the initial, tiny, density perturbations, needed for structure formation.
- a clustering matter component to facilitate structure formation (Dark Matter),
- an energy component to explain the current stage of accelerated expansion (Dark Energy).

Specific solutions for ΛCDM:

- Inflation is given by a single, minimally coupled, slow-rolling scalar field;
- Dark Matter is a pressureless fluid made of cold, i.e., with low momentum, and collisionless particles;
- Dark Energy is a cosmological constant term.

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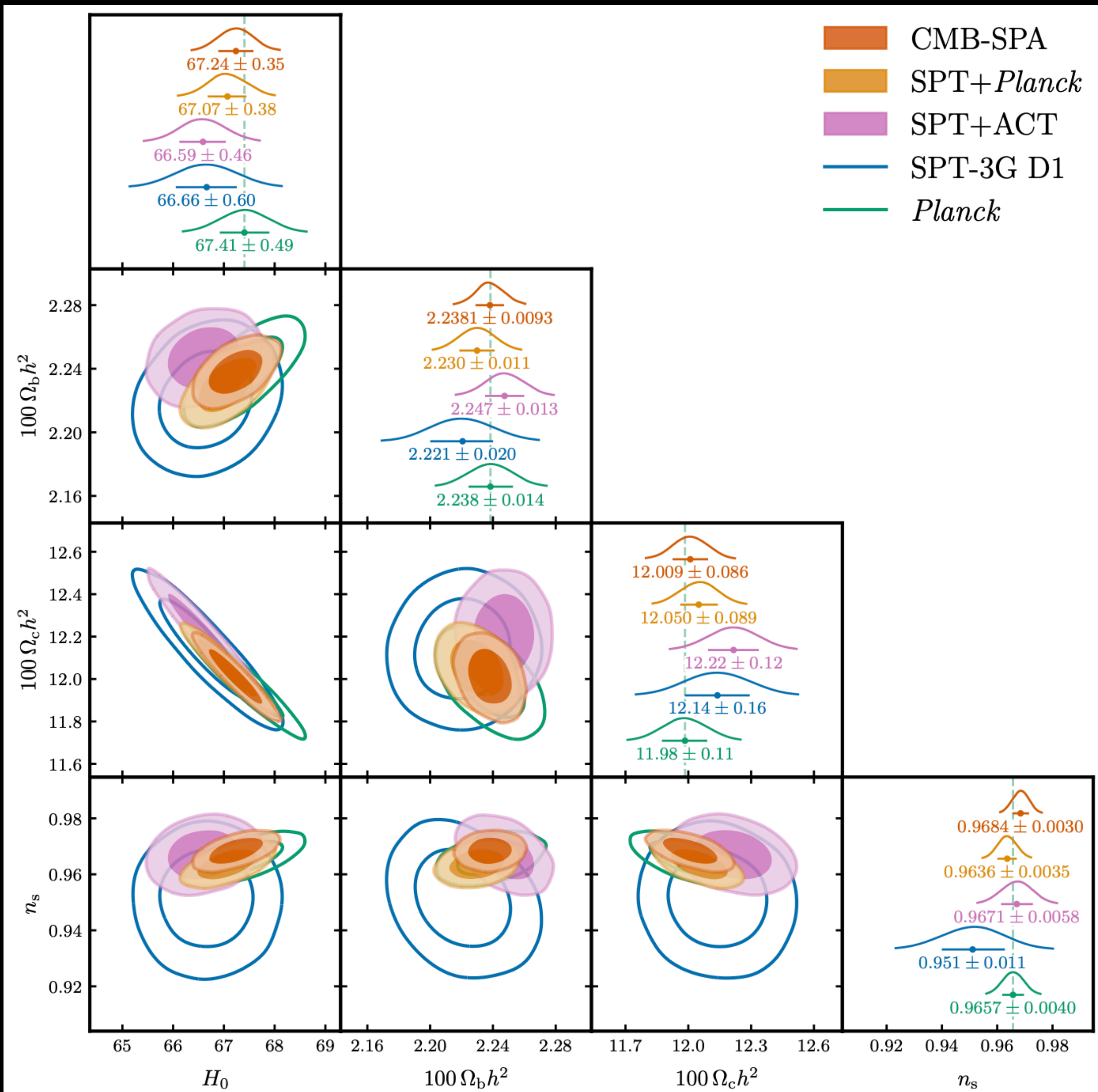
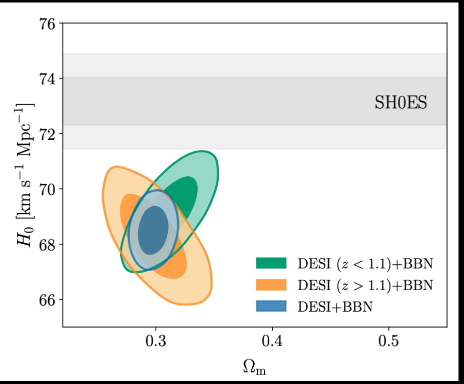
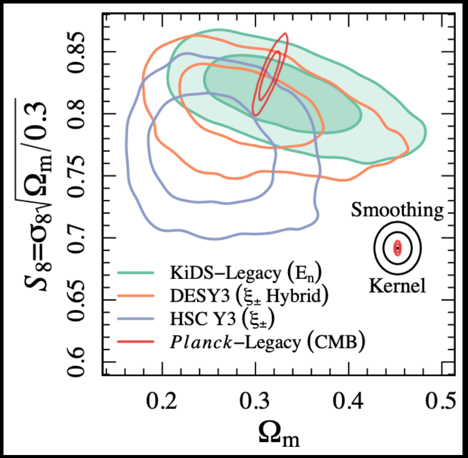
- Inflation is given by a single, minimally coupled, slow-rolling scalar field;
- fluid
- Dark Energy is a cosmological constant term.

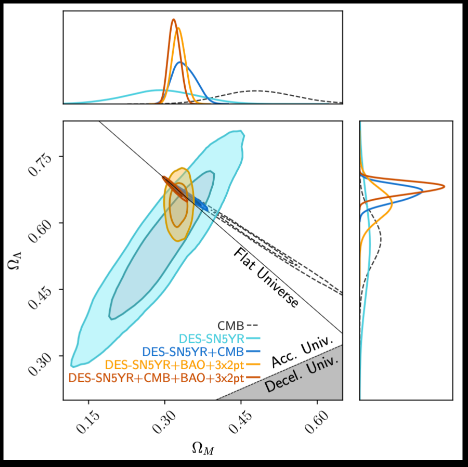
However, despite its theoretical shortcomings,
ΛCDM remains the preferred model
due to its ability to accurately describe
observed phenomena.

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









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

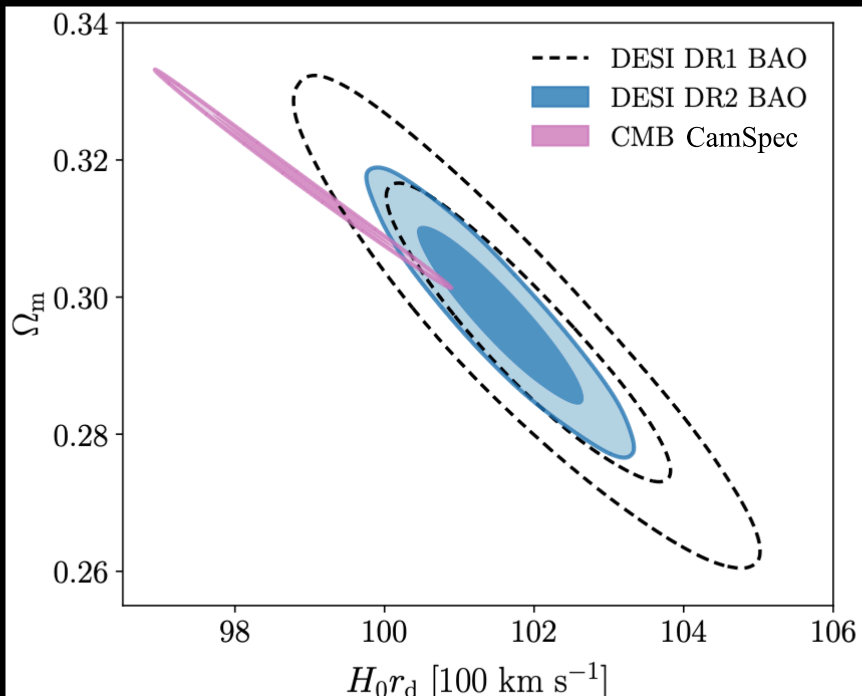
In a Bayesian framework, all models can, in principle, agree with the data.
What matters is whether they are disfavoured due to a poor fit
or because another model is preferred.
Therefore, to me, this means that ΛCDM provides a good fit to the data
and shows no clear signs of deviation, even when extended.

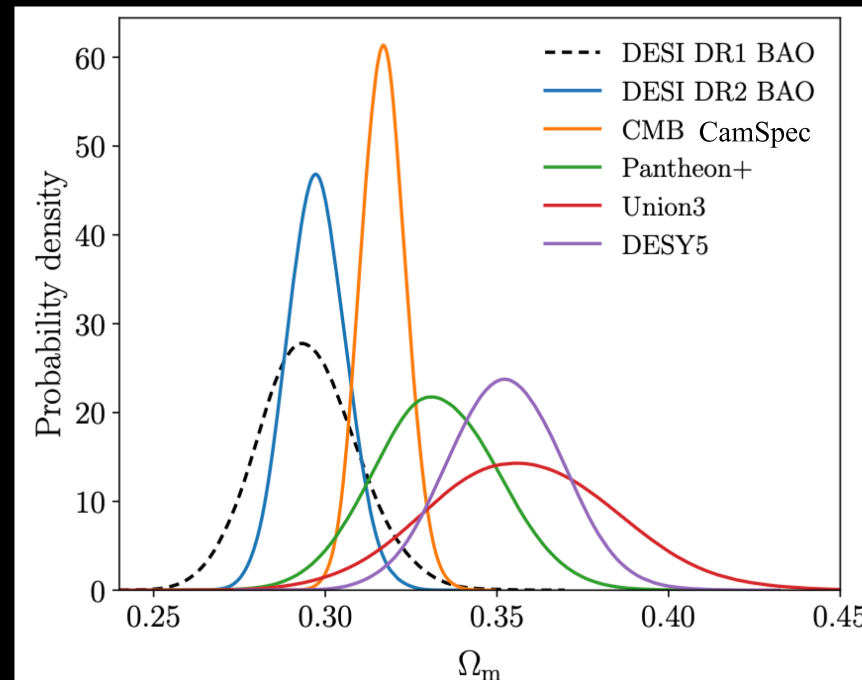
However, currently the cosmological parameters inferred
from different probes are not the same.

So ΛCDM appears different for the different data!

Tensions and Disagreements in ΛCDM

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





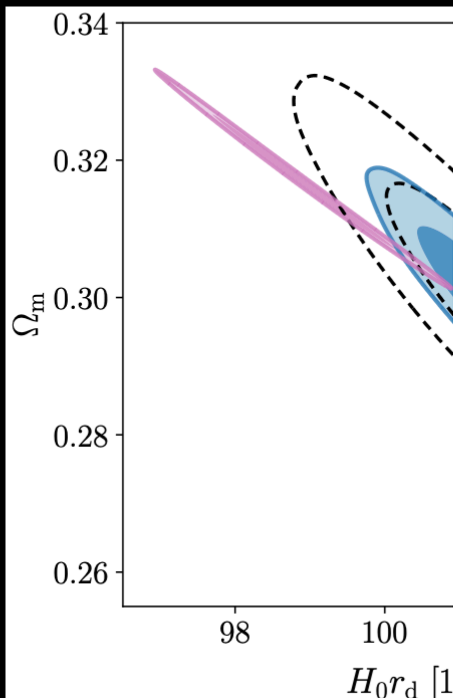
Converting this χ^2 into a probability-to-exceed (PTE) value, we find it is equivalent to a 2.3σ discrepancy between BAO and CMB in ΛCDM, increased from 1.9σ in DR1. However, we note that this reduces to 2.0σ if CMB lensing is excluded. This discrepancy is part of the reason why more models with a more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

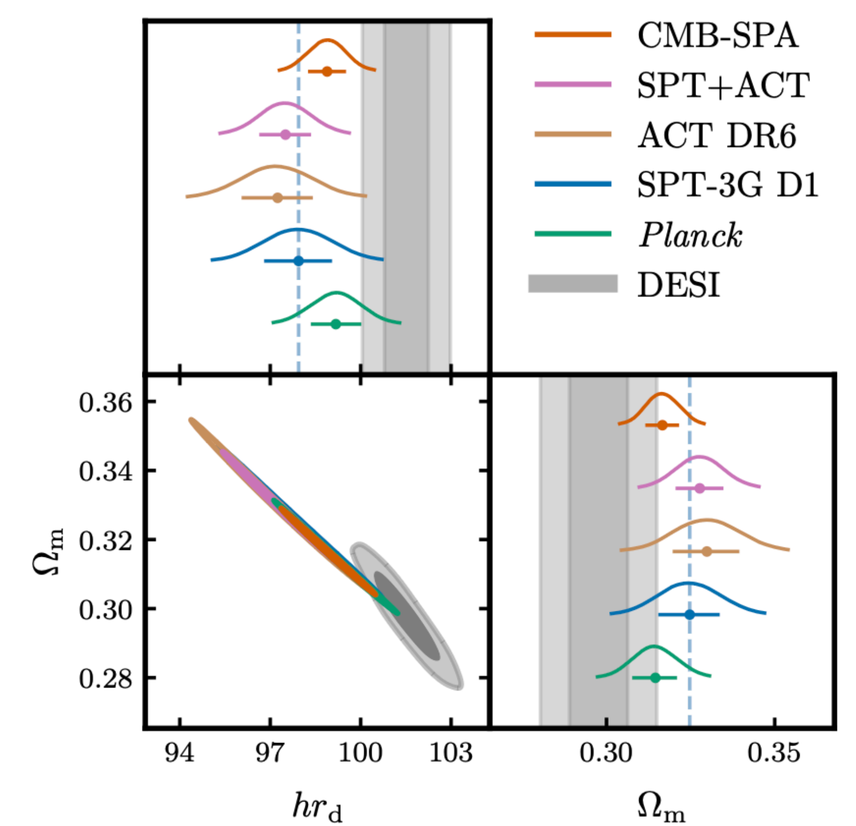
Finally, as in [38], we note a mild to moderate discrepancy between the recovered values of Ω_m from DESI and SNe in the context of the ΛCDM model. This is shown in the marginalized posteriors in Figure 10: the discrepancy is 1.7σ for Pantheon+, 2.1σ for Union3, and 2.9σ for DESY5, with all SNe samples 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

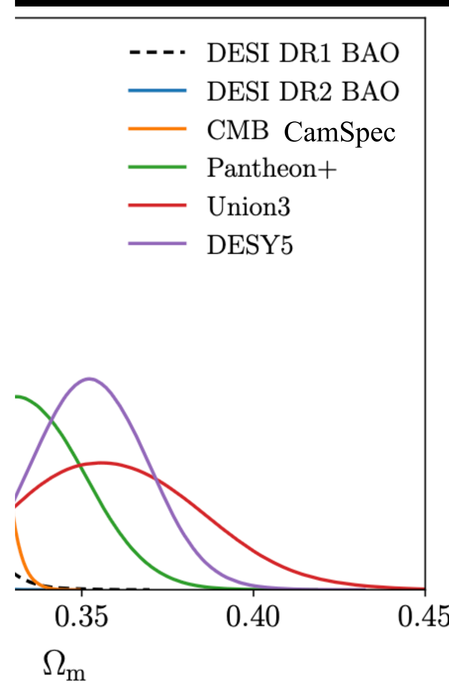
The same ΛCDM cannot fit 2 datasets together!

Tensions and Disagreements in ΛCDM

SPT-3G D1, arXiv:2506.20707 [astro-ph.CO]







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	$100\,\Omega_m$	$h r_d$ [Mpc]	Distance to DESI
CMB-SPA	31.66 ± 0.50	98.89 ± 0.63	$2.8\,\sigma$
SPT+ACT	32.77 ± 0.72	97.51 ± 0.87	$3.7\,\sigma$
SPT+*Planck*	31.89 ± 0.54	98.63 ± 0.67	$3.0\,\sigma$
ACT DR6	33.0 ± 1.0	97.2 ± 1.2	$3.1\,\sigma$
SPT-3G D1	32.47 ± 0.91	97.9 ± 1.1	$2.5\,\sigma$
Planck	31.45 ± 0.67	99.18 ± 0.84	$2.0\,\sigma$
DESI	29.76 ± 0.87	101.52 ± 0.73	

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ΛCDM model. This is shown
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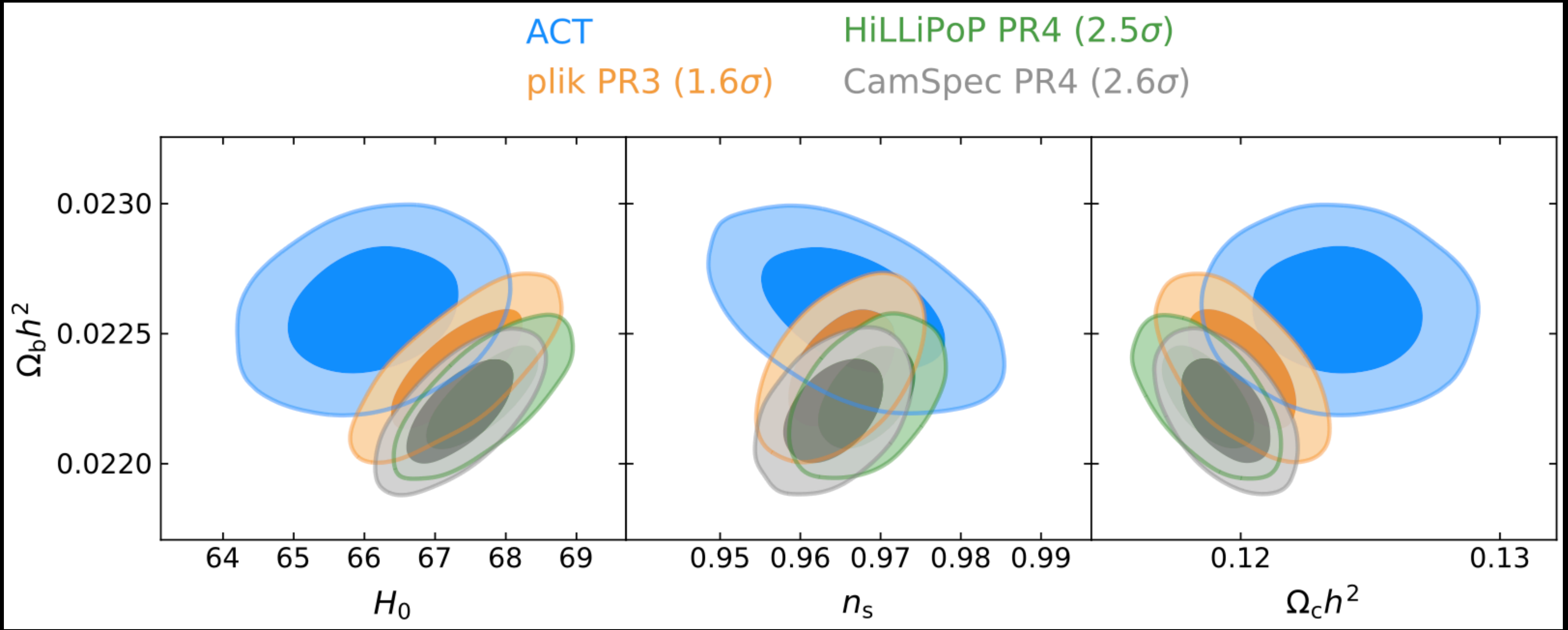
CMB tension in ΛCDM



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

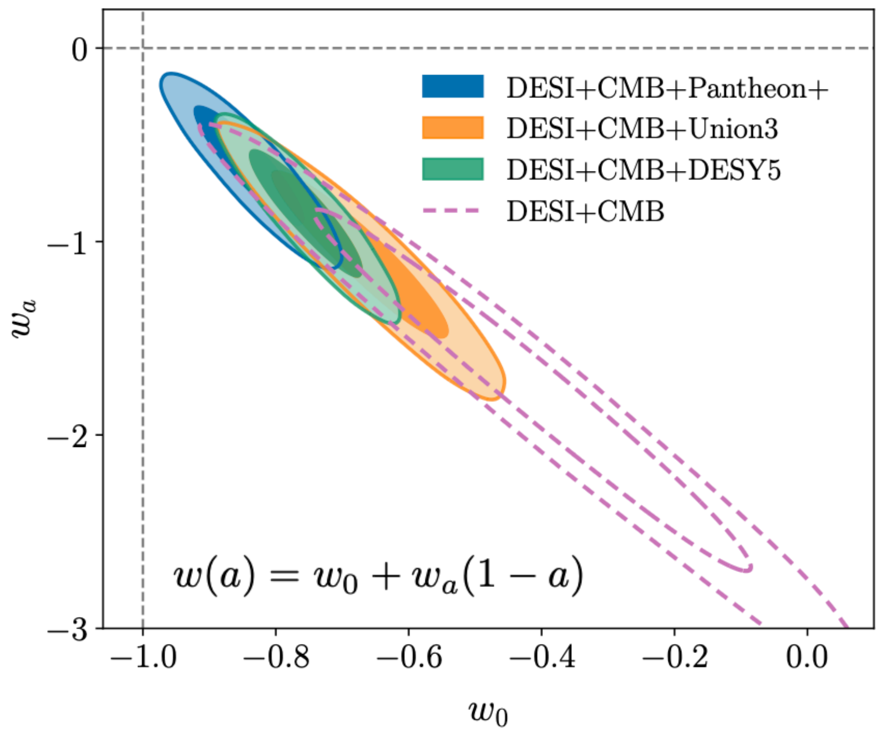
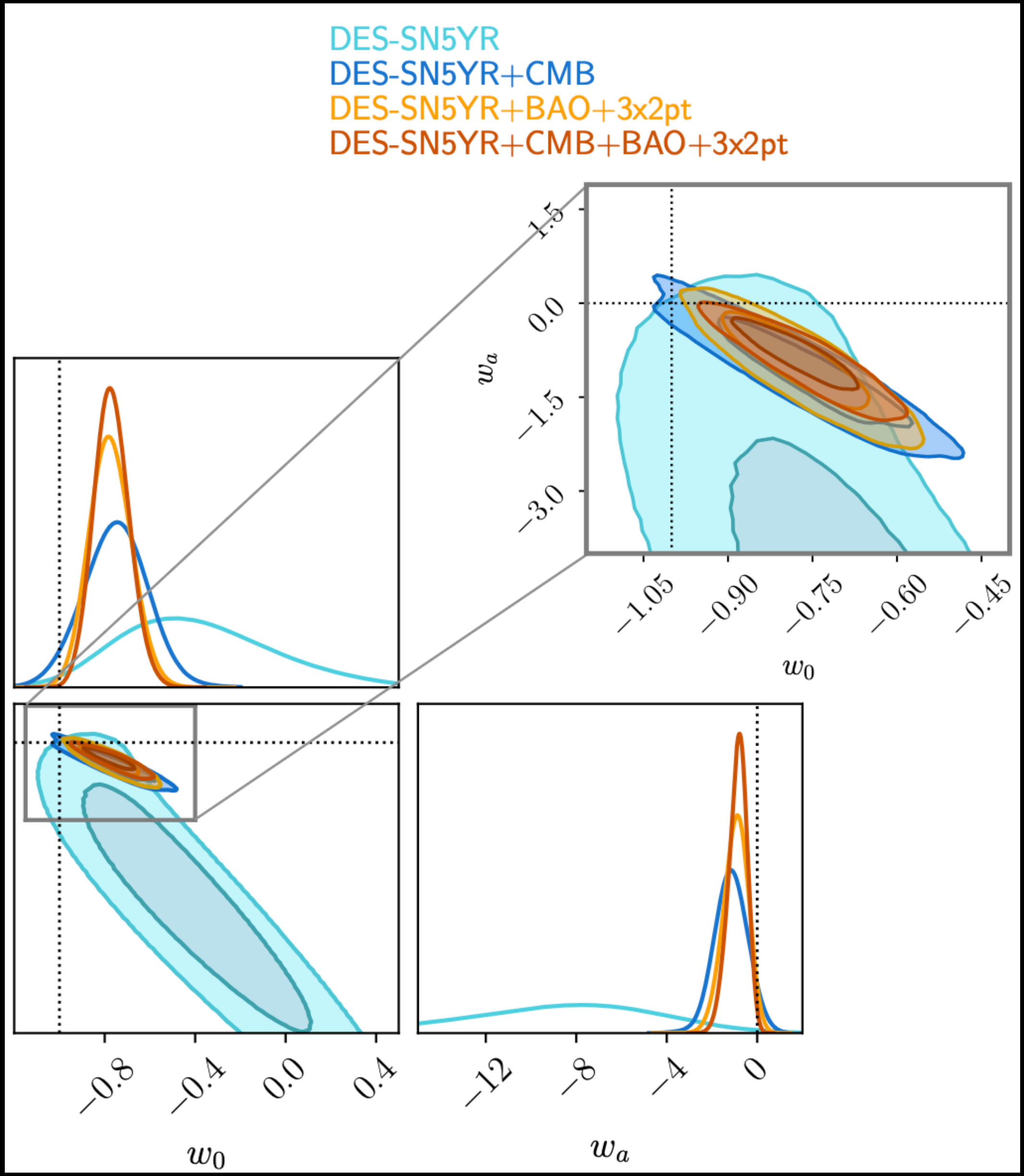


FIG. 11. Results for the posterior distributions of w_0 and w_a, from fits of the w_0w_aCDM model to DESI in combination with CMB and three SNe datasets as labelled. We also show the contour for DESI combined with CMB alone. The contours enclose 68% and 95% of the posterior probability. The gray dashed 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	$\Delta\chi^2_{\rm MAP}$	Significance	Δ(DIC)
DESI	−4.7	1.7σ	−0.8
DESI+$(\theta_*, \omega_{\rm b}, \omega_{\rm bc})_{\rm CMB}$	−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

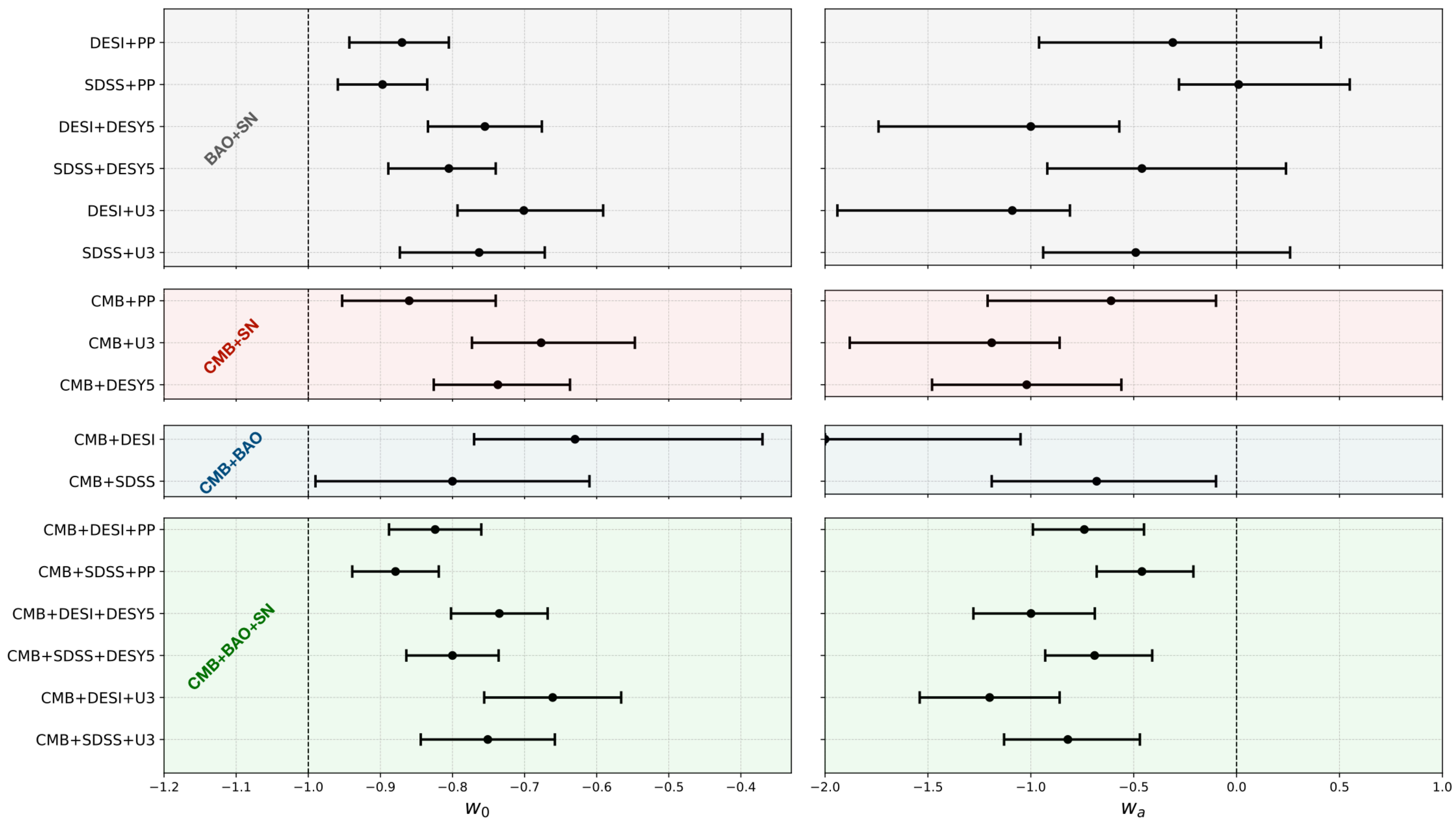
DESI collaboration, Abdul Karim et al., arXiv:2503.14738

Consequences? Indication for DDE



DESY5 collaboration: Abbott et al., arXiv:2401.02929

Hints for DDE robust changing datasets

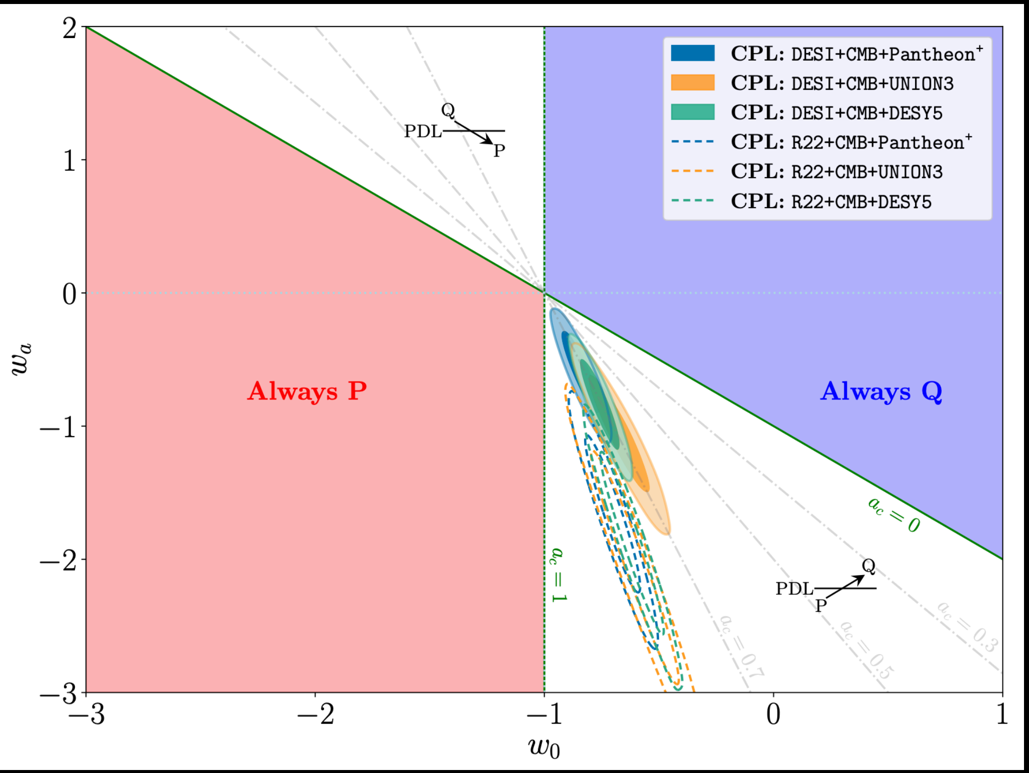


Overall, our findings highlight that combinations that *simultaneously* include PantheonPlus SN and SDSS BAO significantly weaken the preference for DDE. However, intriguing hints supporting DDE emerge in combinations that do not include DESI-BAO measurements: SDSS-BAO combined with SN from Union3 and 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).

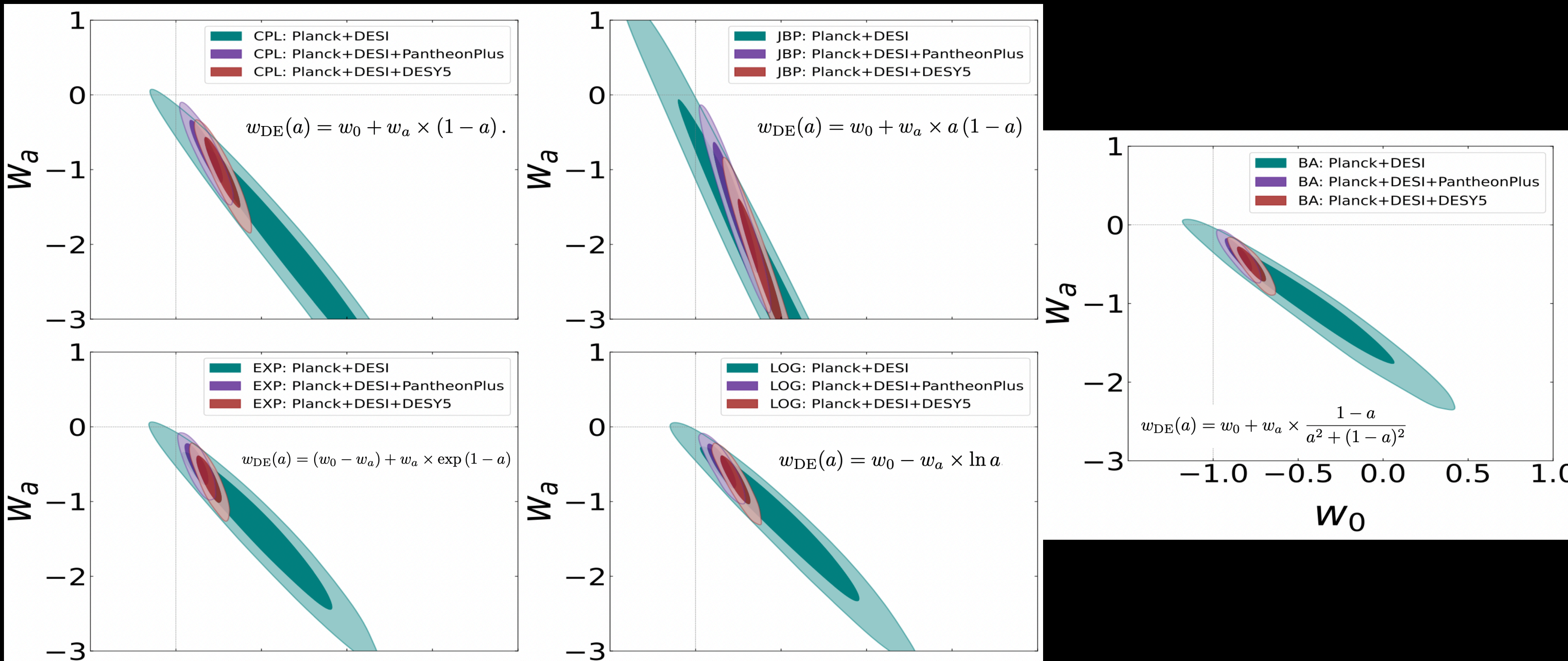
Thus, a strong correlation of the parameters w0 and wa would result in a strong determination of ac.

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

Ozulker, Di Valentino, Giarè, arXiv:2506.19053

Hint for DDE robust changing w(z) parametrizations

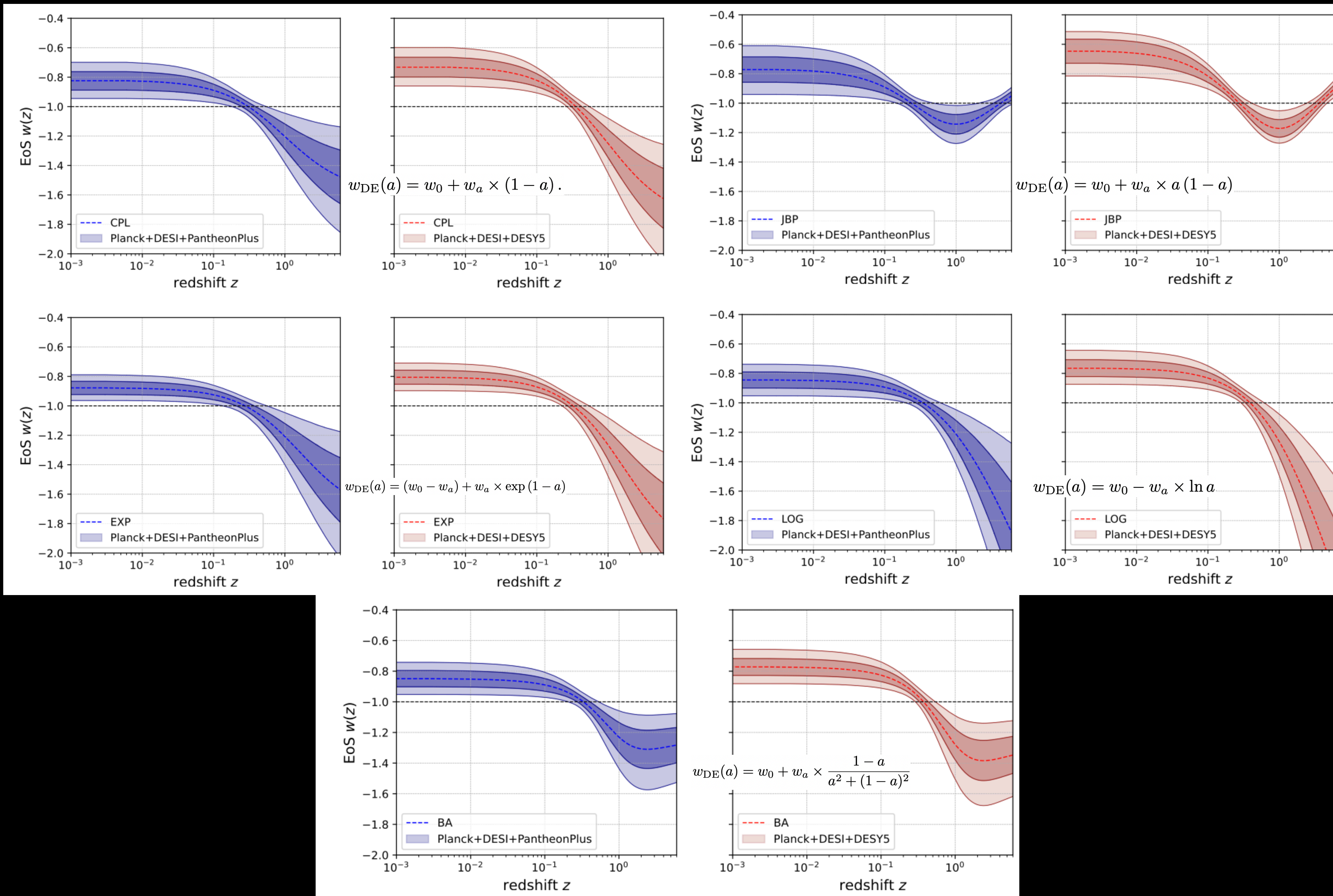
Giarè, Najafi, Pan, Di Valentino & Firouzjaee, *JCAP* 10 (2024) 035



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

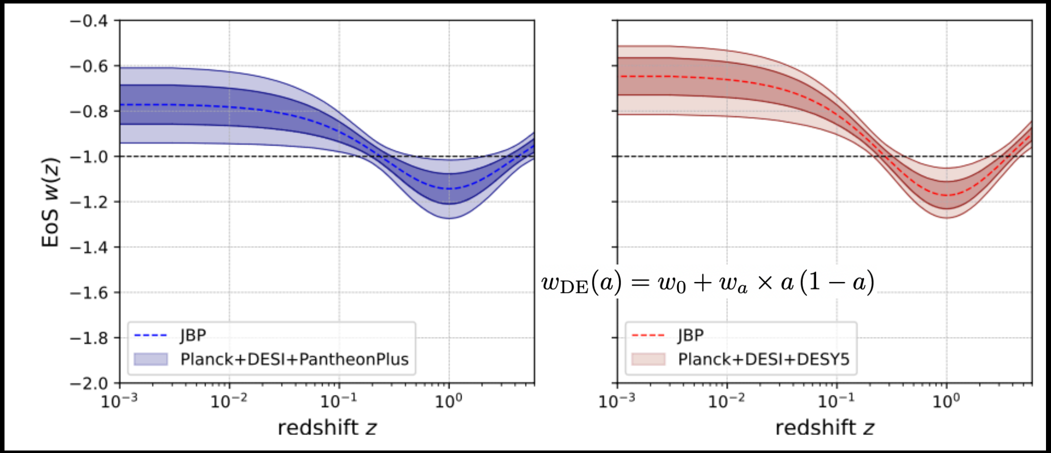
Giarè, Najafi, Pan, Di Valentino & Firouzjaee, *JCAP* 10 (2024) 035



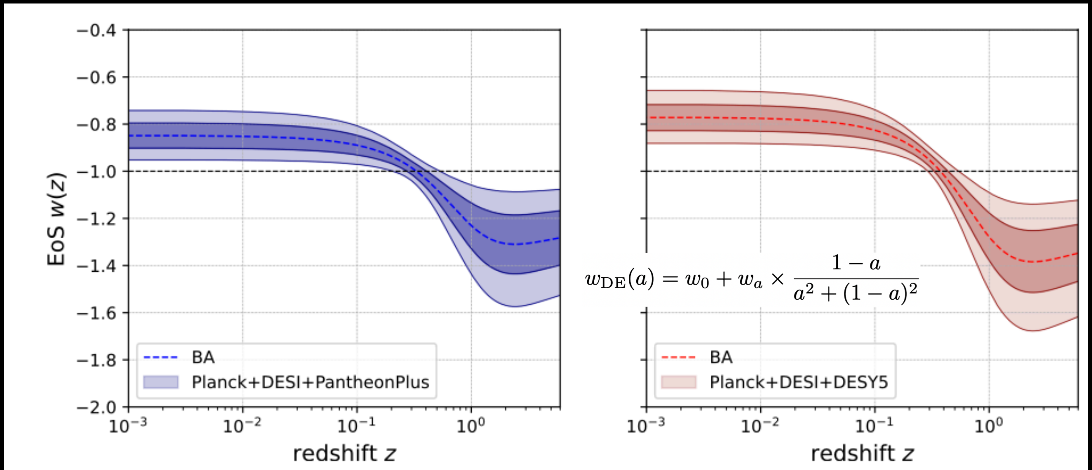
Hint for DDE robust changing w(z) parametrizations

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

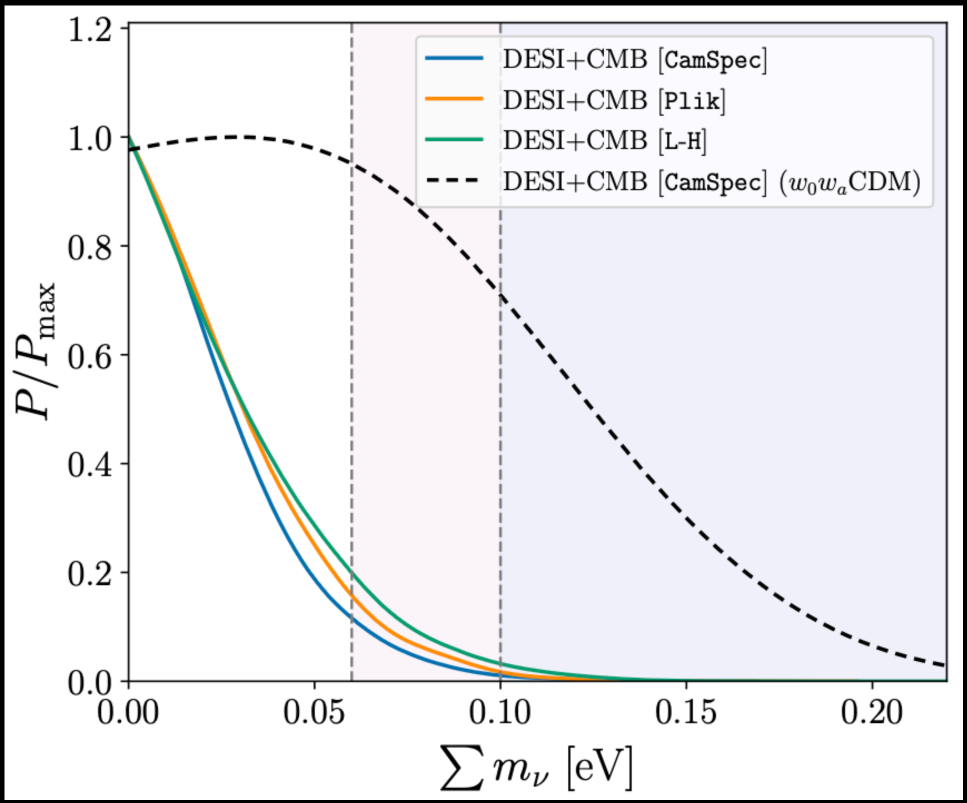
Due to its quadratic nature in the scale factor, the evolution of the EoS within the JBP parameterization crosses w =-1 twice.



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.



Consequences? Neutrino mass tension

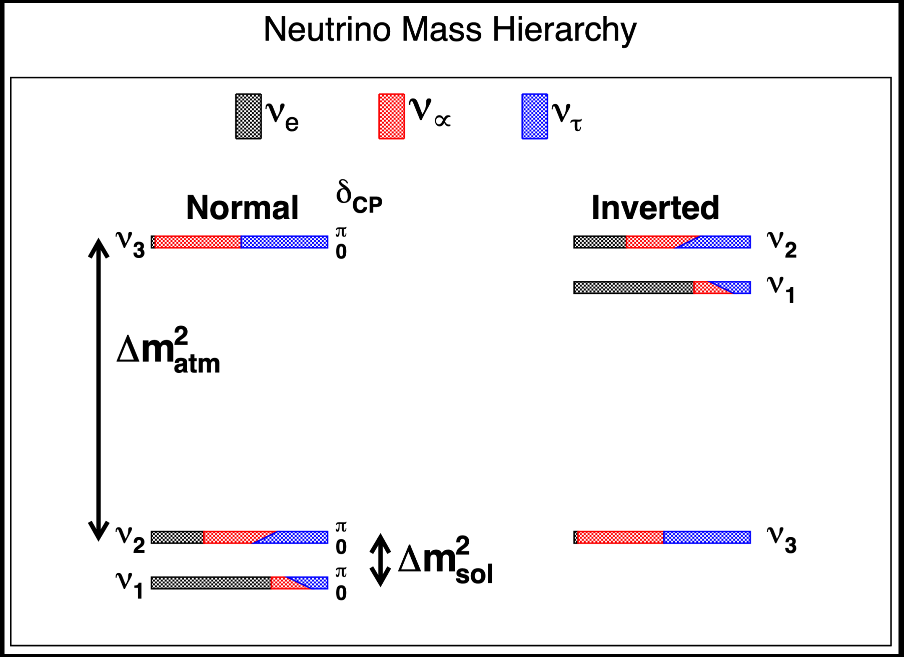


Model/Dataset	$\Omega_{\rm m}$	H_0 [km s^{-1} Mpc^{-1}]	$H_0 r_{\rm d}$ [100 km s^{-1}]	$\sum m_\nu$ [eV]
ΛCDM+$\sum m_\nu$				
DESI BAO+CMB [Camspec]	0.3009 ± 0.0037	68.36 ± 0.29	100.96 ± 0.48	< 0.0642
DESI BAO+CMB [L-H]	0.2995 ± 0.0037	68.48 ± 0.30	101.16 ± 0.49	< 0.0774
DESI BAO+CMB [Plik]	0.2998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

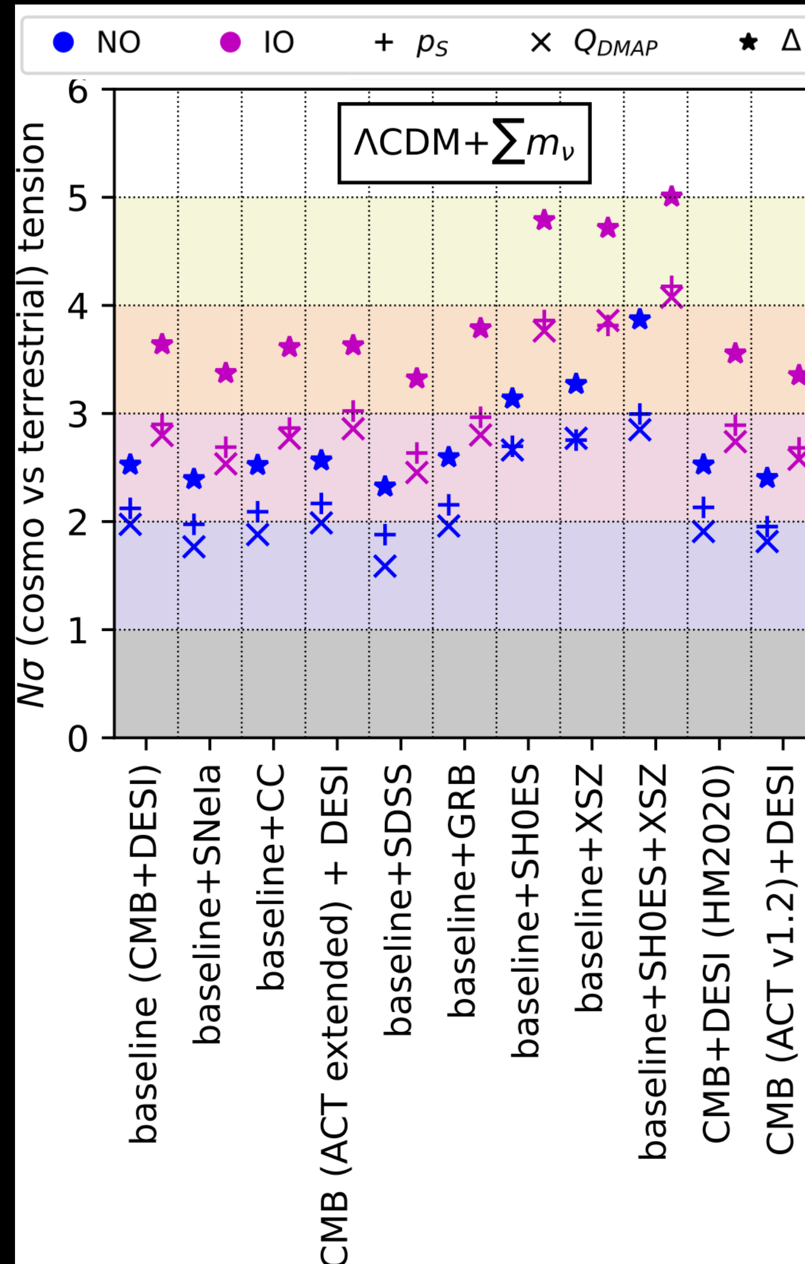
By setting the lightest neutrino mass to zero, we can determine the lower bounds on the total neutrino mass for the normal or inverted ordering:

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

Consequences? Neutrino mass tension

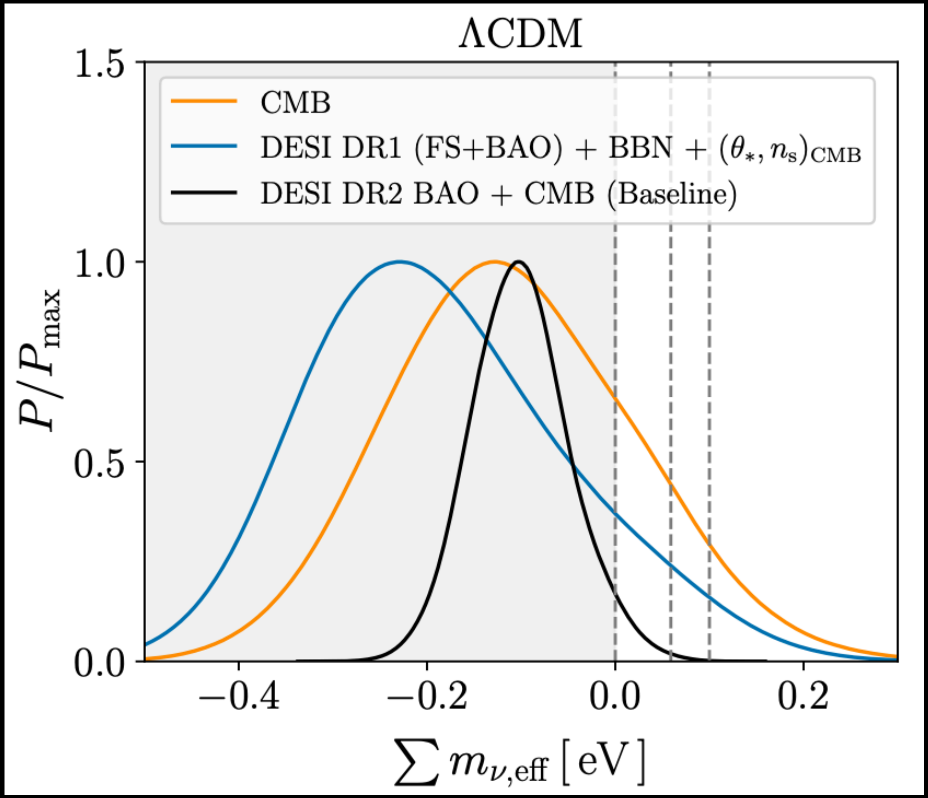
Dataset combination	ΛCDM+$\sum m_\nu$	
	$\sum m_\nu$ (eV)	$B_{\mathrm{NO,IO}}$
baseline (CMB + DESI)	< 0.072	8.1
baseline + SNeIa	< 0.081	7.0
baseline + CC	< 0.073	7.3
baseline + SDSS	< 0.083	6.8
baseline + SH0ES	< 0.048	47.8
baseline + XSZ	< 0.050	46.5
baseline + GRB	< 0.072	8.7
aggressive combination (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}]	$\sum m_{\nu,eff}$ [eV]
ΛCDM+$\sum m_{\nu,eff}$			
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

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Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 5 May 2025]

Baryon Acoustic Oscillations from a Different Angle

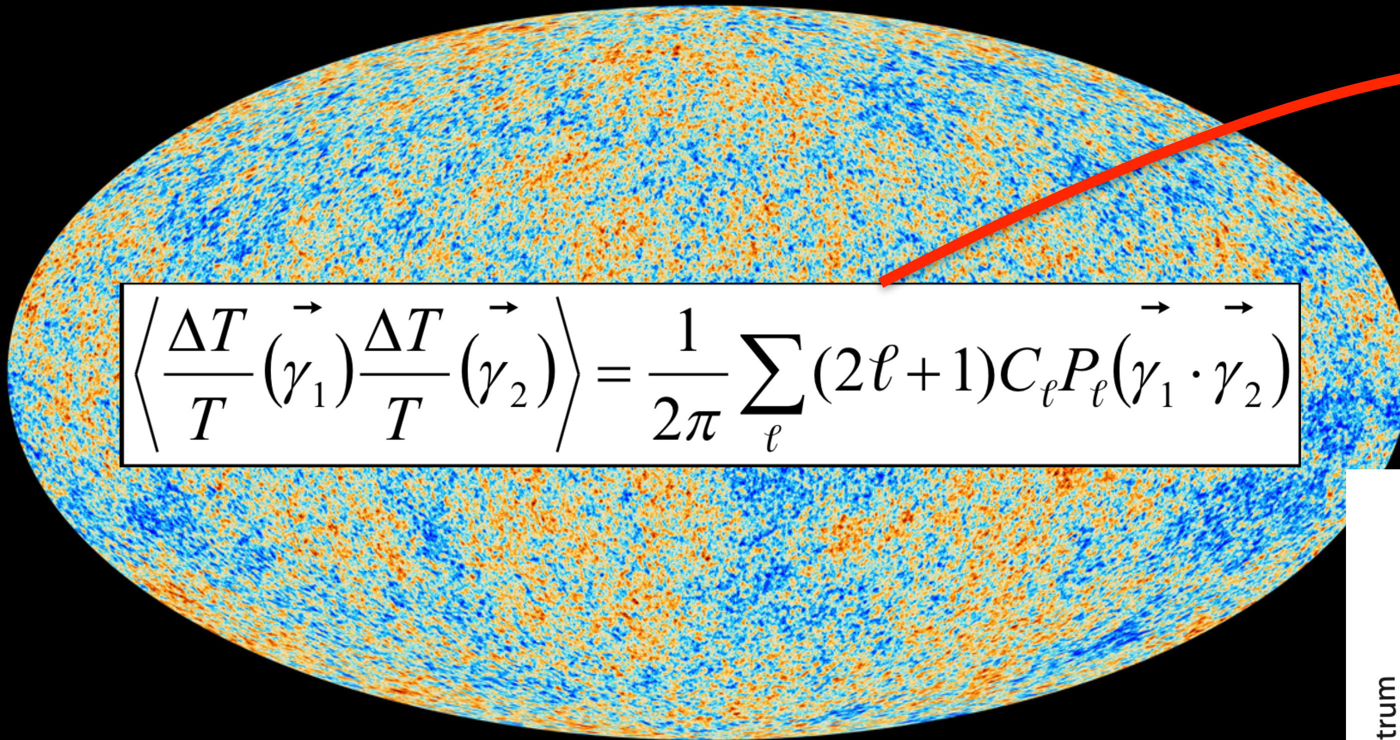
George Efstathiou

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.

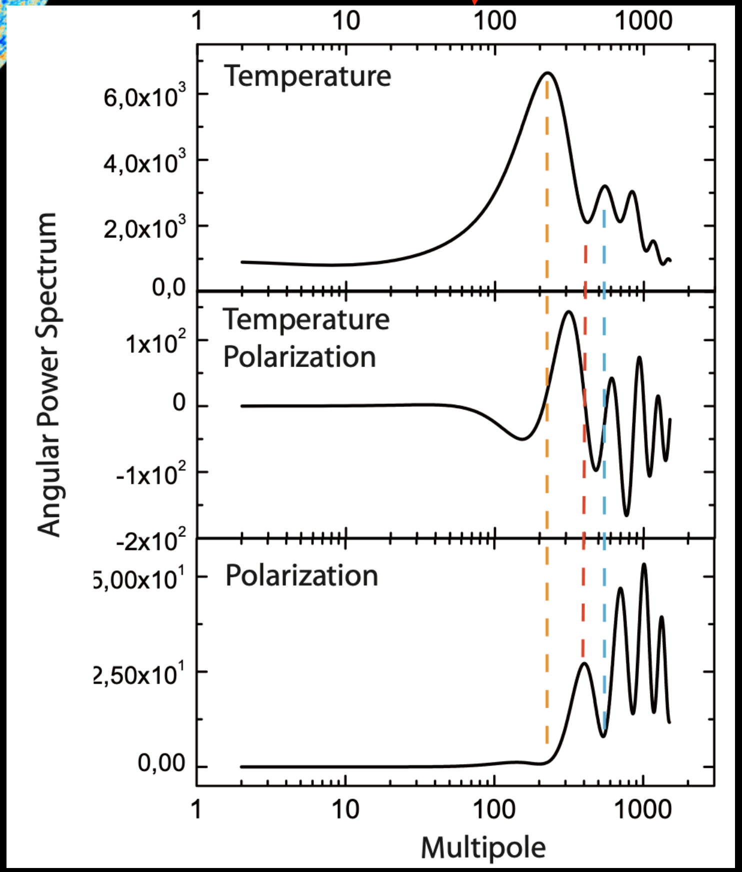
There is a selection bias in our community:
we tend to trust data only when they agree with Planck ΛCDM.

What about the CMB problems?

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



$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$

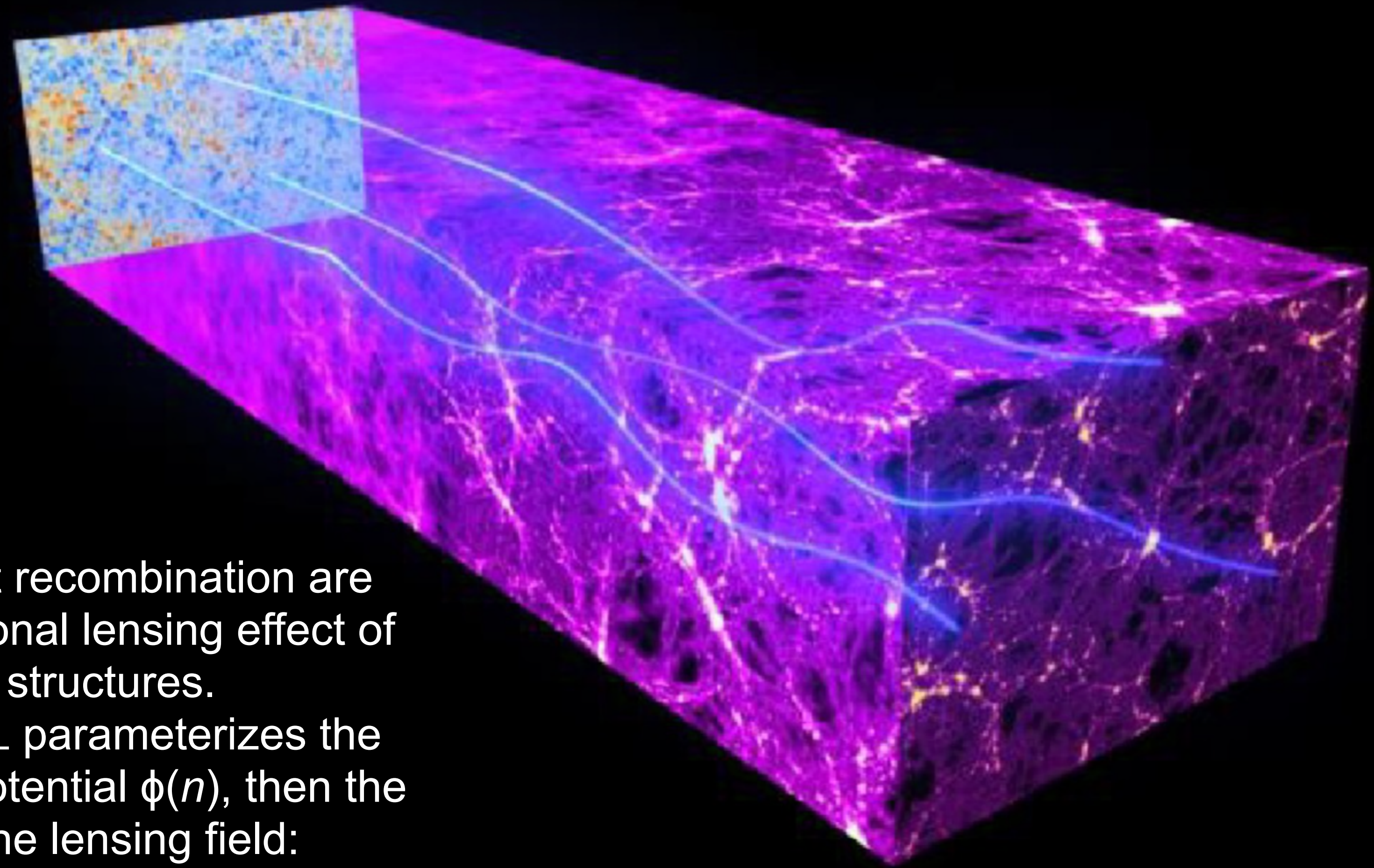


Borstnik et al., hep-ph/0401043

We can extract 4 independent angular spectra from the CMB:

- Temperature
- Cross Temperature Polarization E
- Polarization type E (density fluctuations)
- Polarization type B (gravitational waves)

Plik PR3 A_L problem



CMB photons emitted at recombination are deflected by the gravitational lensing effect of massive cosmic structures.
The lensing amplitude A_L parameterizes the rescaling of the lensing potential ϕ(*n*), then the power spectrum of the lensing field:

$$C_\ell^{\phi\phi} \rightarrow A_\mathrm{L} C_\ell^{\phi\phi}$$

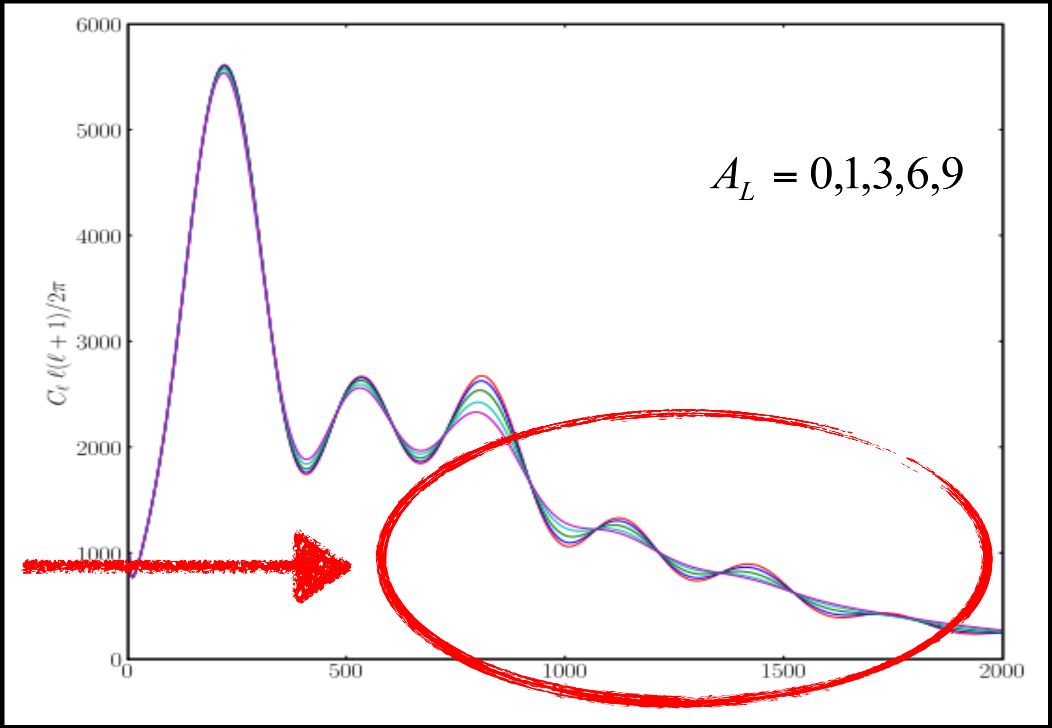
The gravitational lensing deflects the photon path by a quantity defined by the gradient of the lensing potential ϕ(*n*), integrated along the line of sight *n*, remapping the temperature field.

Plik PR3 A_L problem

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.

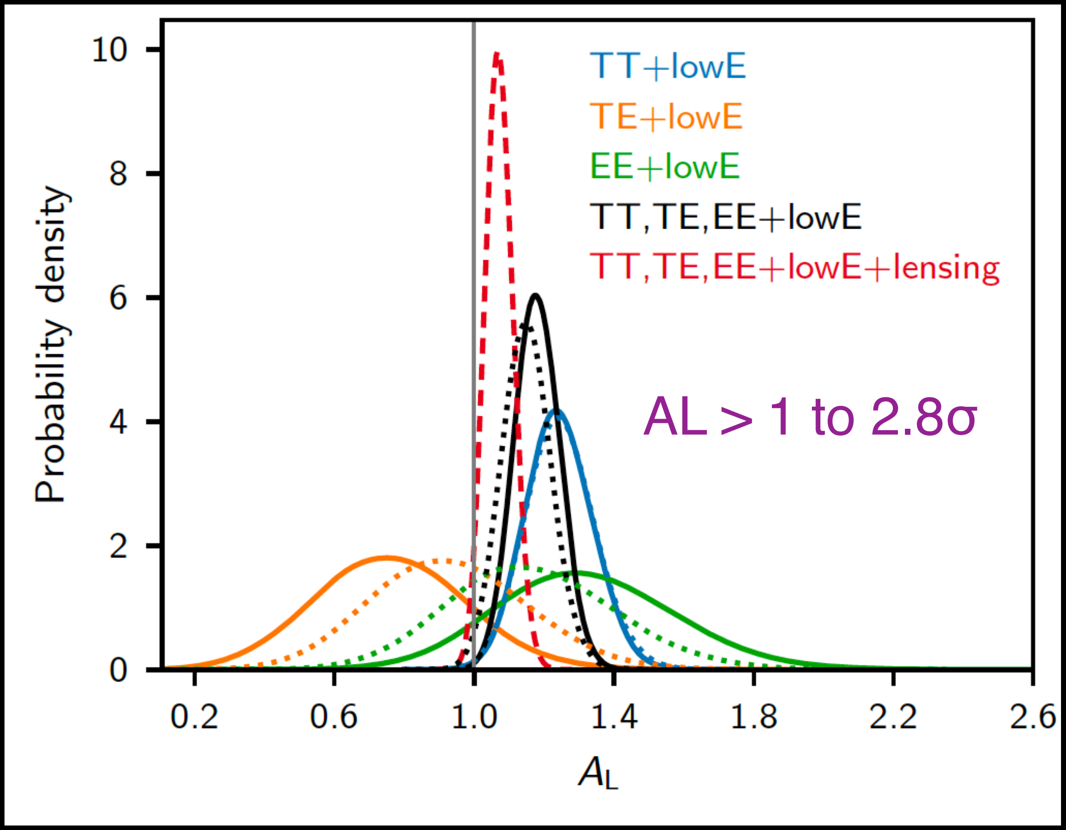
If AL =1 then the theory is correct, otherwise we have a new physics or systematics.



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

Plik PR3 A_L problem

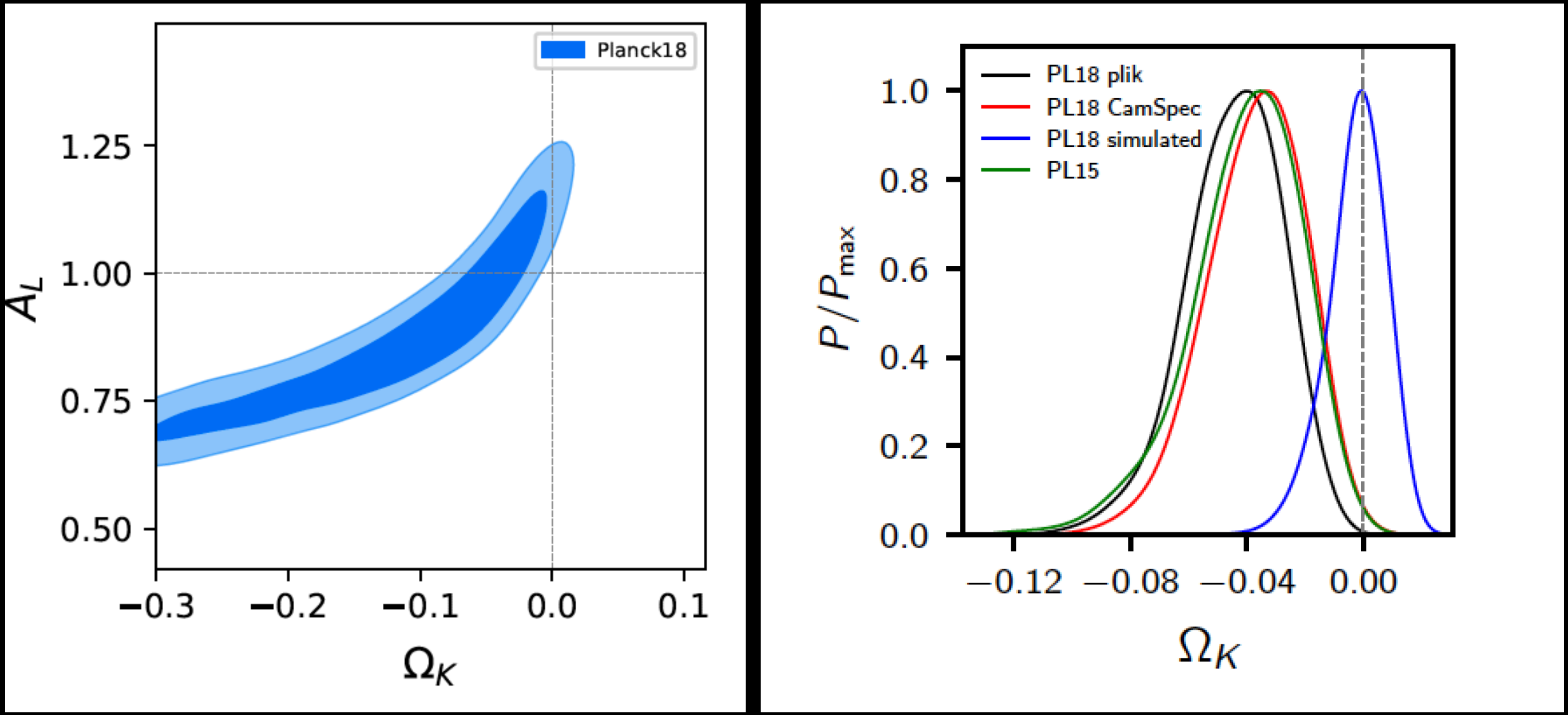
Planck 2018, Astron.Astrophys. 641 (2020) A6



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

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

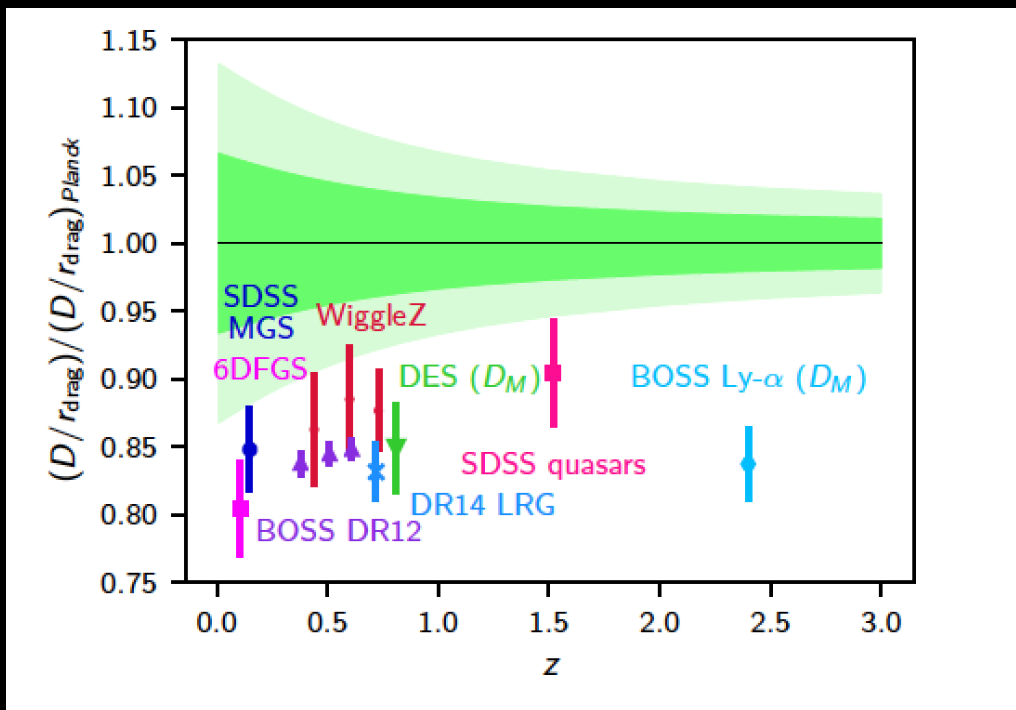
This excess of lensing affects the constraints on the curvature of the universe:

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

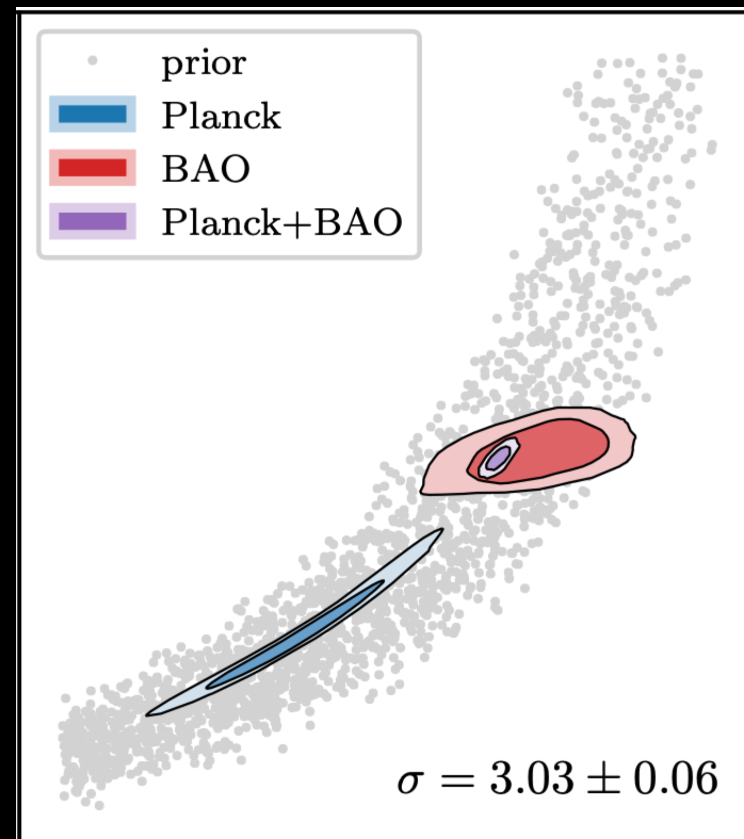
Planck 2018, Astron.Astrophys. 641 (2020) A6

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

Plik PR3 - SDSS tension in kΛCDM



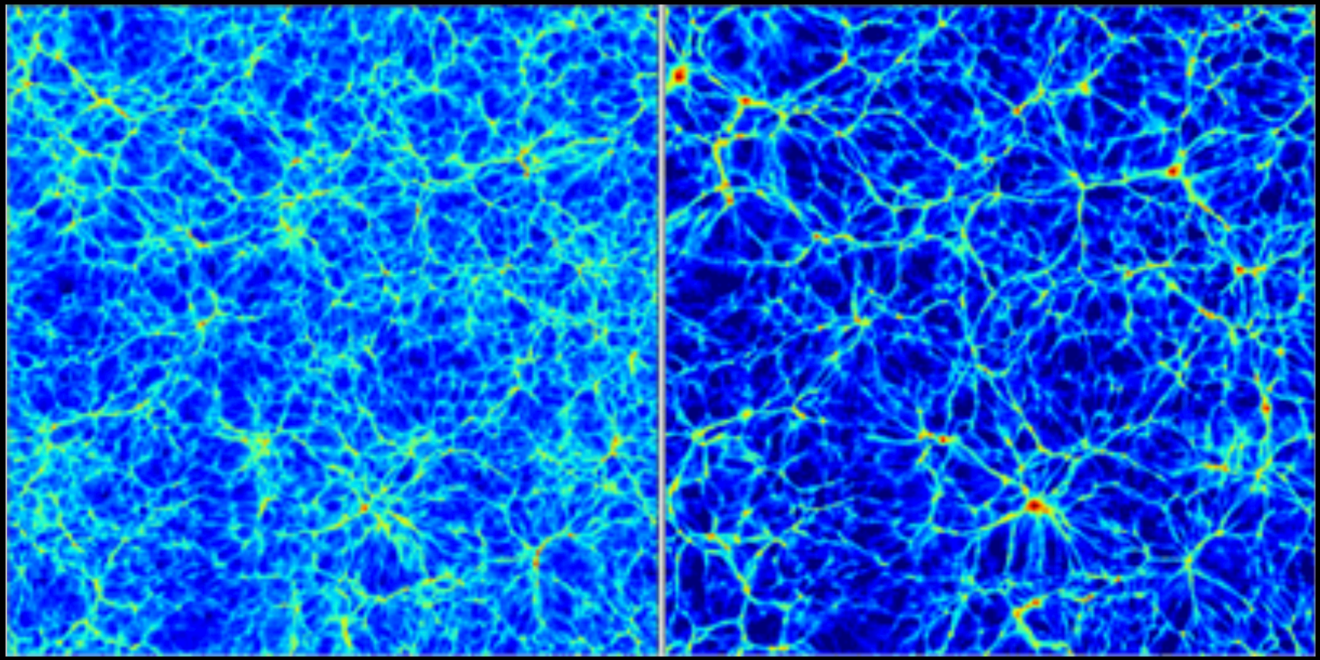
Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203



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

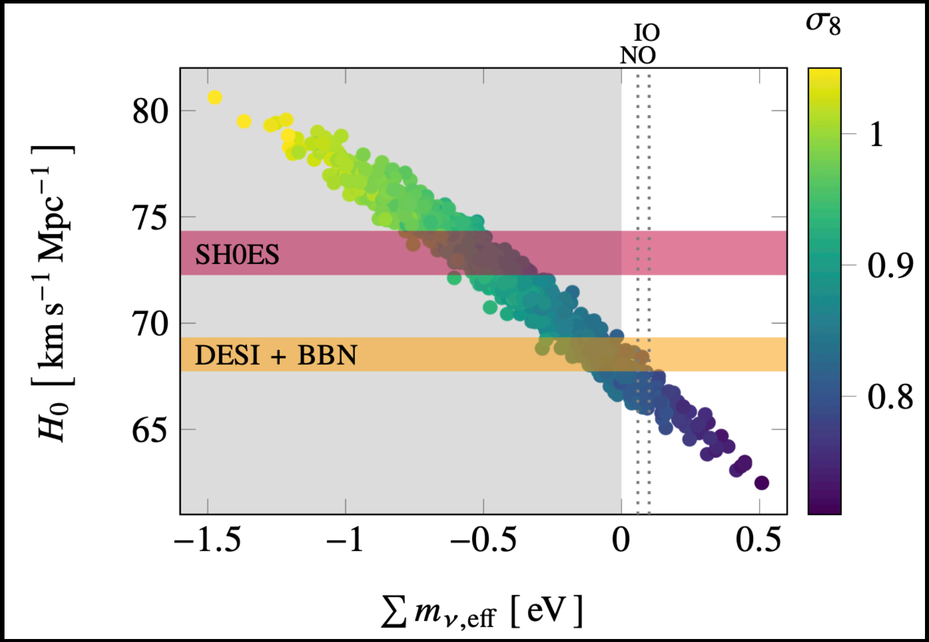
Allowing curvature to vary reveals a significant disagreement between the Planck spectra and BAO data.

The total neutrino mass and CMB lensing

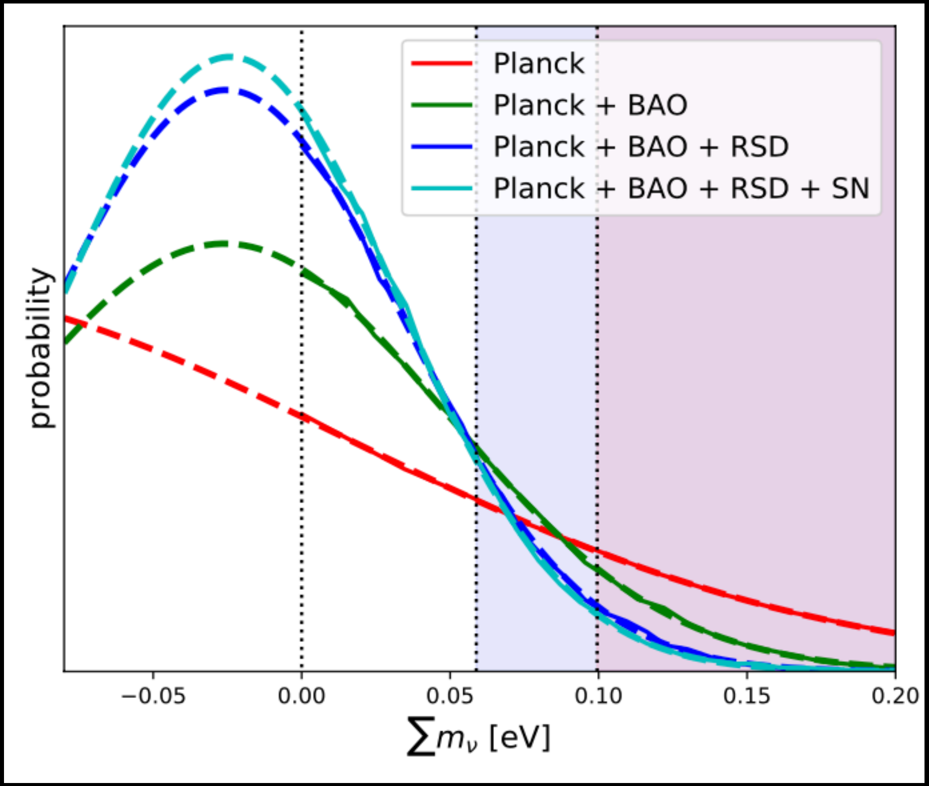


Given that massive neutrinos practically do not form structure,
more massive the neutrino is less structure we have, less the CMB lensing will be.
So a larger signal of lensing means a smaller neutrino mass.

Negative total neutrino mass



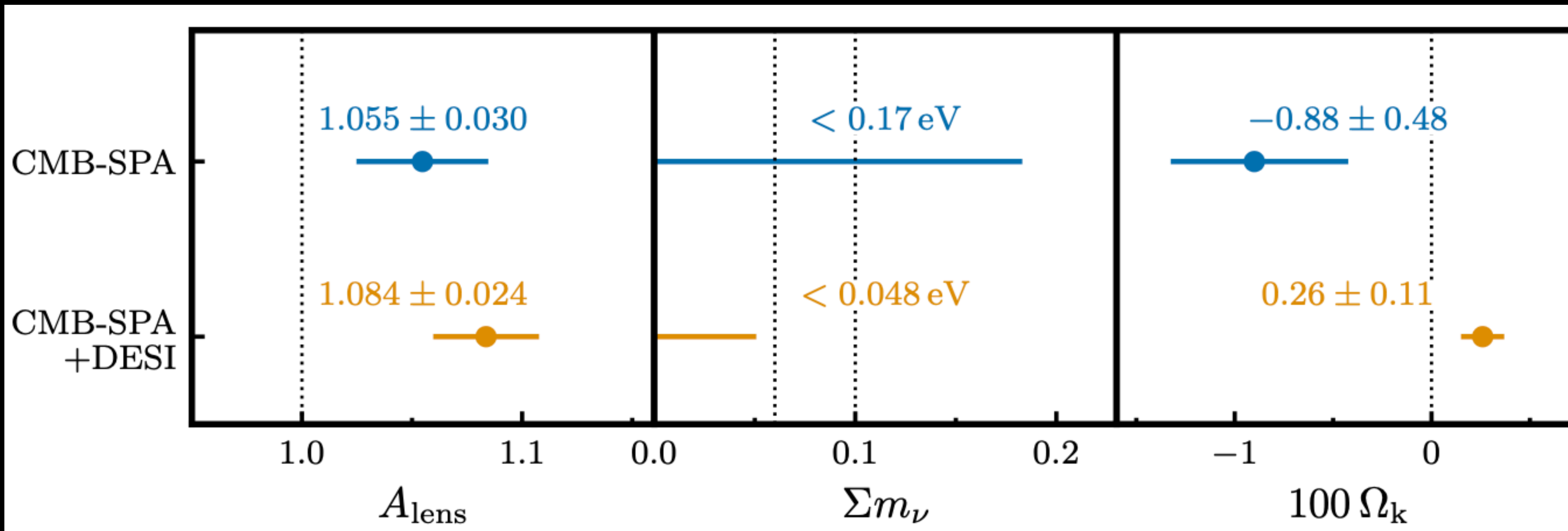
Elbers et al., arXiv: 2407.10965



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.

SPT A_L problem



$$A_{\rm lens} = 1.084 \pm 0.035 \text{ for SPT-3G D1} + \text{DESI}, \quad (74)$$
$$A_{\rm lens} = 1.092 \pm 0.026 \text{ for SPT+ACT} + \text{DESI}, \quad (75)$$
$$A_{\rm lens} = 1.084 \pm 0.024 \text{ for CMB-SPA} + \text{DESI}. \quad (76)$$

which are deviations from the standard model prediction of $2.4\,\sigma$, $3.5\,\sigma$, and $3.5\,\sigma$, respectively. We note that

SPT-3G D1, arXiv:2506.20707 [astro-ph.CO]

When adding DESI to SPT-3G D1 and CMB-SPA, we find at the 95% confidence level:

$$\Sigma m_\nu < 0.081\,\text{eV for SPT-3G D1} + \text{DESI}, \quad (96)$$
$$\Sigma m_\nu < 0.048\,\text{eV for CMB-SPA} + \text{DESI}. \quad (97)$$

The preference for a high AL is at the 3.5σ level without Planck, but when combining SPT with DESI. This leads to a very strong upper limit on the total neutrino mass and favors a non-flat universe.

What about Planck PR4 (NPIPE) with CamSpec?

arXiv > astro-ph > arXiv:2205.10869

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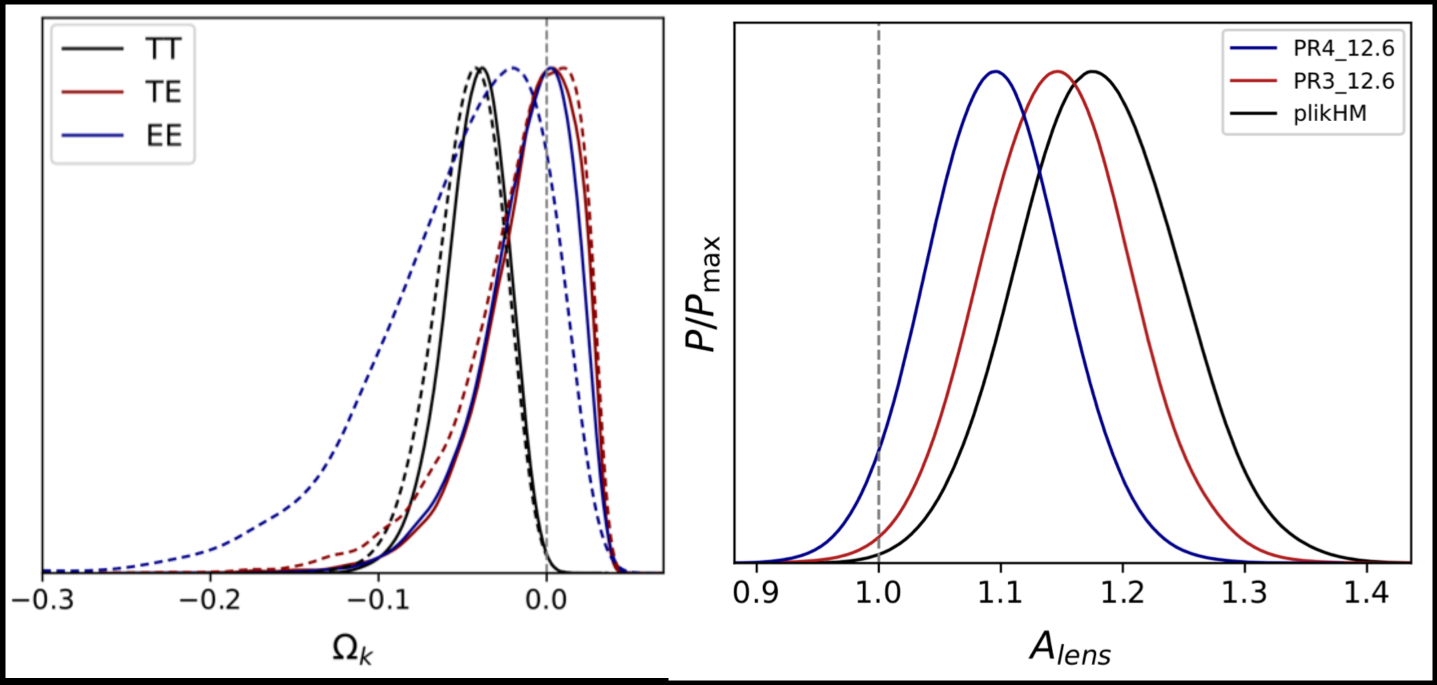
Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 22 May 2022 (v1), last revised 11 Nov 2022 (this version, v2)]

CMB power spectra and cosmological parameters from Planck PR4 with CamSpec

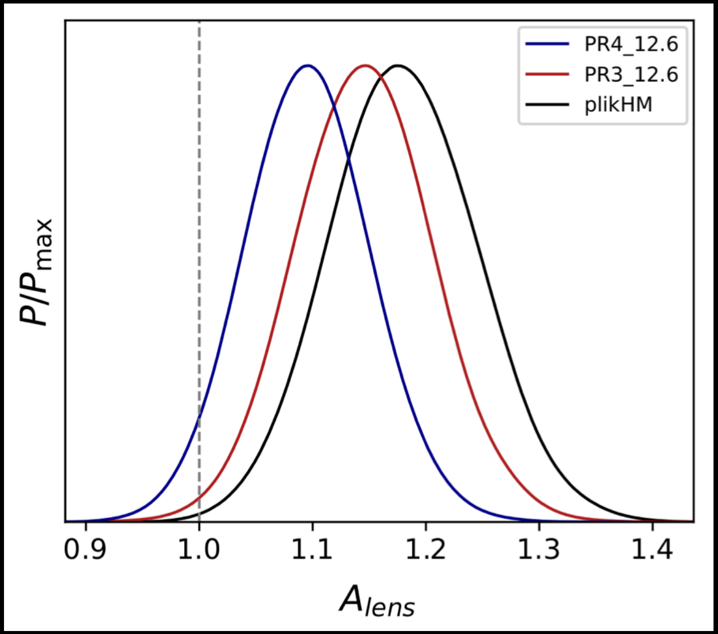
Erik Rosenberg, Steven Gratton, George Efstathiou

We present angular power spectra and cosmological parameter constraints derived from the Planck PR4 (NPIPE) maps of the Cosmic Microwave Background. NPIPE, released by the Planck Collaboration in 2020, is a new processing pipeline for producing calibrated frequency maps from Planck data. We have created new versions of the CamSpec likelihood using these maps and applied them to constrain LCDM and single-parameter extensions. We find excellent consistency between NPIPE and the Planck 2018 maps at the parameter level, showing that the Planck cosmology is robust to substantial changes in the mapmaking. The lower noise of NPIPE leads to ~10% tighter constraints, and we see both smaller error bars and a shift toward the LCDM values for beyond-LCDM parameters including Omega_K and A_Lens.

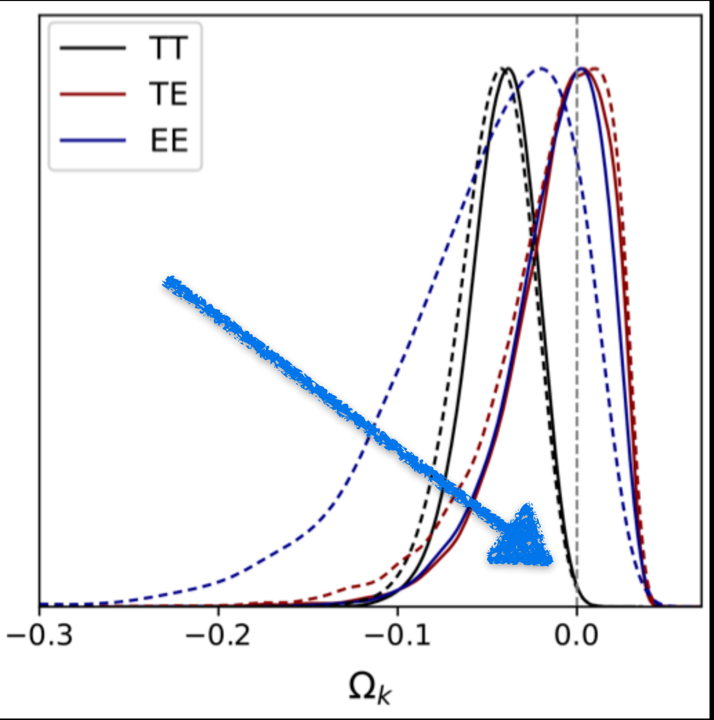


CamSpec PR4

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

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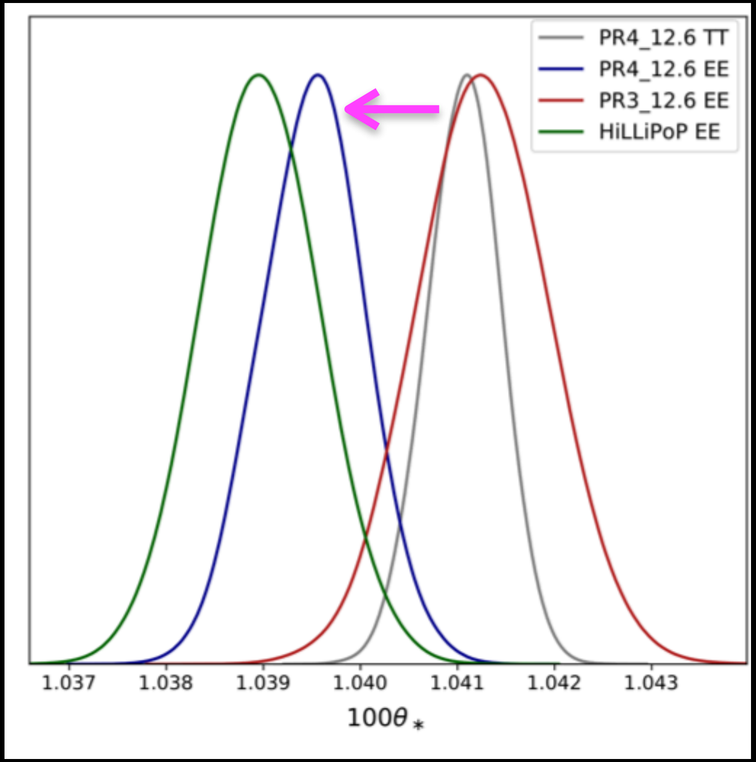


Rosenberg et al., arXiv:2205.10869

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

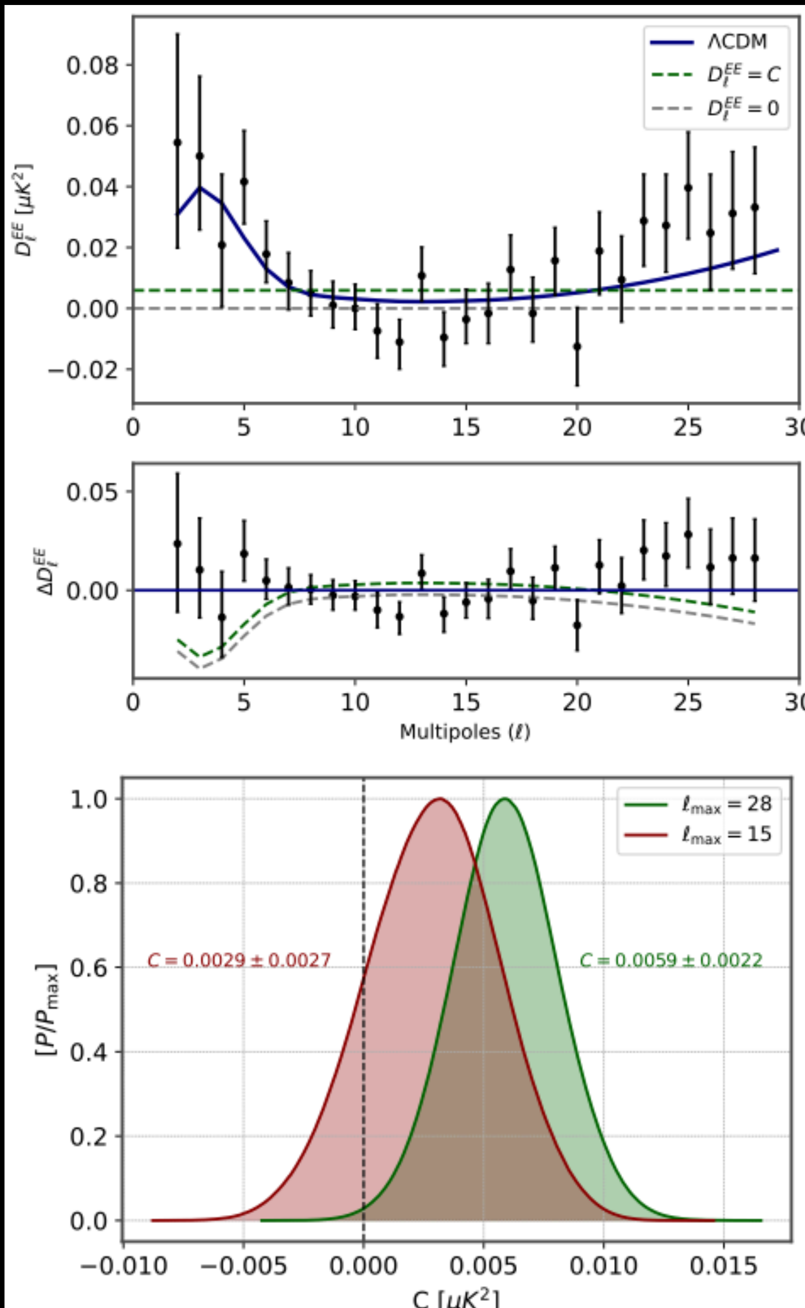
	ℓ range	N_D	$\hat{\chi}^2$	$(\hat{\chi}^2 - 1)/\sqrt{2/N_D}$
TT 143x143	30 – 2000	1971	1.021	0.67
TT 143x217	500 – 2500	2001	0.985	-0.47
TT 217x217	500 – 2500	2001	1.002	0.05
TT All	30 – 2500	5973	1.074	4.07
TE	30 – 2000	1971	1.055	1.73
EE	30 – 2000	1971	1.026	0.82
TEEE	20 – 2000	3942	1.046	2.02
TTTEEE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

The role of the optical depth



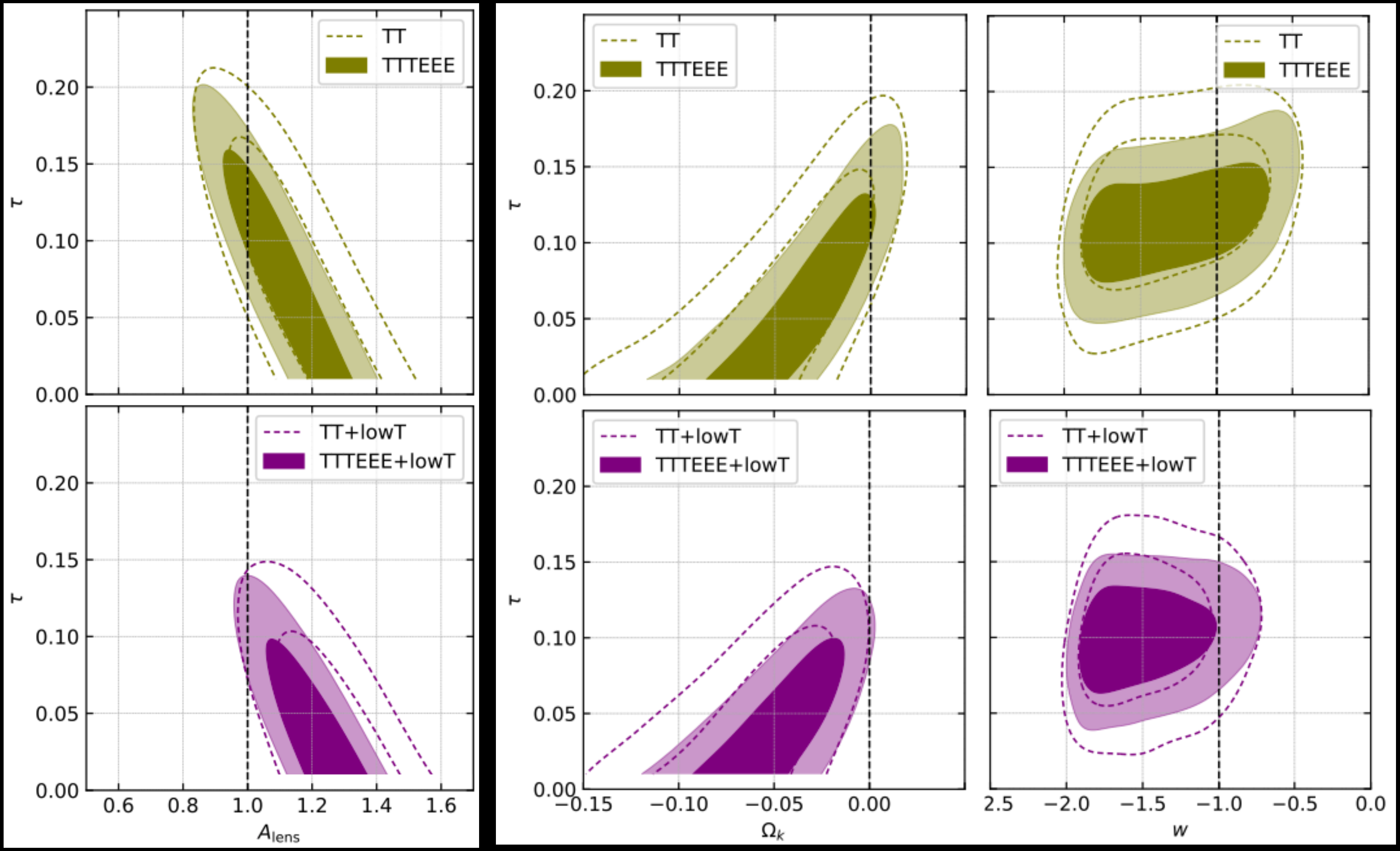
$$C_\ell^{EE} \propto \tau^2/\ell^4$$

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.

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

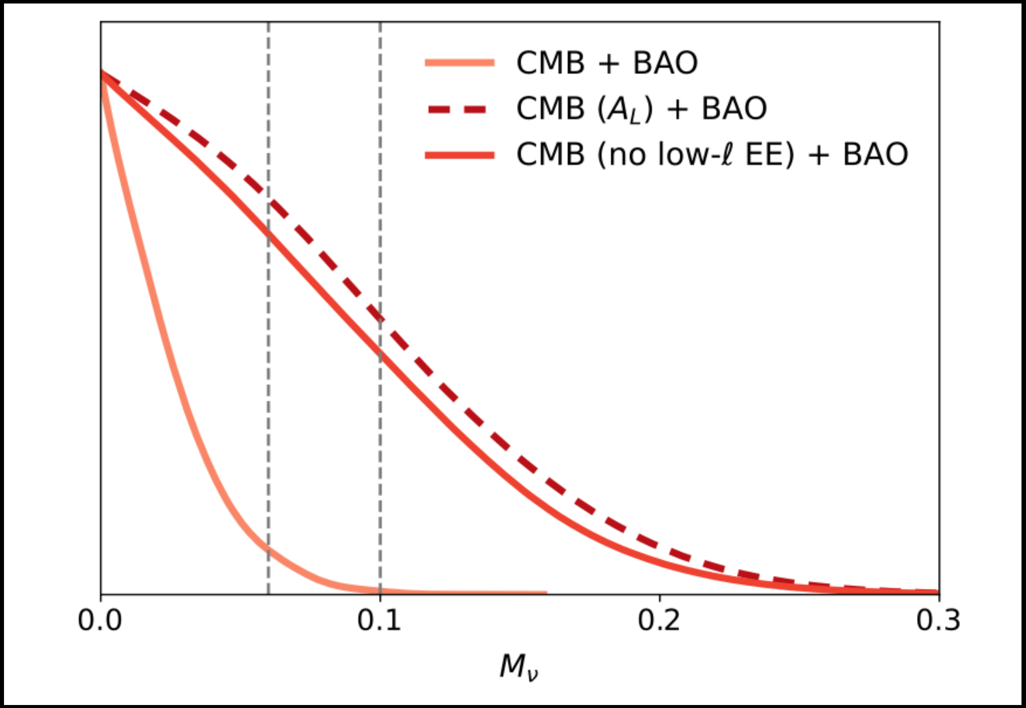
The role of the optical depth



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

The role of the optical depth



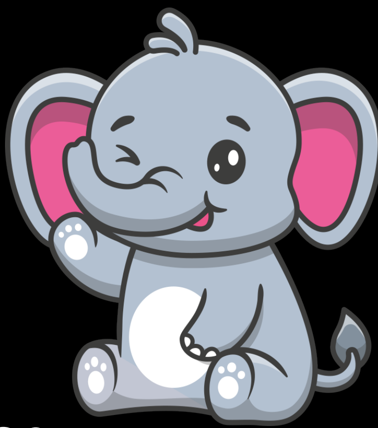
Jhaveri et al., arXiv:2504.21813

In the CMB TT spectrum, massive neutrinos suppress small-scale power, which can be compensated by increasing the optical depth τ.
Since TT measures $A_s e^{-2\tau}$, raising τ requires raising As, but As also controls structure growth, that is entangled with Σmν effects.
This degeneracy means CMB-only data allow biased Σmν values; low-ℓ polarization is essential to pin down τ and break the degeneracy.

The apparent CMB+BAO preference for negative neutrino masses could be an artifact of the τ–Σmν degeneracy.
Allowing either a free lensing amplitude AL or dropping low-ℓ EE τ constraints both restore consistency with minimal neutrino masses.
In other words: the “negative neutrino mass” problem disappears if τ is allowed to rise, highlighting that τ systematics strongly impact cosmological neutrino mass bounds.

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.

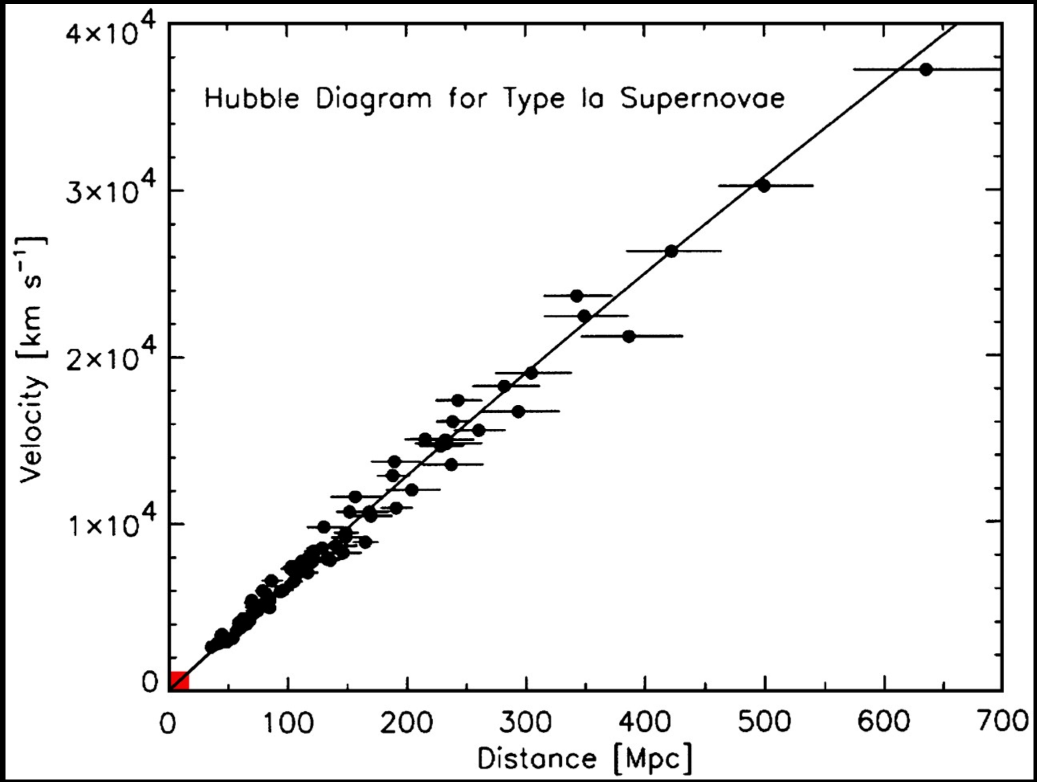
This can be obtained in two ways:

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.

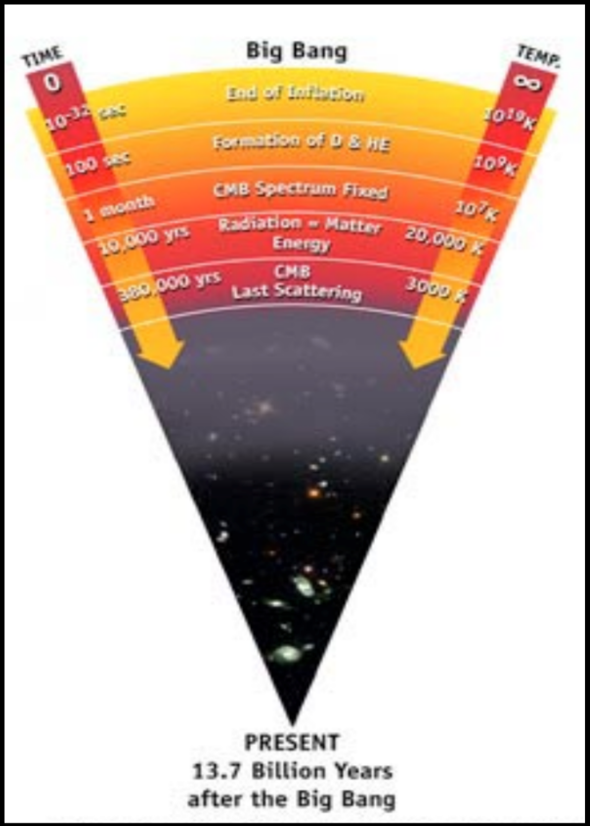
This can be obtained in two ways:

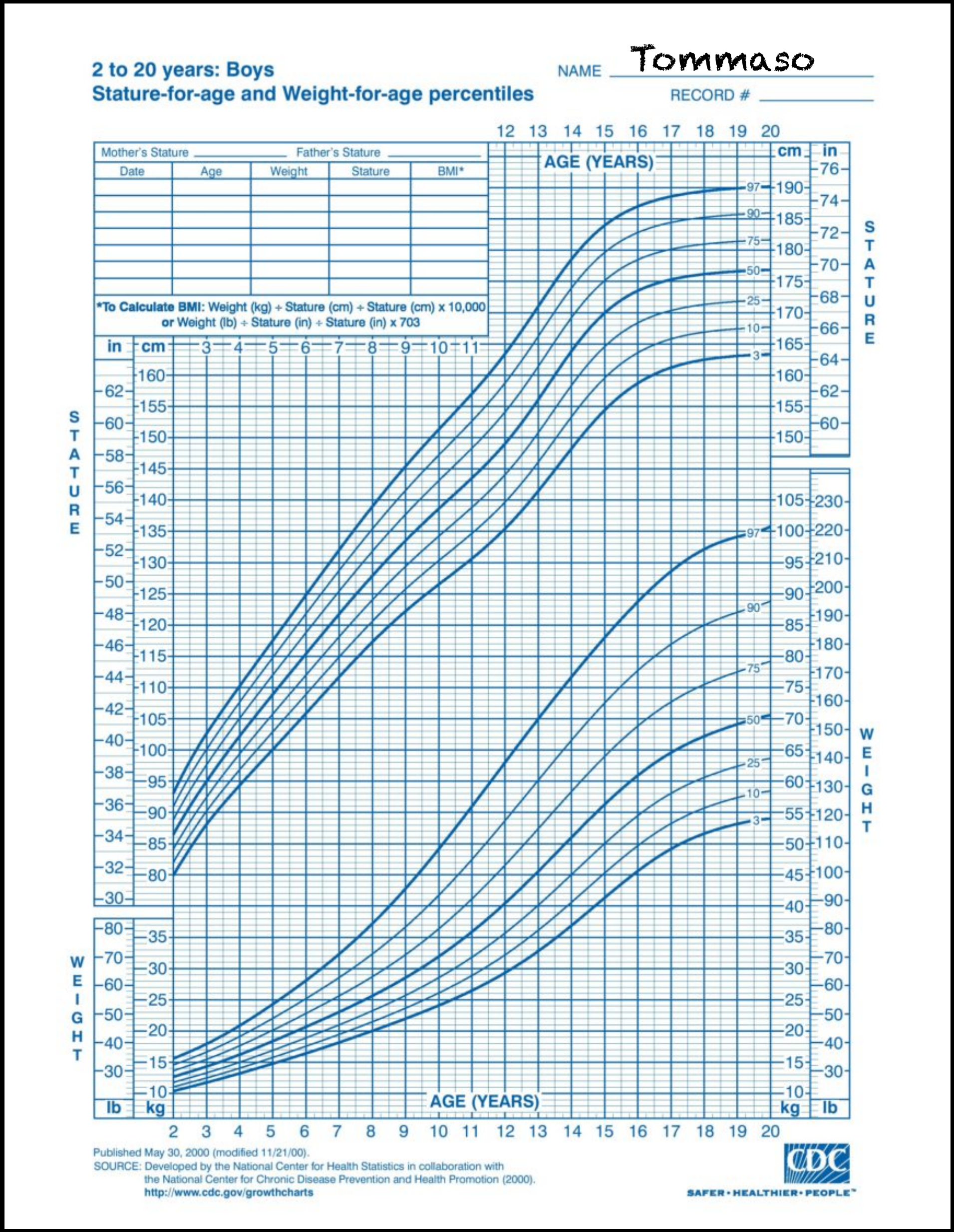
1. measuring the luminosity distance and the recessional velocity of known galaxies, and computing the proportionality factor.
2. considering early universe measurements, and assuming a model for the expansion history of the universe.

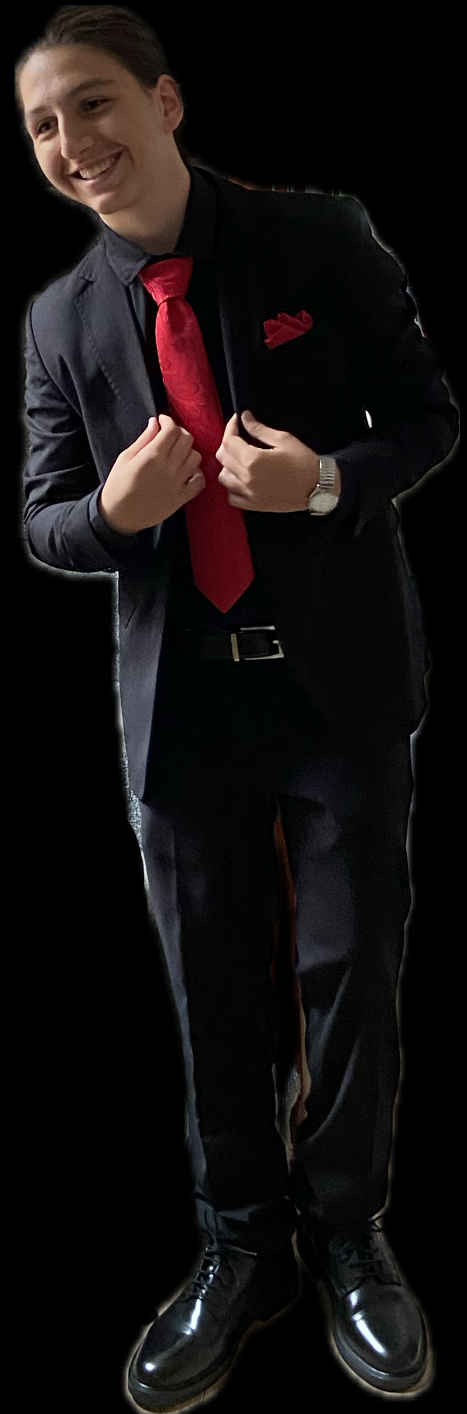
For example, we have CMB measurements and we assume the standard model of cosmology, i.e. the ΛCDM scenario.

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™

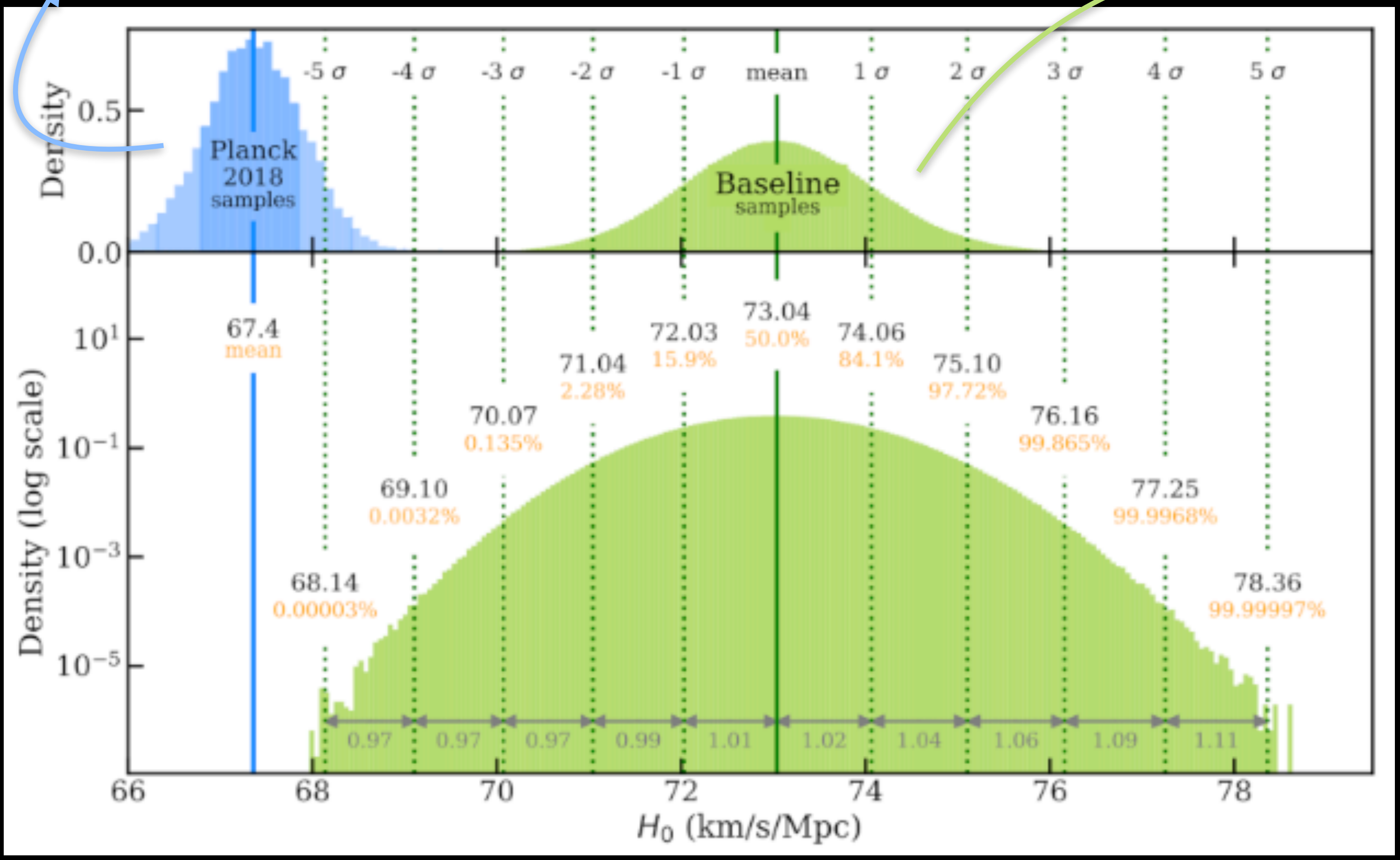


H0 tension

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

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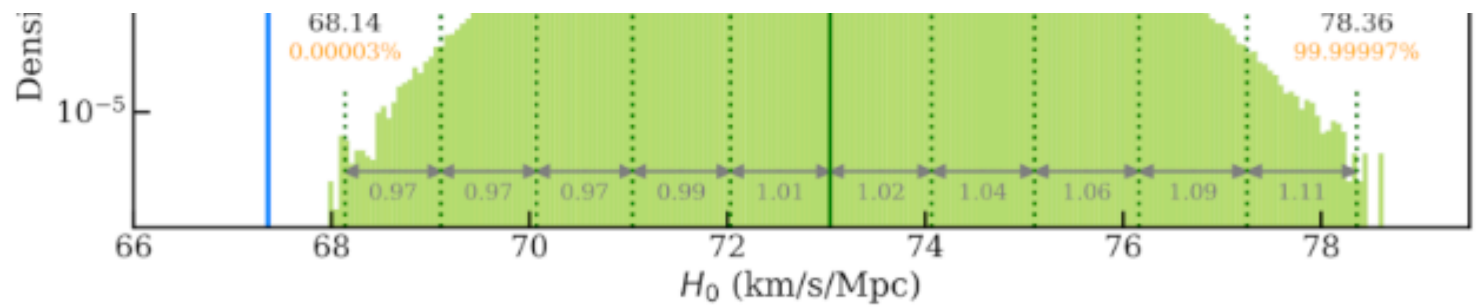
Astrophysics > Cosmology and Nongalactic Astrophysics

[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

H0 tension

arXiv > astro-ph > arXiv:2506.20707

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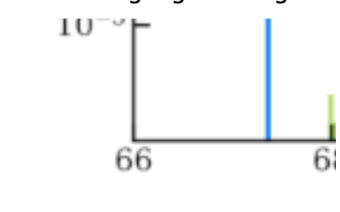
Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 25 Jun 2025]

SPT-3G D1: CMB temperature and polarization power spectra and cosmology from 2019 and 2020 observations of the SPT-3G Main field

E. Camphuis, W. Quan, L. Balkenhol, A. R. Khalife, F. Ge, F. Guidi, N. Huang, G. P. Lynch, Y. Omori, C. Trendafilova, A. J. Anderson, B. Ansarinejad, M. Archipley, P. S. Barry, K. Benabed, A. N. Bender, B. A. Benson, F. Bianchini, L. E. Bleem, F. R. Bouchet, L. Bryant, M. G. Campitiello, J. E. Carlstrom, C. L. Chang, P. Chaubal, P. M. Chichura, A. Chokshi, T.-L. Chou, A. Coerver, T. M. Crawford, C. Daley, T. de Haan, K. R. Dibert, M. A. Dobbs, M. Doohan, A. Doussot, D. Dutcher, W. Everett, C. Feng, K. R. Ferguson, K. Fichman, A. Foster, S. Galli, A. E. Gambrel, R. W. Gardner, N. Goeckner-Wald, R. Gualtieri, S. Guns, N. W. Halverson, E. Hivon, G. P. Holder, W. L. Holzapfel, J. C. Hood, A. Hryciuk, F. Kéruzoré, L. Knox, M. Korman, K. Kornoelje, C.-L. Kuo, K. Levy, A. E. Lowitz, C. Lu, A. Maniyar, E. S. Martsen, F. Menanteau, M. Millea, J. Montgomery, Y. Nakato, T. Natoli, G. I. Noble, A. Ouellette, Z. Pan, P. Paschos, K. A. Phadke, A. W. Pollak, K. Prabhu, S. Raghunathan, M. Rahimi, A. Rahlin, C. L. Reichardt, M. Rouble, J. E. Ruhl, E. Schiappucci, A. Simpson, J. A. Sobrin, A. A. Stark, J. Stephen, C. Tandoi, B. Thorne, C. Umilta, J. D. Vieira, A. Vitrier, Y. Wan, N. Whitehorn, W. L. K. Wu, M. R. Young, J. A. Zebrowski

We present measurements of the temperature and E-mode polarization angular power spectra of the cosmic microwave background (CMB) from observations of 4% of the sky with SPT-3G, the current camera on the South Pole Telescope (SPT). The maps used in this analysis are the deepest used in a CMB TT/TE/EE analysis to date. The maps and resulting power spectra have been validated through blind and unblind tests. The measurements of the lensed EE and TE spectra are the most precise to date at l=1800-4000 and l=2200-4000, respectively. Combining our TT/TE/EE spectra with previously published SPT-3G CMB lensing results, we find parameters for the standard LCDM model consistent with Planck and ACT-DR6 with comparable constraining power. We report a Hubble constant of $H_0 = 66.66 \pm 0.60$ km/s/Mpc from SPT-3G alone, 6.2 sigma away from local measurements from SH0ES. For the first time, combined ground-based (SPT+ACT) CMB primary and lensing data have reached Planck's constraining pow ... CMB constraints to date, with $H_0 = 67.24 \pm$ ... CDM; however, we observe a 2.8 sigma d ... ls. The combination of CMB and ... ion of state. It also drives mild preferenc ... universe. This work highlights the growi

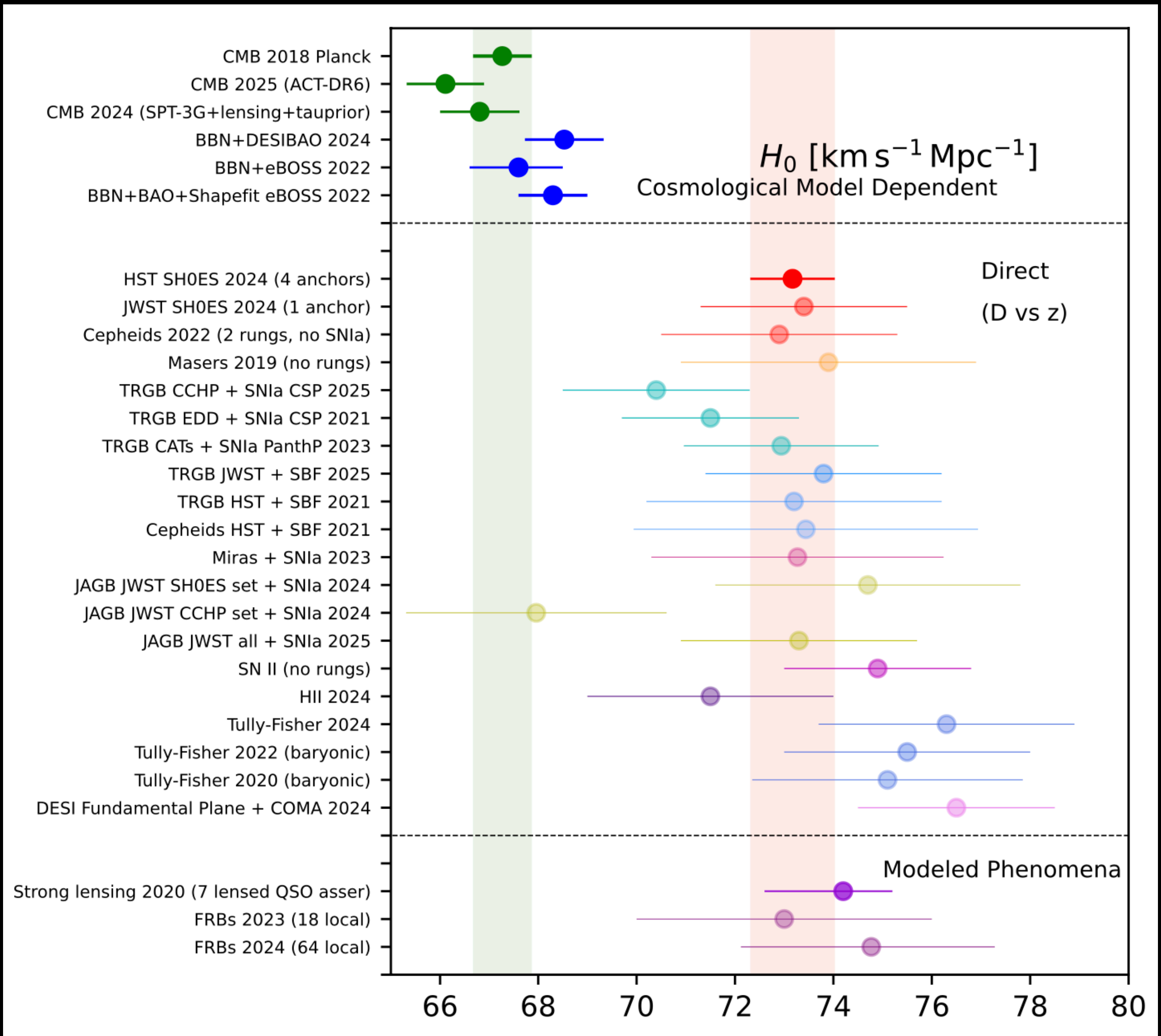


Parameter	*Planck*	SPT-3G D1	ACT DR6	SPT+ACT	SPT+*Planck*	CMB-SPA
Sampled						
$10^4\theta_s^\star$	104.184 ± 0.029	104.171 ± 0.060	104.157 ± 0.030	104.158 ± 0.025	04.176 ± 0.026	104.162 ± 0.023
$100\,\Omega_b h^2$	2.238 ± 0.014	2.221 ± 0.020	2.257 ± 0.016	2.247 [illegible]	230 ± 0.011	2.2381 ± 0.0093
$100\,\Omega_c h^2$	11.98 ± 0.11	12.14 ± 0.16	12.26 ± 0.17	[illegible]	050 ± 0.089	12.009 ± 0.086
n_s	0.9657 ± 0.0040	0.951 ± 0.011	0.9682 ± 0.0[illegible]	[illegible]	$.9636 \pm 0.0035$	0.9684 ± 0.0030
$\log(10^{10} A_s)$	3.042 ± 0.011	3.054 ± 0.015	3.038 ± 0.012	[illegible] ± 0.011	$.046 \pm 0.010$	3.0479 ± 0.0099
τ_{reio}	0.0535 ± 0.0056	0.0506 ± 0.0059	0.0513 ± 0.0060	0.0514 ± 0.0059	$.0538 \pm 0.0054$	0.0559 ± 0.0055
Derived						
H_0 [km/s/Mpc]	67.41 ± 0.49	66.66 ± 0.60	66.51 ± 0.64	66.59 ± 0.46	7.07 ± 0.38	67.24 ± 0.35

6.7 sigma

Are there other H0 estimates?

Latest H0 measurements



CosmoVerse network, Di Valentino et al., Phys.Dark Univ. 49 (2025) 101965

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

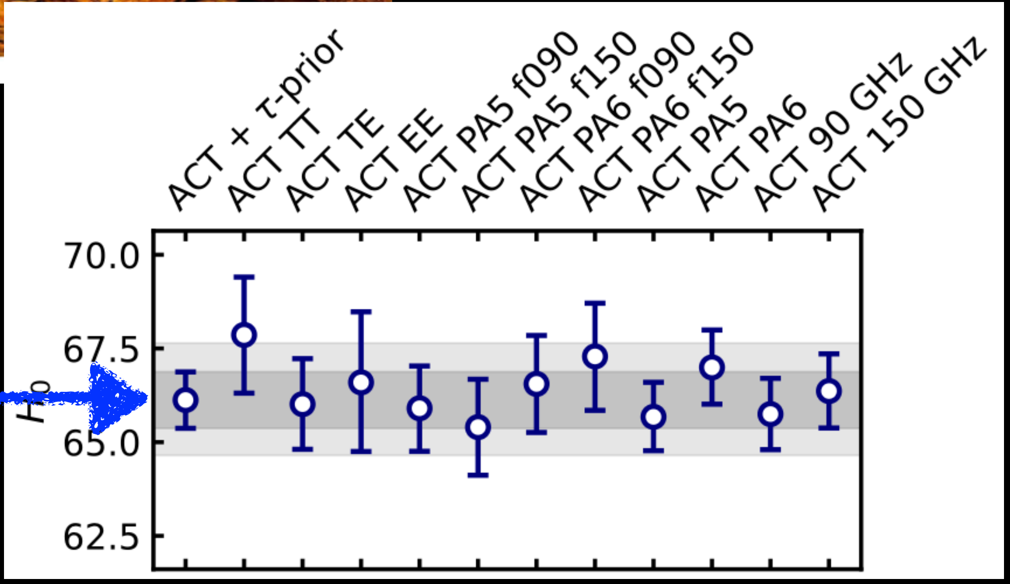
The red vertical band corresponds to the H0 value from SH0ES Team and the grey vertical band corresponds to the H0 value as reported by Planck 2018 team within a ΛCDM scenario.

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

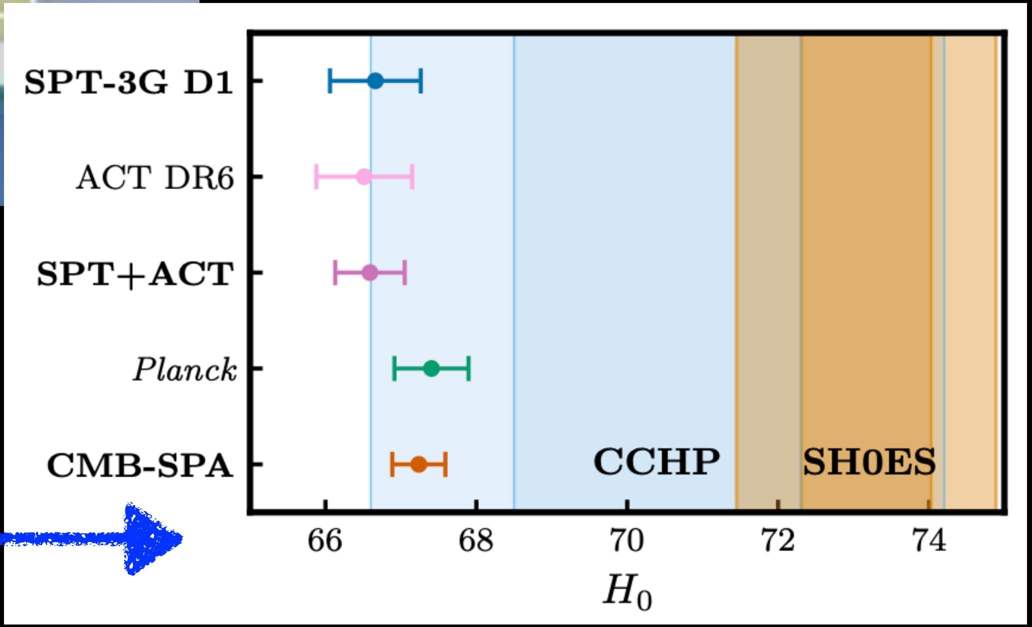


ACT-DR6, arXiv:2503.14452 [astro-ph.CO]

ΛCDM - dependent

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

Ground based CMB telescope



SPT-3G D1:
H0 = 66.66 ± 0.60 km/s/Mpc in ΛCDM

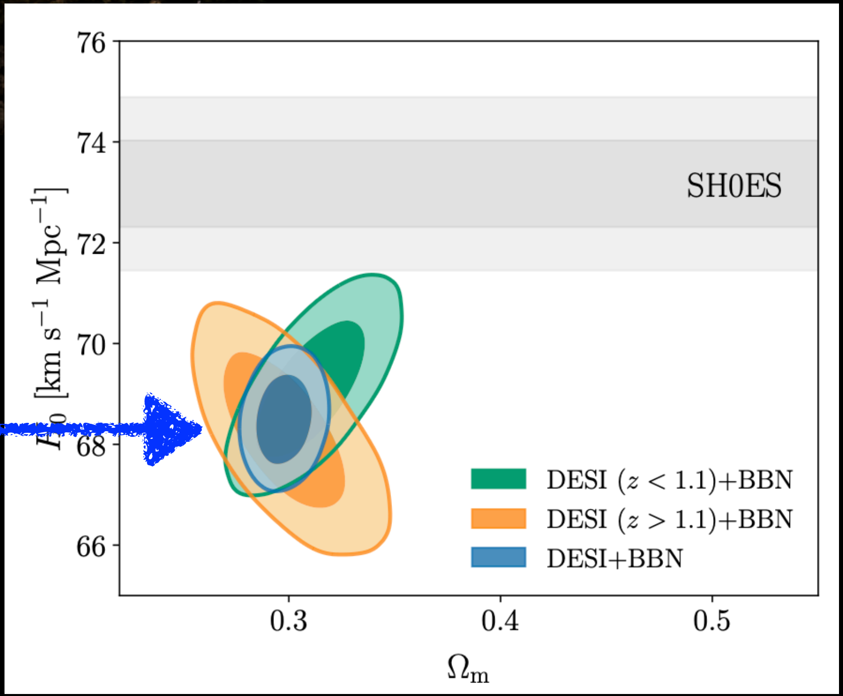
ΛCDM - dependent

SPT-3G D1, arXiv:2506.20707 [astro-ph.CO]

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

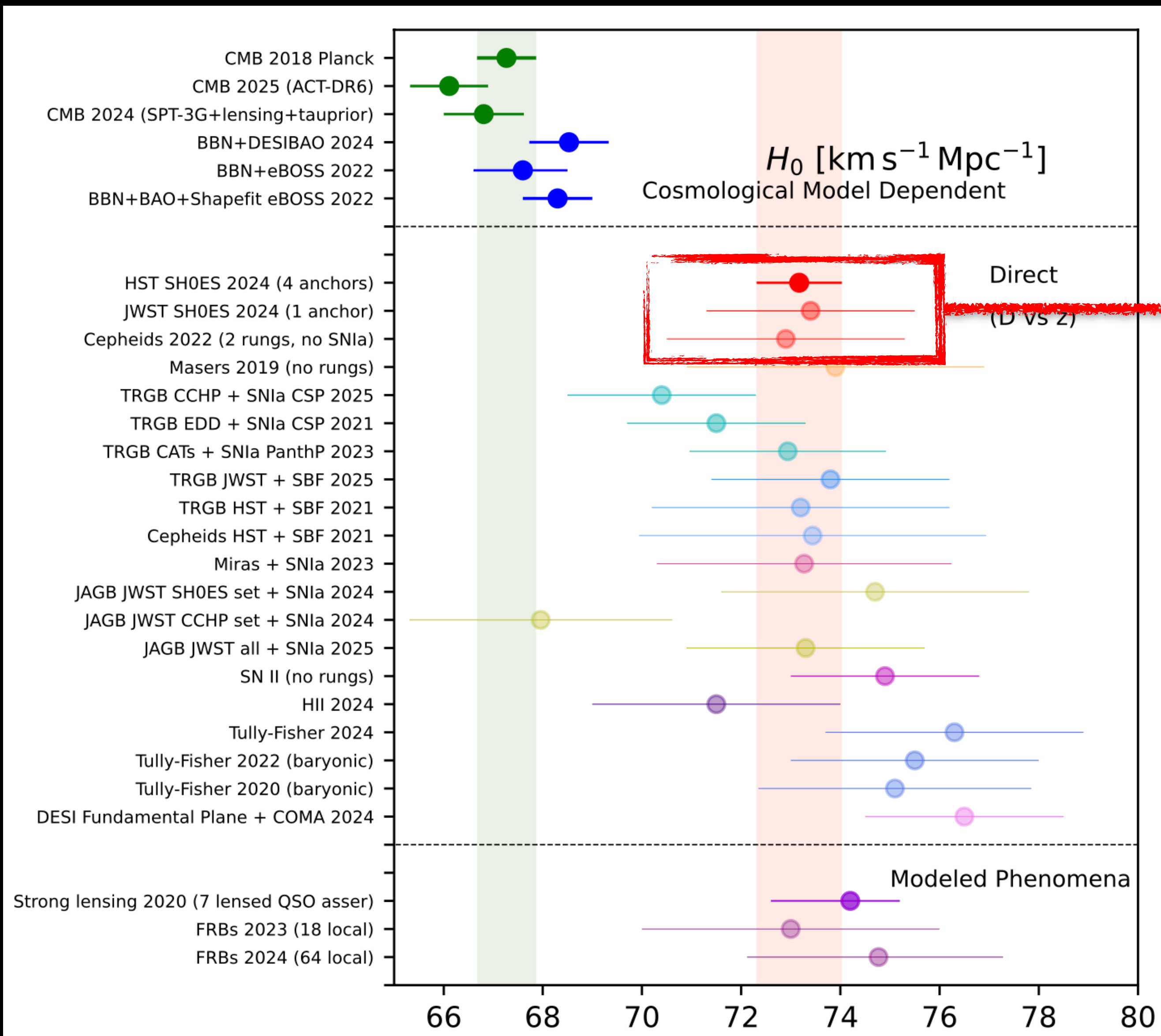
DESI+BBN:
H0 = 68.51 ± 0.58 km/s/Mpc in ΛCDM



ΛCDM - dependent

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

Latest H0 measurements



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

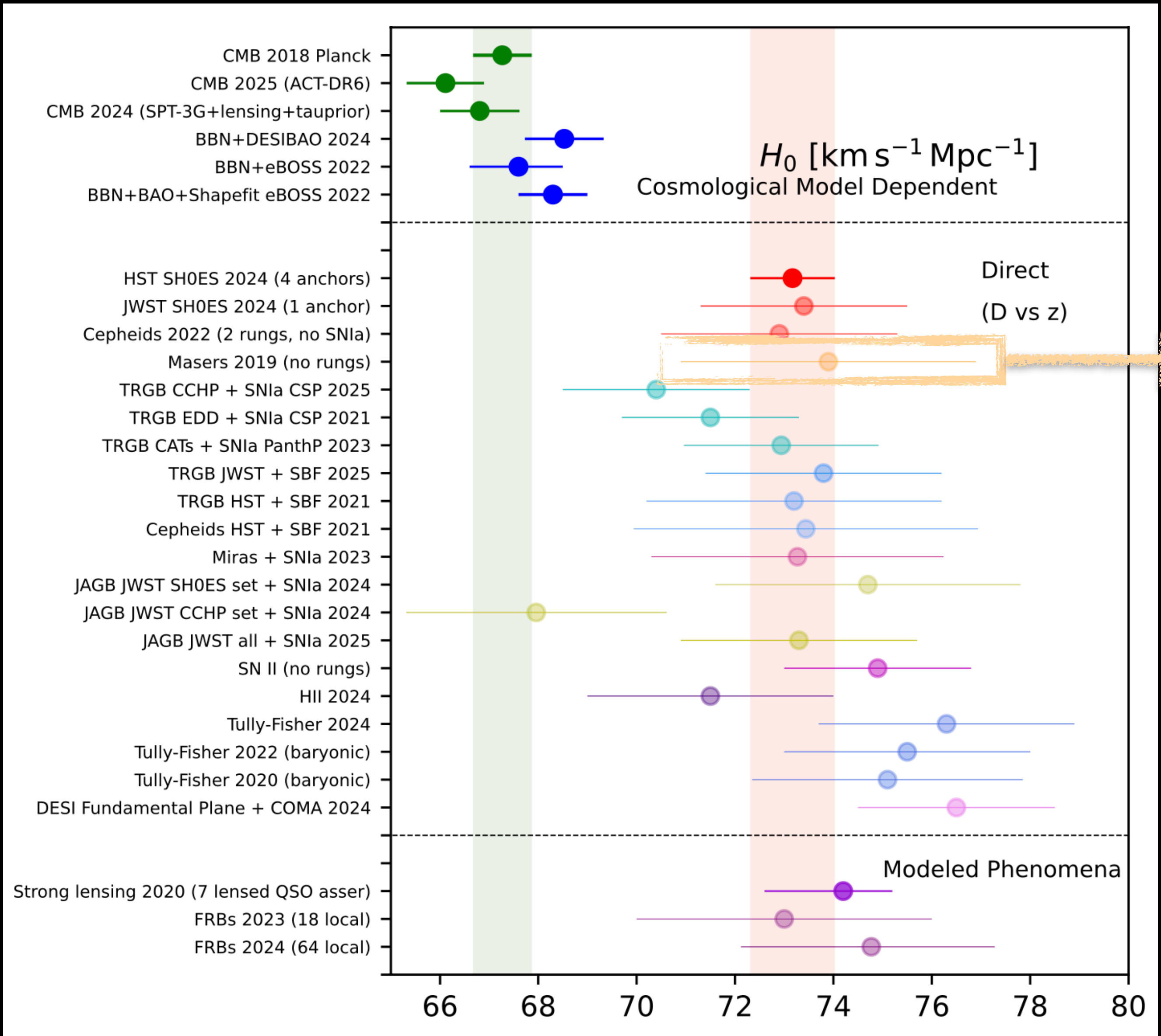
Breuval et al., arXiv:*2404.08038*

H0 = 72.9 ± 2.4 km/s/Mpc

Kenworthy et al., arXiv:2204.10866

CosmoVerse network, Di Valentino et al., Phys.Dark Univ. 49 (2025) 101965

Latest H0 measurements



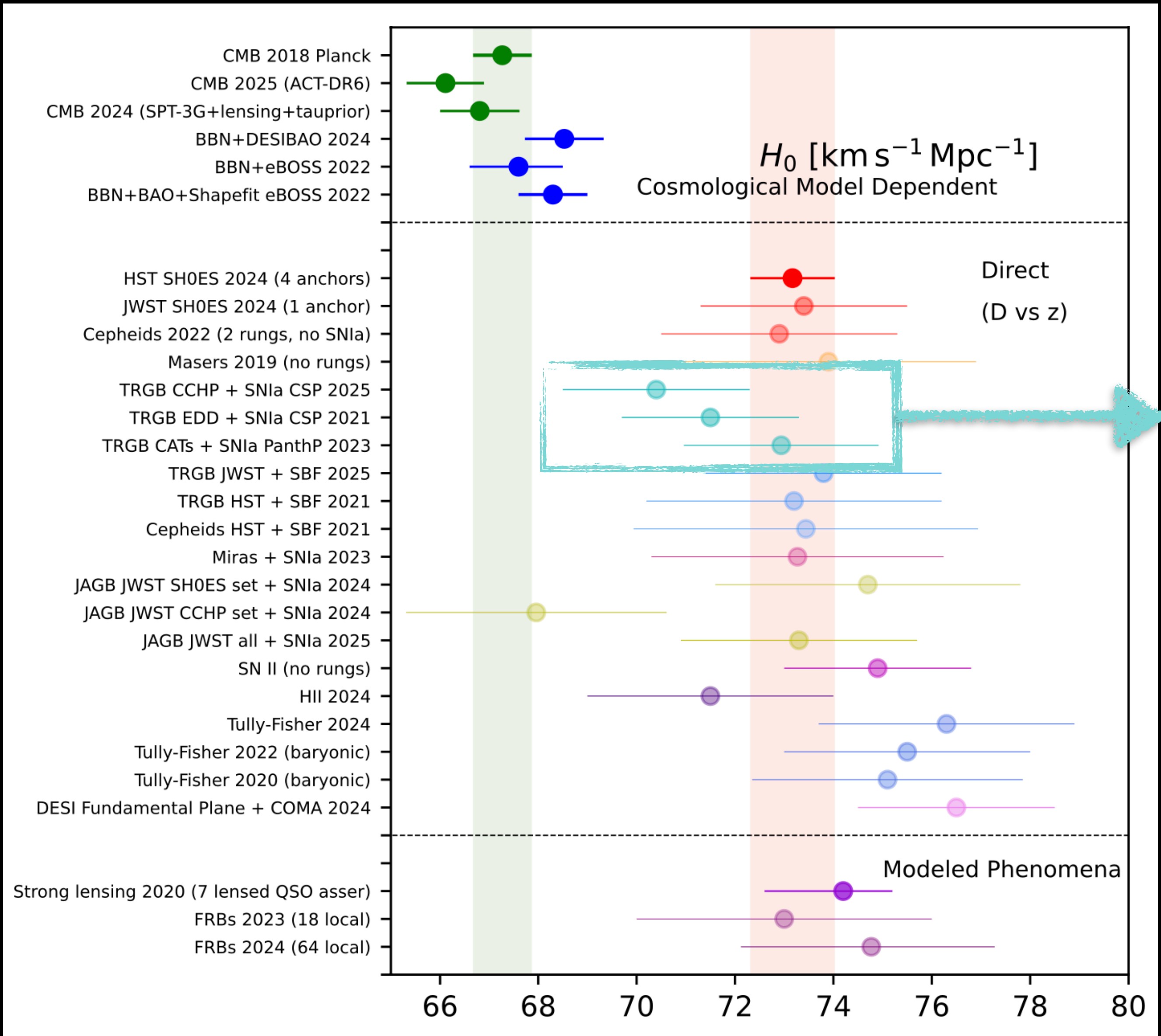
The Megamaser Cosmology Project measures H0 using geometric distance measurements to six Megamaser - hosting galaxies. This approach avoids any distance ladder by providing geometric distance directly into the Hubble flow.

H0 = 73.9 ± 3.0 km/s/Mpc

Pesce et al. arXiv:2001.09213

CosmoVerse network, Di Valentino et al., Phys.Dark Univ. 49 (2025) 101965

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

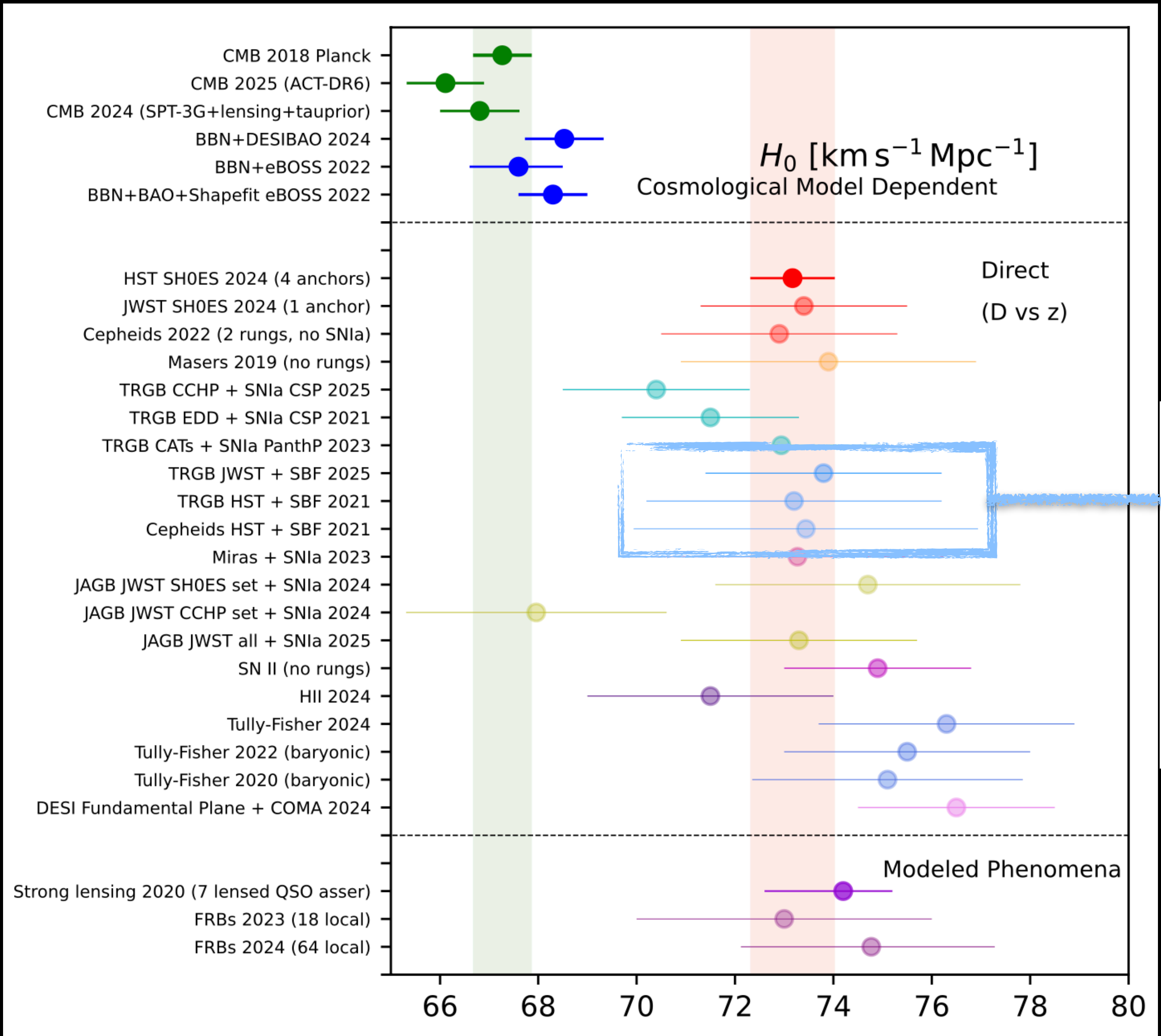
Anand et al., arXiv: *2108.00007*

H0 = 73.22 ± 2.06 km/s/Mpc

Scolnic et al., arXiv:2304.06693

CosmoVerse network, Di Valentino et al., Phys.Dark Univ. 49 (2025) 101965

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

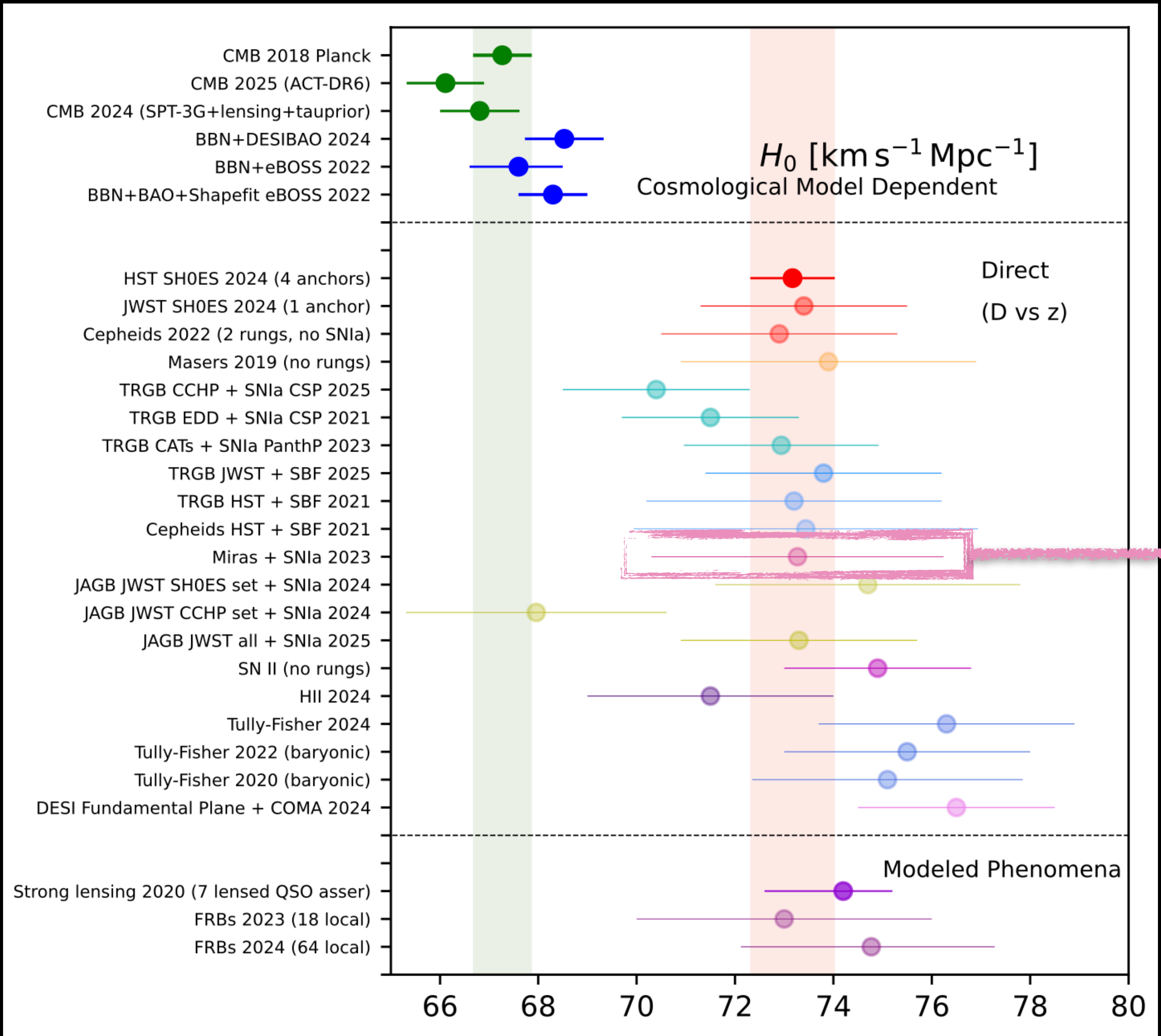
H0 = 73.44 ± 3.0 km/s/Mpc

Blakeslee et al., arXiv:2101.02221

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

CosmoVerse network, Di Valentino et al., Phys.Dark Univ. 49 (2025) 101965

Latest H0 measurements



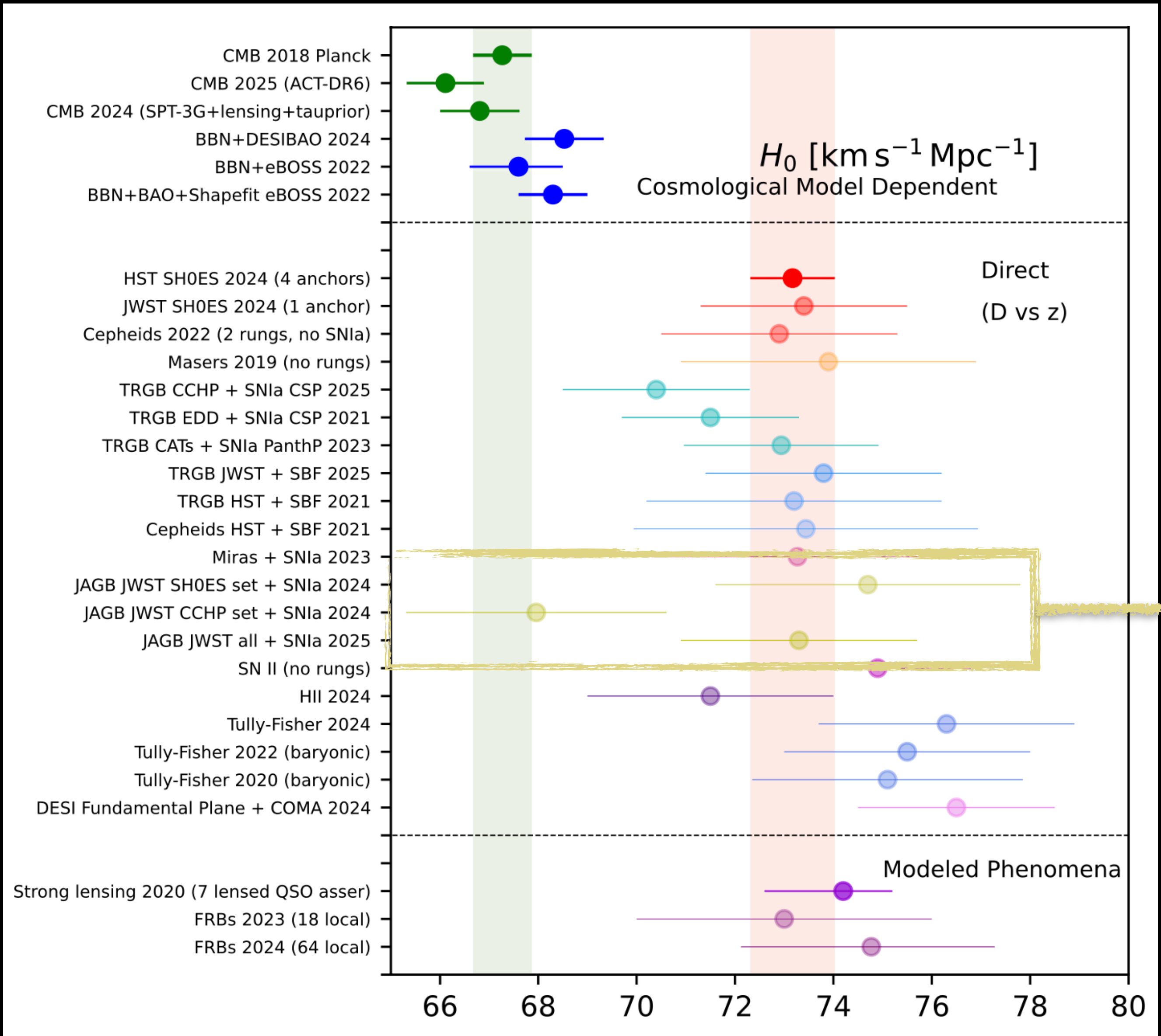
MIRAS
variable red giant stars from older stellar populations

H0 = 72.37 ± 2.97 km/s/Mpc

Huang et al., arXiv:2312.08423]

CosmoVerse network, Di Valentino et al., Phys.Dark Univ. 49 (2025) 101965

Latest H0 measurements



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

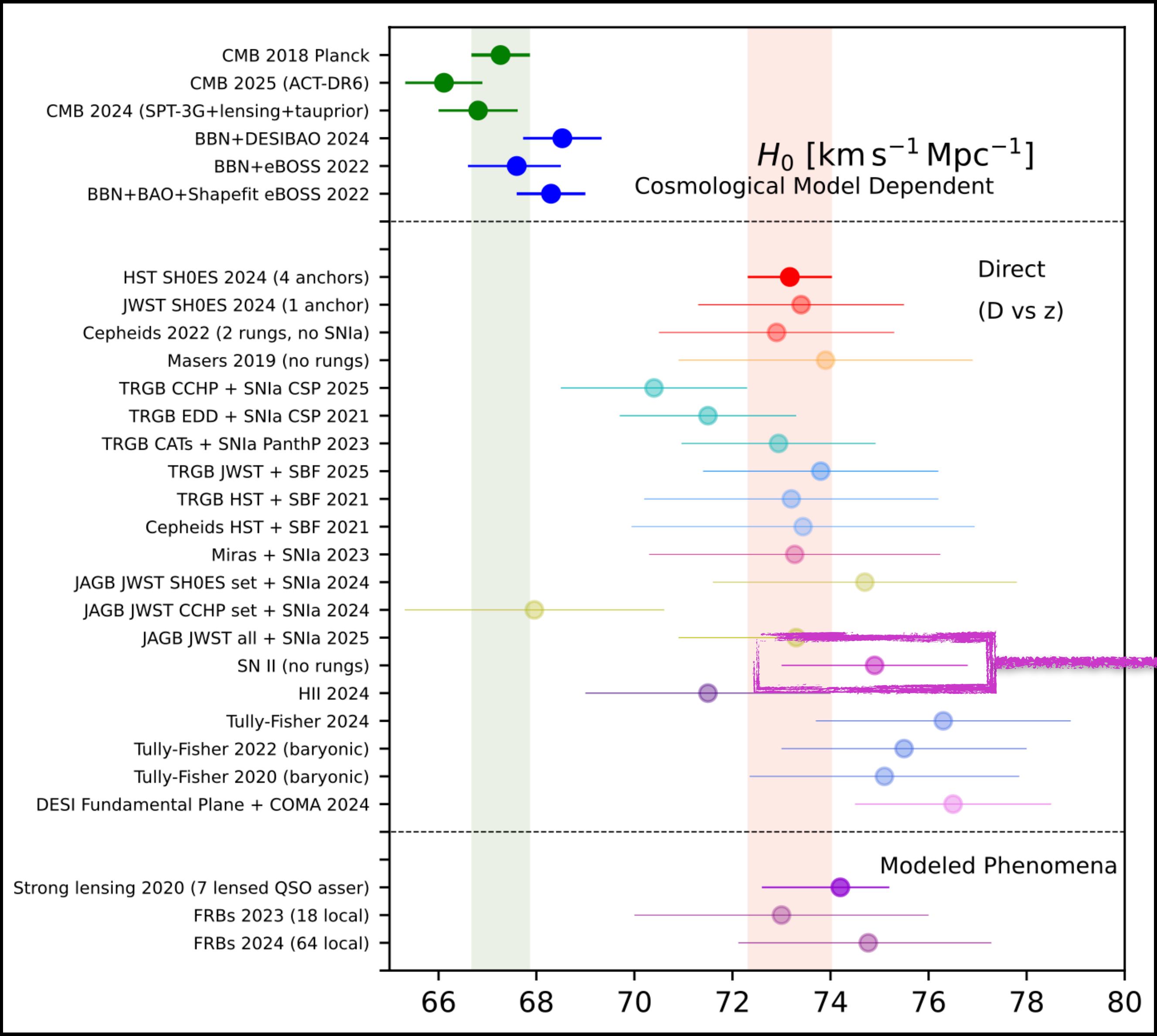
Li et al., arXiv: *2502.05259*

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.

CosmoVerse network, Di Valentino et al., Phys.Dark Univ. 49 (2025) 101965

Latest H0 measurements



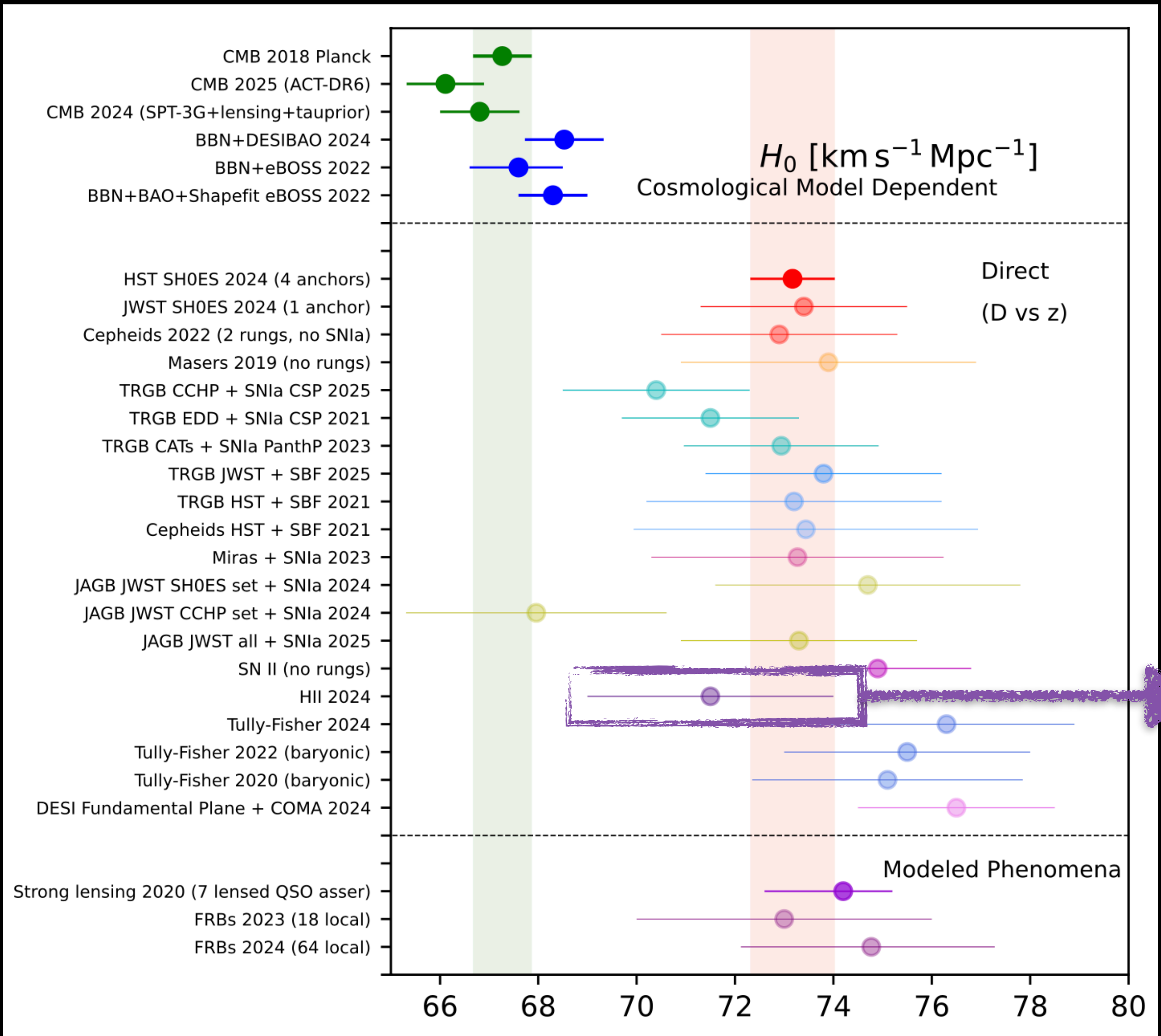
H0 = 74.9 ± 1.9 km/s/Mpc

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 network, Di Valentino et al., Phys.Dark Univ. 49 (2025) 101965

Latest H0 measurements



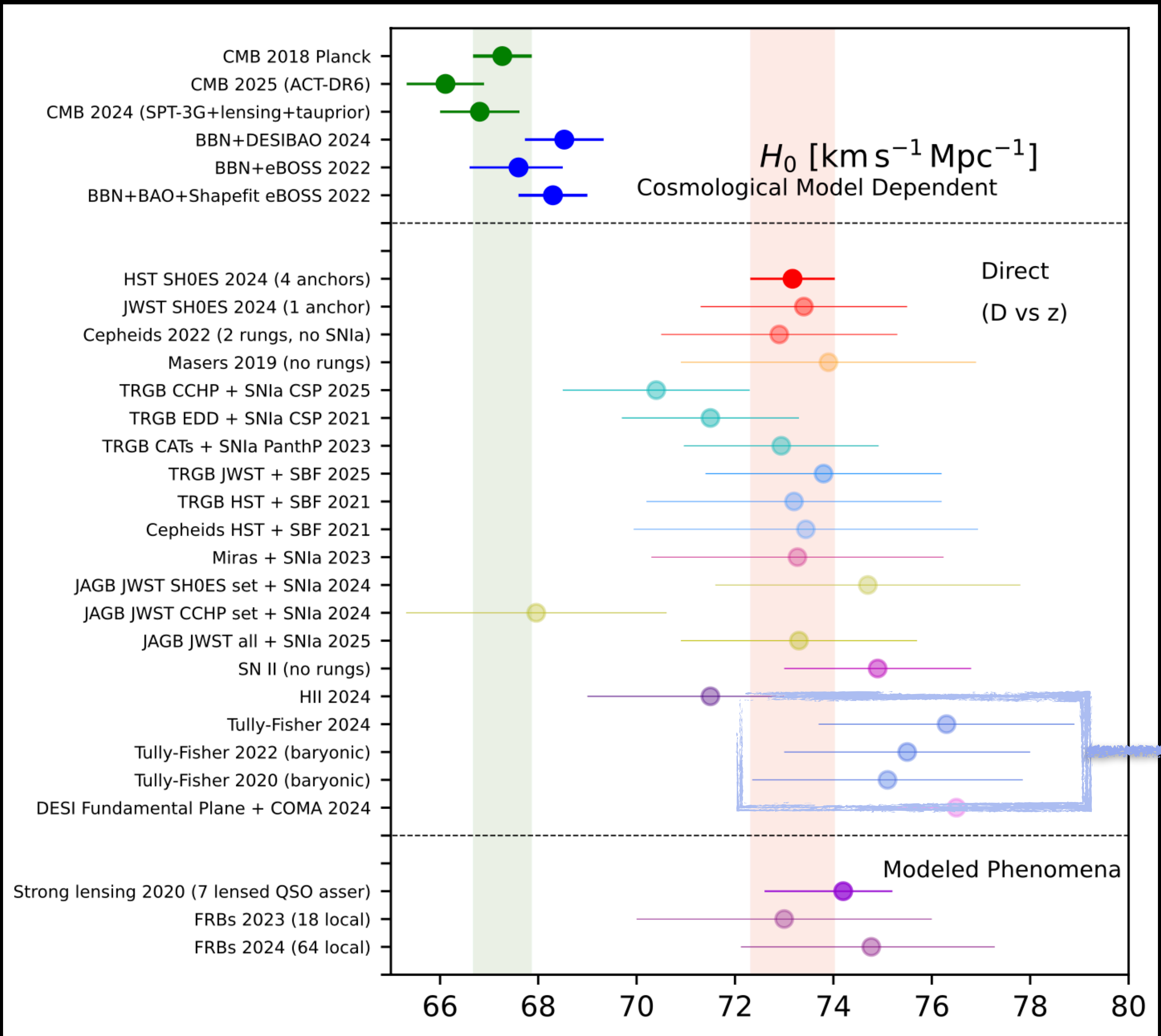
H0 = 71.5 ± 2.5 km/s/Mpc

Chávez et al., arXiv:2404.16261

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

CosmoVerse network, Di Valentino et al., Phys.Dark Univ. 49 (2025) 101965

Latest H0 measurements



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

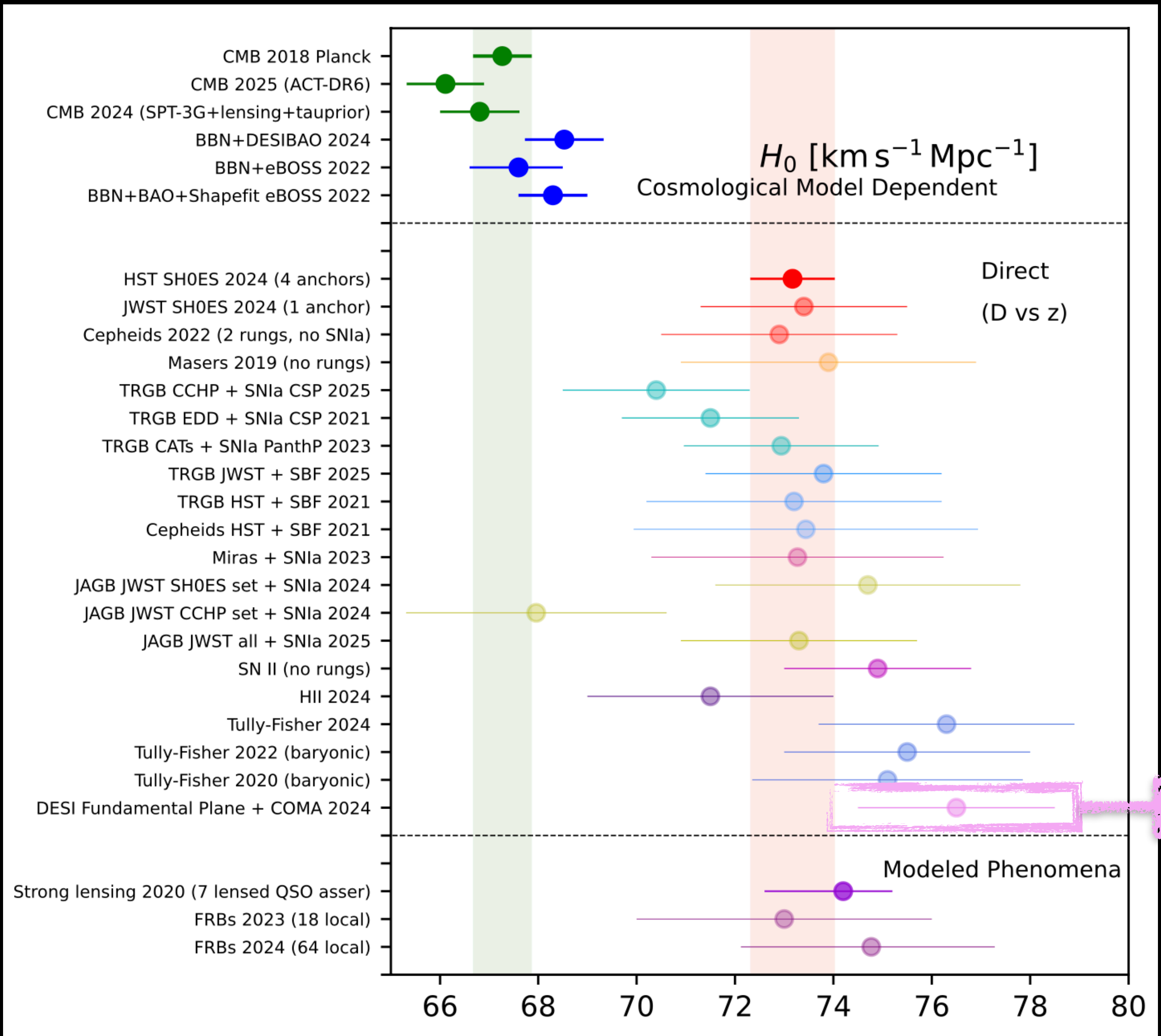
H0 = 75.10 ± 2.75 km/s/Mpc

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)

CosmoVerse network, Di Valentino et al., Phys.Dark Univ. 49 (2025) 101965

Latest H0 measurements



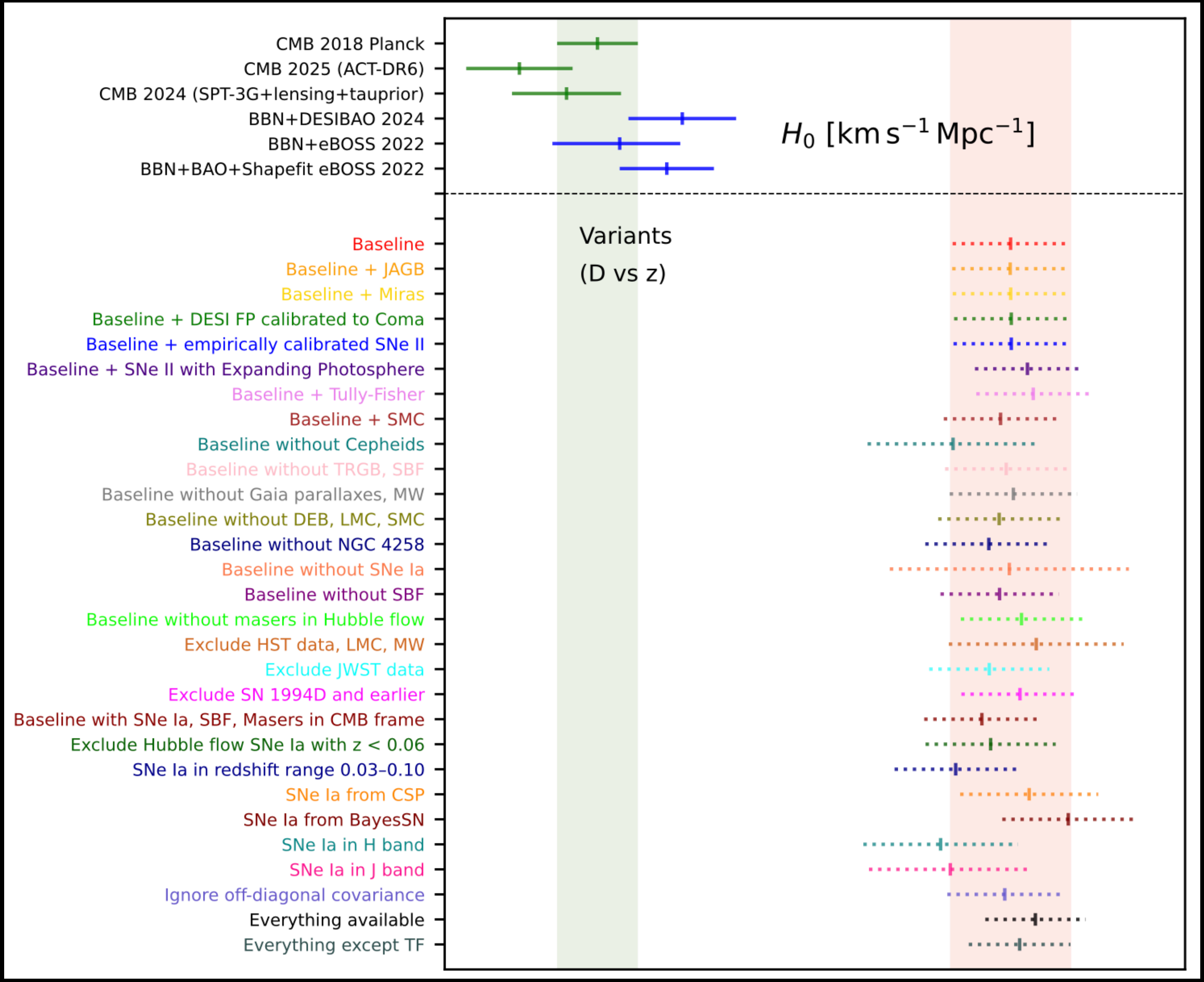
DESI measured relation between H0 and the distance to the Coma cluster using the fundamental plane relation of early-type galaxies.

H0 = 76.5 ± 2.2 km/s/Mpc

Scolnic et al., arXiv: *2409.14546*

CosmoVerse network, Di Valentino et al., Phys.Dark Univ. 49 (2025) 101965

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



We obtained a decorrelated, optimized, multi-method mean.

Excluding Cepheids or some of the distance anchors does not lead to significant changes in the result.

Casertano et al., in preparation

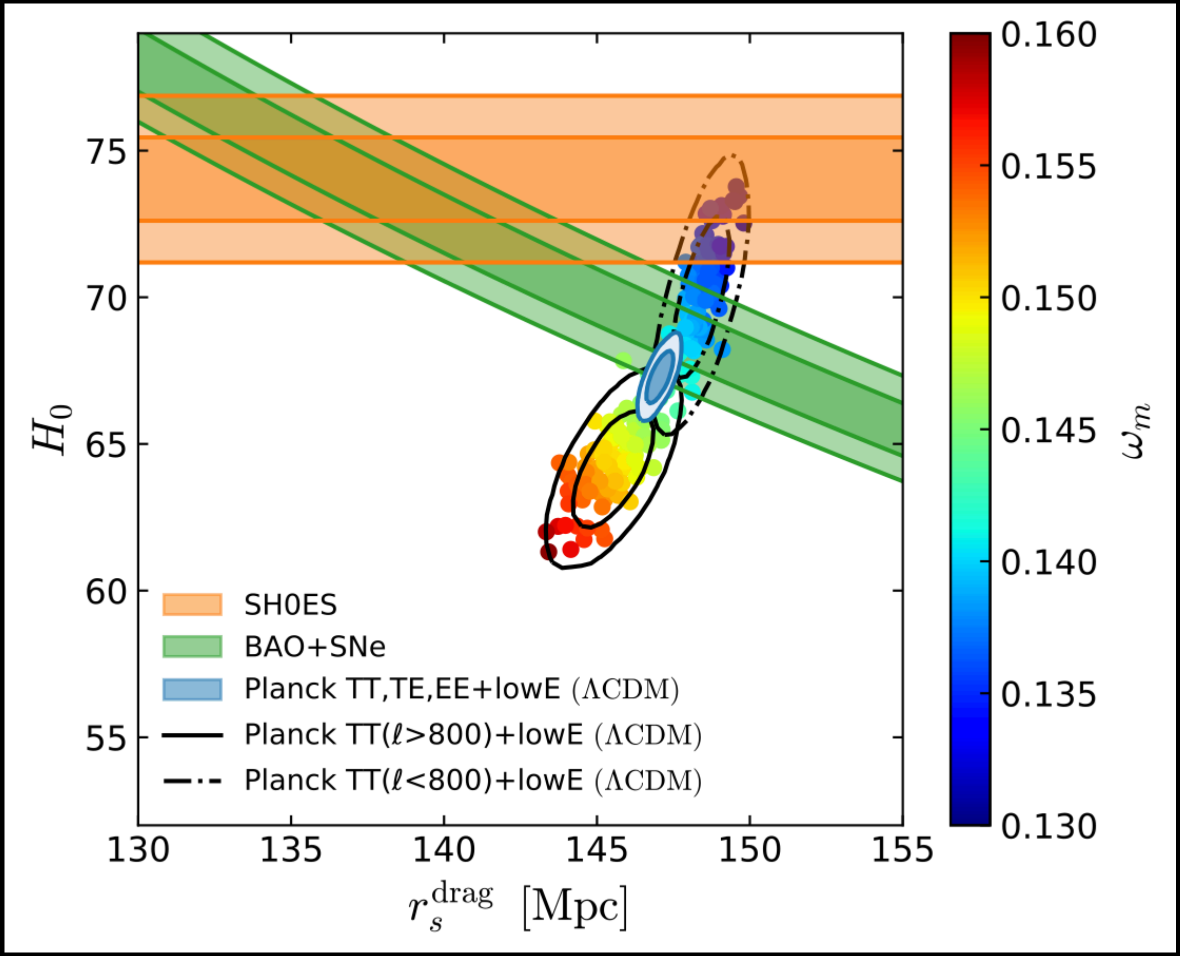
The Hubble tension doesn't depend on any one source!

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.

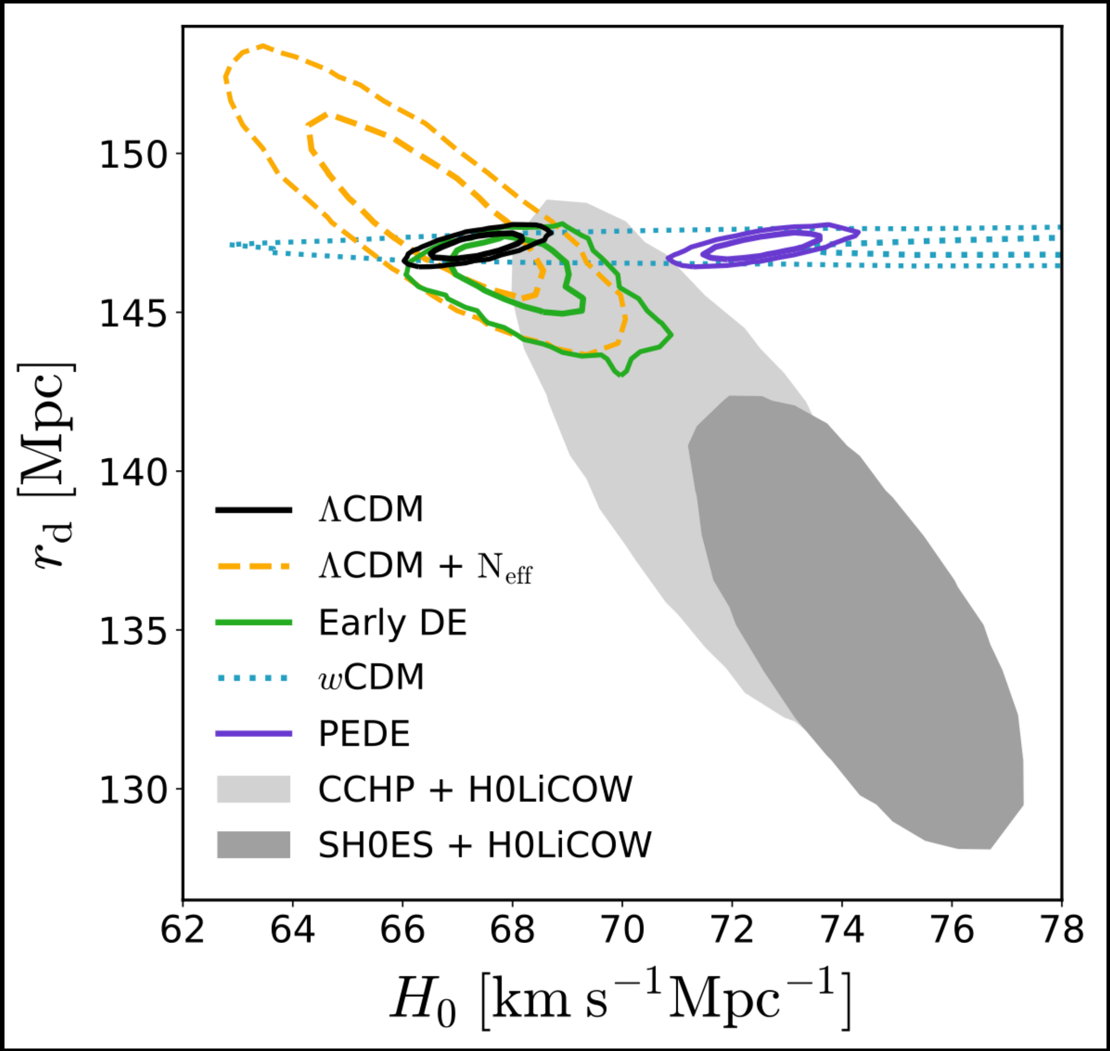


Knox and Millea, *Phys.Rev.D* 101 (2020) 4, 043533

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.



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

The Dark energy equation of state

Changing the cosmological constant to a form of dark energy
with an equation of state w alters the universe's expansion rate:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = H_0^2 \left(\frac{\Omega_r}{a^4} + \frac{\Omega_m}{a^3} + \frac{\Omega_k}{a^2} + \Omega_\Lambda\right)$$

$$H^2 = H_0^2 \left[\Omega_m (1+z)^3 + \Omega_r (1+z)^4 + \Omega_{\rm de} (1+z)^{3(1+w)} + \Omega_k (1+z)^2\right]$$

w introduces a geometrical degeneracy with the Hubble constant that is almost unconstrained using the CMB data only, resulting in agreement with SH0ES.
We have from Planck only $w = -1.58^{+0.52}_{-0.41}$ with $H0 > 69.9$ km/s/Mpc at 95% c.l.

Planck data suggest a preference for phantom dark energy ($w<-1$), which implies a density increasing over time and could lead to a Big Rip scenario.
Phantom dark energy violates the energy condition $\rho \geq |p|$,
allowing matter to move faster than light, leading to negative energy densities and potential vacuum instabilities due to negative kinetic energy.

The state of the Dark energy equation of state

Dataset combination	w	H_0 [km/s/Mpc]
CMB	$-1.57^{+0.16}_{-0.36}$ $(-1.57^{+0.53}_{-0.42})$	> 82.4 (> 69.3)
CMB+BAO	-1.039 ± 0.059 $(-1.04^{+0.11}_{-0.12})$	68.6 ± 1.5 $(68.6^{+3.1}_{-2.8})$
CMB+SN	-0.976 ± 0.029 $(-0.976^{+0.055}_{-0.056})$	66.54 ± 0.81 $(66.5^{+1.6}_{-1.6})$

Escamilla, Giarè, Di Valentino et al., JCAP 05 (2024) 091

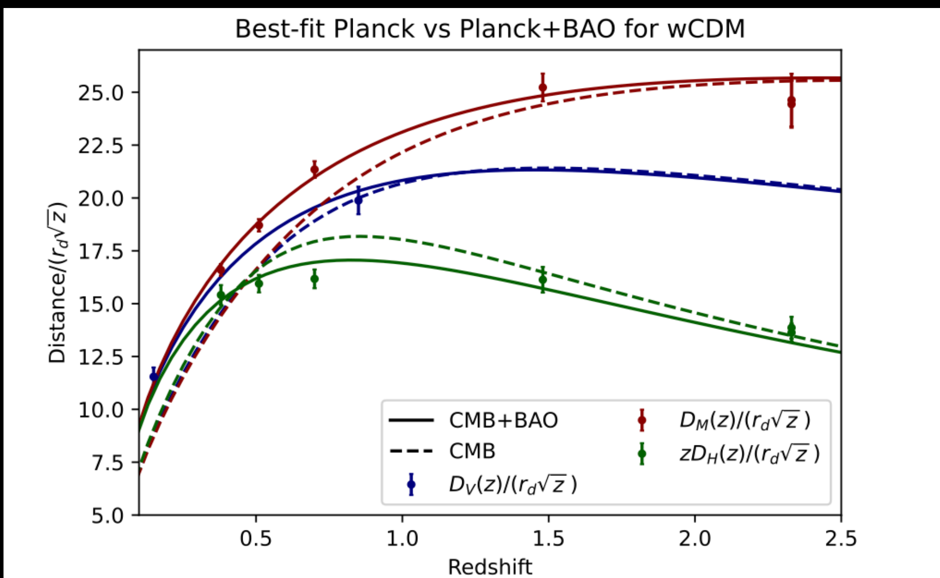


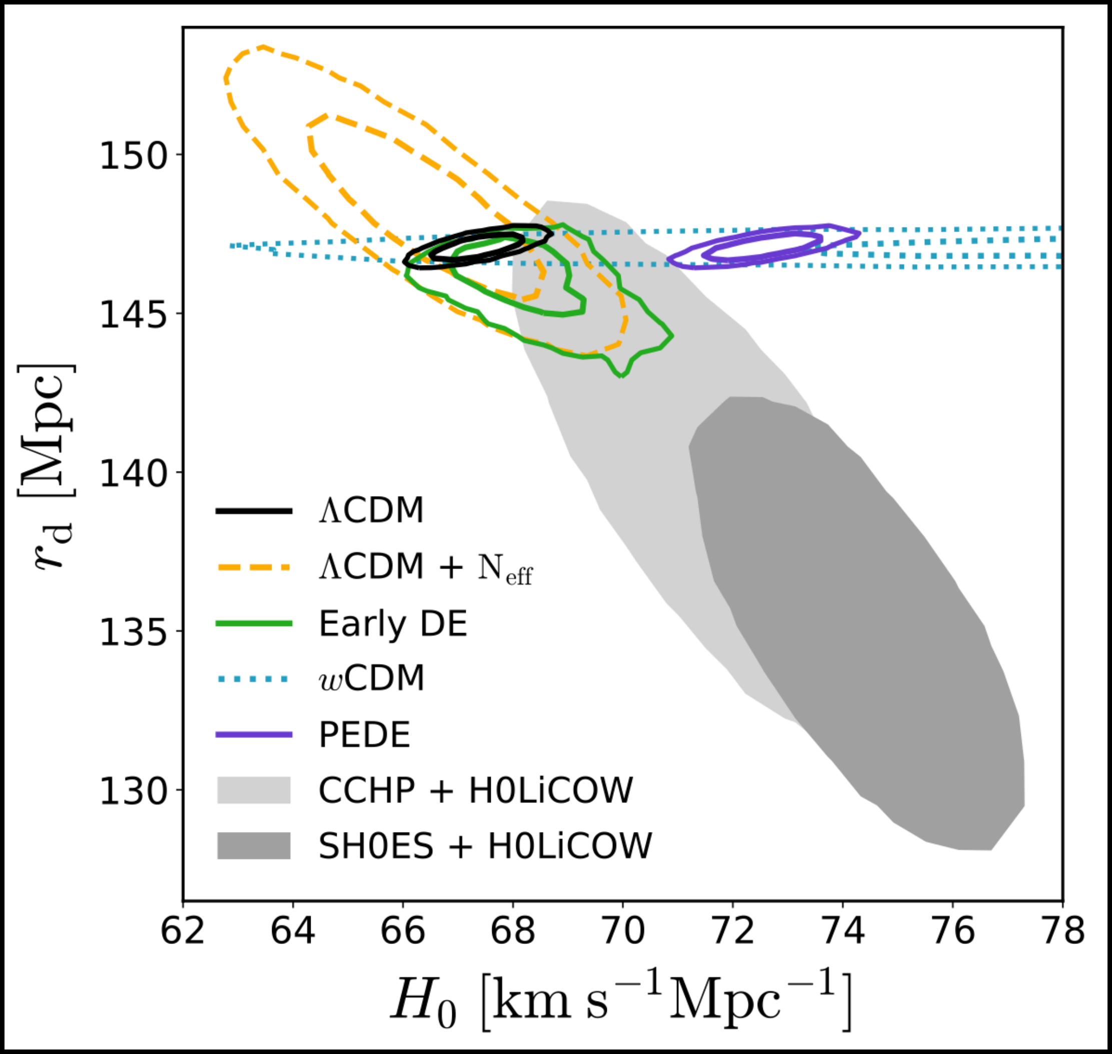
FIG. 5. Best-fit predictions for (rescaled) distance-redshift relations from a wCDM fit to *Planck* CMB data alone (dashed curves) and the CMB+BAO dataset (solid curves). These predictions are presented for the three different types of distances probed by BAO measurements (rescaled as per the y label), each indicated by the colors reported in the legend. The error bars represent $\pm 1\sigma$ uncertainties.

However, if BAO data are included, the wCDM model with w<-1 worsens considerably the fit of the BAO data because the best fit from Planck alone fails in recover the shape of H(z) at low redshifts. Therefore, when the CMB is combined with BAO data, the favoured model is again the ΛCDM one and the H0 tension is restored.

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).

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

Early Dark Energy

Early dark energy (EDE) scenario assumes that there is a new fundamental field that accelerates the cosmic expansion rate before recombination. This field contributes roughly 10-12% of the total energy density near the matter-radiation equality, but eventually dissipates like radiation or at a faster rate (depending on the shape of the potential).
In order to have an effect on the sound horizon we should have $H \sim T^2/M_{pl} \approx m$ just before the recombination, so the mass of the scalar field should be $m \approx 10^{-27}$ eV, similar to an axion particle:

$$V(\phi) = m^2 f^2 \left(1 - \cos(\phi/f)\right)^n$$

At the minimum of the potential the field oscillates yielding to an effective equation of state

$$w_\phi = (n-1)/(n+1)$$

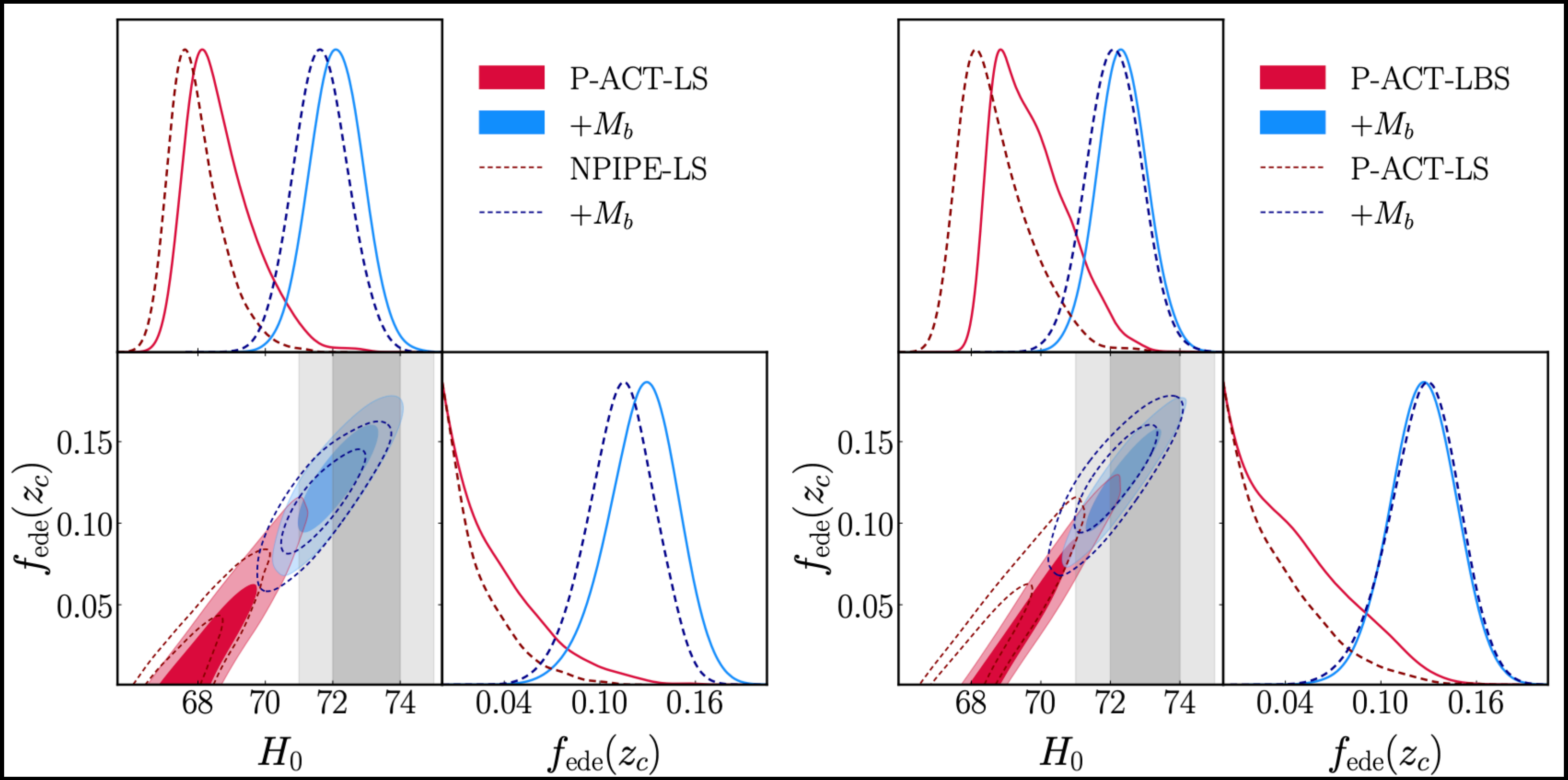
If we take n = 1 (the standard axion potential) then $w_\phi = 0$ near the potential minimum, and the EDE energy density redshifts as matter creating problems in the late-time cosmology, therefore it does not work phenomenologically.
For n = 2 instead it decays away like radiation ($\propto a^{-4}$),
and for $n \to \infty$ like kinetic energy ($\propto a^{-6}$). However, values n > 5 are disfavored.

Karwal & Kamionkowski *PRD* 94 (2016) 10, 103523 and Poulin et al. *PRL* 122 (2019) 22, 221301)

Early Dark Energy

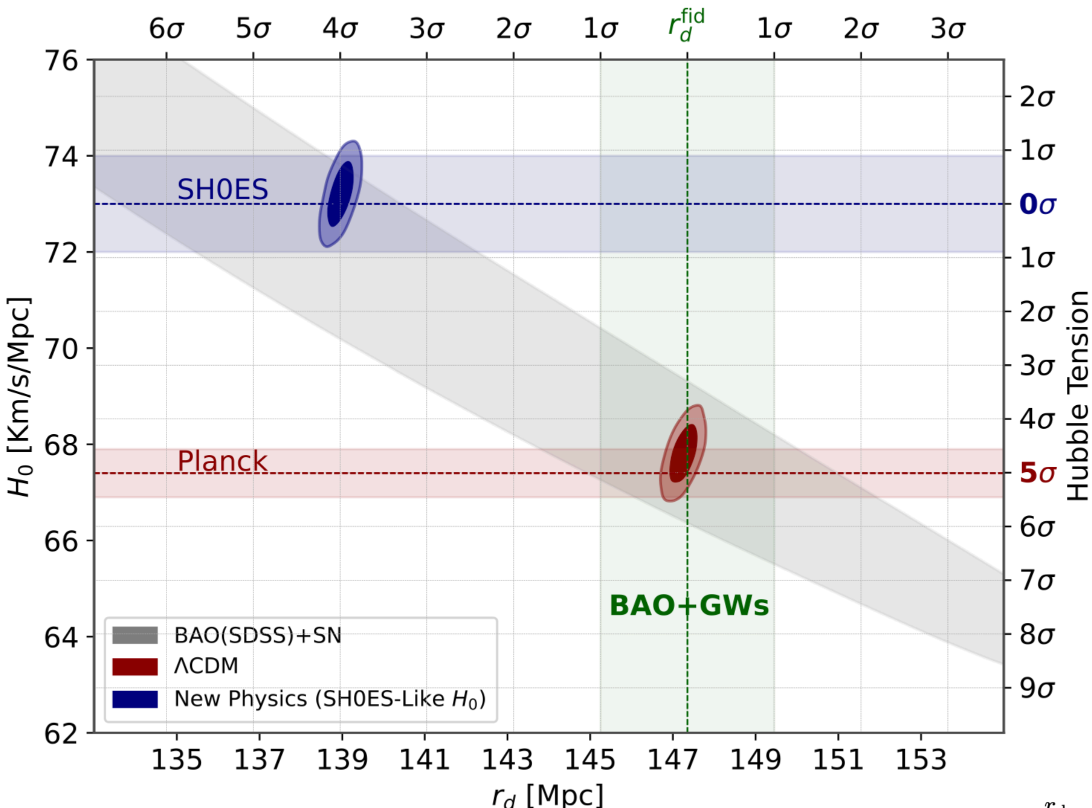
Constraints at 68% cl.

	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*

Sound Horizon from GWSS and 2D BAO



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

Figure 1. Illustrative plot in the $r_{\rm d}$ - 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 ~ 4σ.

Giarè, Betts, van de Bruck, and Di Valentino, *Phys.Rev.Lett.* 135 (2025) 7, 071003

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	$0.243^{+0.054}_{-0.030}$	$0.261^{+0.038}_{-0.025}$	$0.299^{+0.015}_{-0.007}$

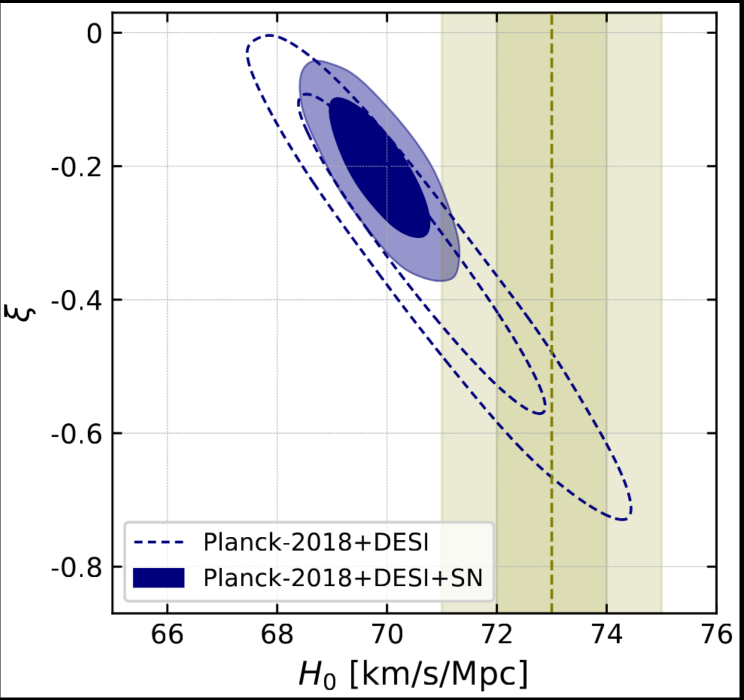
Nunes, Vagnozzi, Kumar, Di Valentino, and Mena, *Phys.Rev.D* 105 (2022) 12, 123506

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.

Beyond IDE: Other Dark Sector Interactions

So far I showed dark matter interacting with dark energy…
…but dark matter could also couple to other light species.

A well-motivated possibility is an elastic scattering between dark matter and neutrinos through a new light mediator.

ν–DM scattering

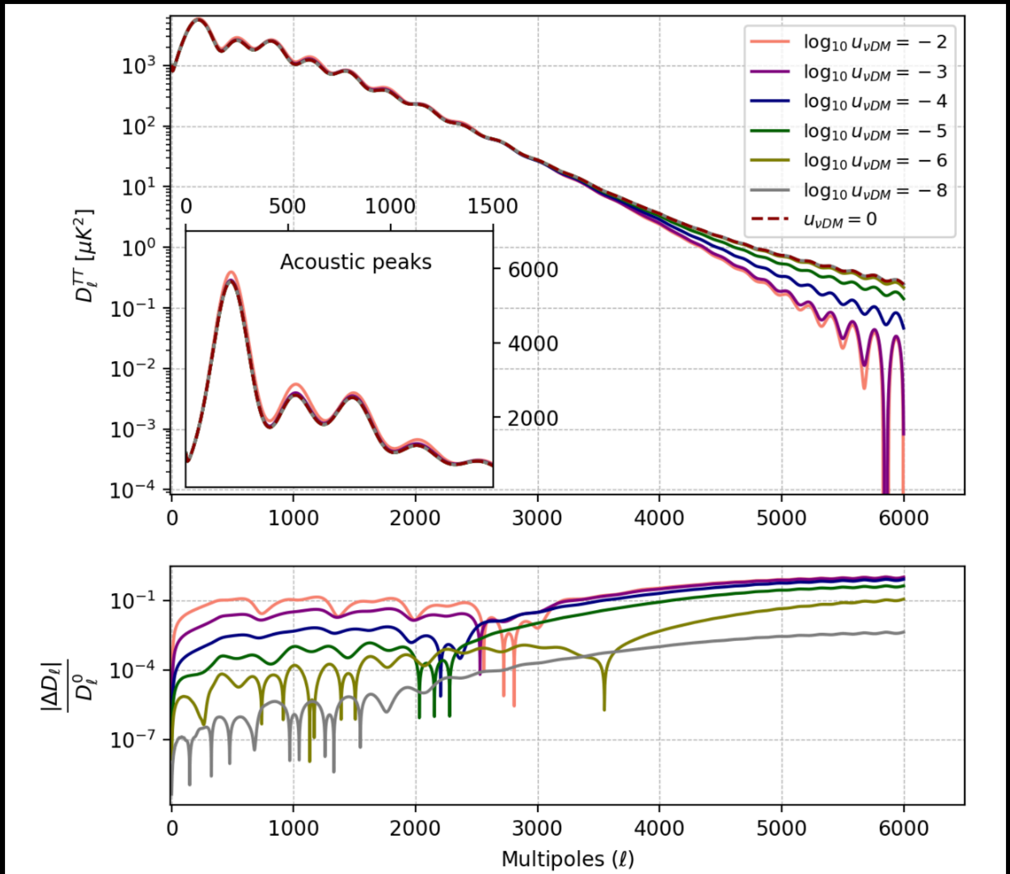


Figure 1. The top panel displays the theoretical D_ℓ^{TT}, while the percentage difference $|\Delta D_\ell|/D_\ell^0$ with respect to the non interacting case (D_ℓ^0) for different coupling values is shown in the bottom panel. The figure highlights that feeble interactions can result in undetectable changes in the Planck's probed multipole range, but can produce substantial differences on smaller scales (i.e., higher multipoles) like those measured by ACT.

Brax, van de Bruck, Di Valentino, Giarè, and Trojanowski
Mon.Not.Roy.Astron.Soc. 527 (2023) 1, L122-L126

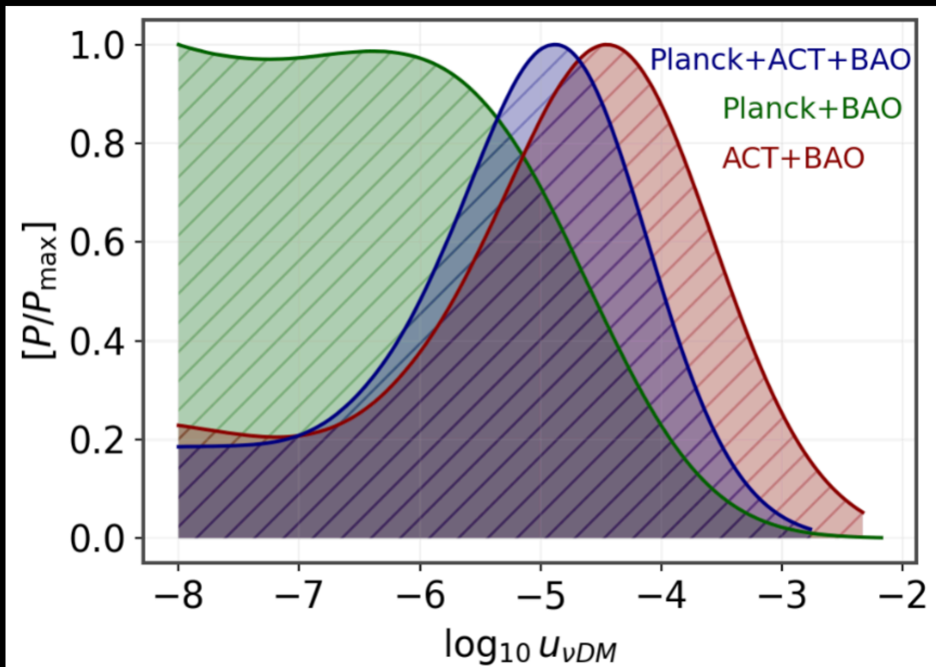
This can be parameterized by a dimensionless coupling:

$$u_{\nu\mathrm{DM}} = \frac{\sigma_{\nu\mathrm{DM}}}{\sigma_\mathrm{T}} \left(\frac{m_\mathrm{DM}}{100\ \mathrm{GeV}}\right)^{-1}$$

where $\sigma_{\nu\mathrm{DM}}$ and $\sigma\mathrm{T}$ are the νDM and Thomson scattering cross sections and m_DM is the mass of the dark matter particle. Increasing $u_{\nu\mathrm{DM}}$, the impact on the CMB temperature power spectrum is the suppression of the small-scale clustering and the modification of the damping tail. While Planck-scale multipoles ($\ell \lesssim 2500$) cannot resolve such small effects, at higher multipoles ($\ell \gtrsim 3000$), probed by ACT/SPT, small couplings have a more significant impact, changing the TT power spectrum at the few-% level.

High-ℓ data are opening a new observational window on models that would otherwise be indistinguishable at lower multipoles.

ν–DM scattering



Brax, van de Bruck, Di Valentino, Giarè, and Trojanowski
Mon.Not.Roy.Astron.Soc. 527 (2023) 1, L122-L126

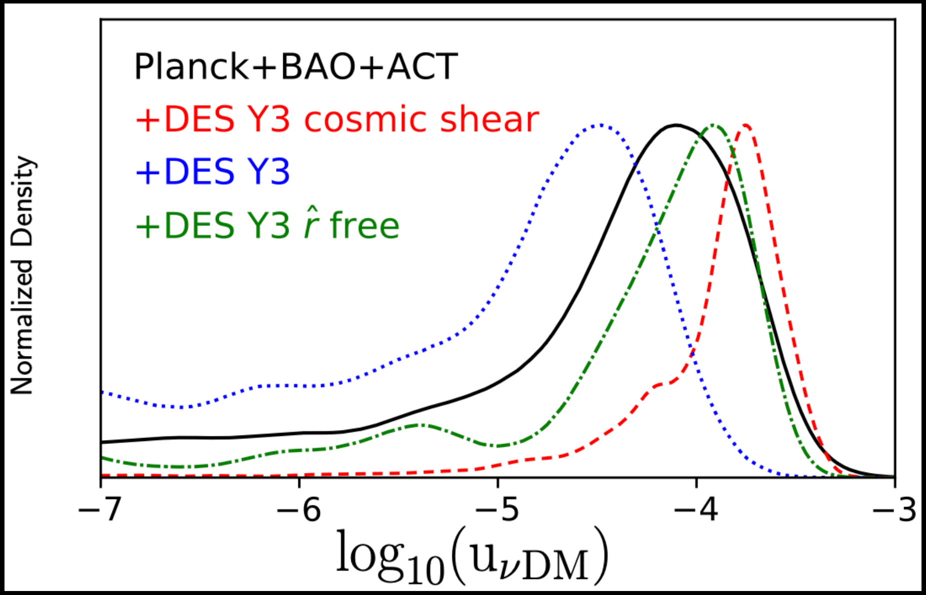
We find that Planck alone constrains ν–DM scattering only through an upper limit $\log_{10} u_{\nu DM} < -4.39$ at 95% CL, since for $u_{\nu DM} \ll 10^{-5}$ the effects are too small to be detected. In this regime, the corrections are smaller than one part in 10^5 when compared to the non-interacting case, so all the models become indistinguishable, leading to a flat posterior distribution for smaller values.

In contrast, ACT small-scale data shows a clear preference for a non-zero coupling: ACT+BAO gives $\log_{10} u_{\nu DM} \simeq -4.86^{+1.5}_{-0.83}$ at 68% CL.

It is crucial to observe that the two datasets are not in tension regarding the predicted value for this parameter, and that for $u_{\nu DM} \ll 10^{-6}$ the effect remains too small to be detected even by ACT.

ν–DM scattering

Parameter	Planck+BAO+ACT	+DES Y3 cosmic shear
$100\Omega_b h^2$	$2.235^{+0.014}_{-0.014}$	$2.247^{+0.014}_{-0.014}$
Ω_m	$0.3060^{+0.0060}_{-0.0060}$	$0.2983^{+0.0048}_{-0.0048}$
$100\theta_s$	$1.04218^{+0.00034}_{-0.00049}$	$1.04225^{+0.00047}_{-0.00028}$
$\ln(10^{10}A_s)$	$3.036^{+0.015}_{-0.015}$	$3.029^{+0.016}_{-0.013}$
n_s	$0.9728^{+0.0047}_{-0.0047}$	$0.9742^{+0.0046}_{-0.0046}$
$\tau_{\rm reio}$	$0.0487^{+0.0069}_{-0.0081}$	$0.0484^{+0.0088}_{-0.0070}$
$\log_{10} u_{\nu DM}$	$-4.24^{+0.56}_{-0.71}$	$-3.77^{+0.28}_{-0.27}$
S_8	$0.811^{+0.024}_{-0.017}$	$0.766^{+0.024}_{-0.020}$
$\hat{r}$	—	—



Zu, Giarè, Zhang, Di Valentino, Sming Tsai and Trojanowski, arXiv:2501.13785

Combining Planck low-ℓ with high-ℓ ACT data shows a clear preference for non-zero ν–DM coupling around $\log_{10} u_{\nu DM} \simeq -4.2$.
Adding weak lensing (DES Y3) data strengthens the signal:
using cosmic shear only, we find a ~3σ preference for ν–DM scattering,
with the central value shifting to $\log_{10} u_{\nu DM} \simeq -3.8$.
This indicates that the suppression of small-scale clustering is consistent with WL data.

Cosmology thus provides a unique window on neutrino portals and light mediators, inaccessible to laboratory experiments.

Summary – Where Do We Stand?

ΛCDM still fits each dataset impressively well,
but it fails when we try to fit them all together.
It is a pragmatic model, built on ingredients (dark matter, dark energy, inflation)
that lack fundamental explanation or direct detection.
We use them because they work phenomenologically, not because we understand them.

Yet today we face persistent and growing cracks:

- The H_0 tension > 6σ across multiple independent methods.
- The CMB lensing anomaly (AL > 1), curvature hints ($\Omega_k \neq 0$), and low τ, challenging internal consistency.
- Neutrino mass bounds from cosmology increasingly at odds with terrestrial results.
- Hints of dynamical dark energy from BAO and SN.

The lesson:
Precision cosmology is only meaningful if the data are internally consistent and trustworthy.
Otherwise, we risk confusing artifacts for discovery,
and turning “precision” into a false sense of certainty.

We must let the data speak honestly, even if that means re-evaluating our assumptions and methods, before claiming to measure the universe to percent-level accuracy.

Thank you!

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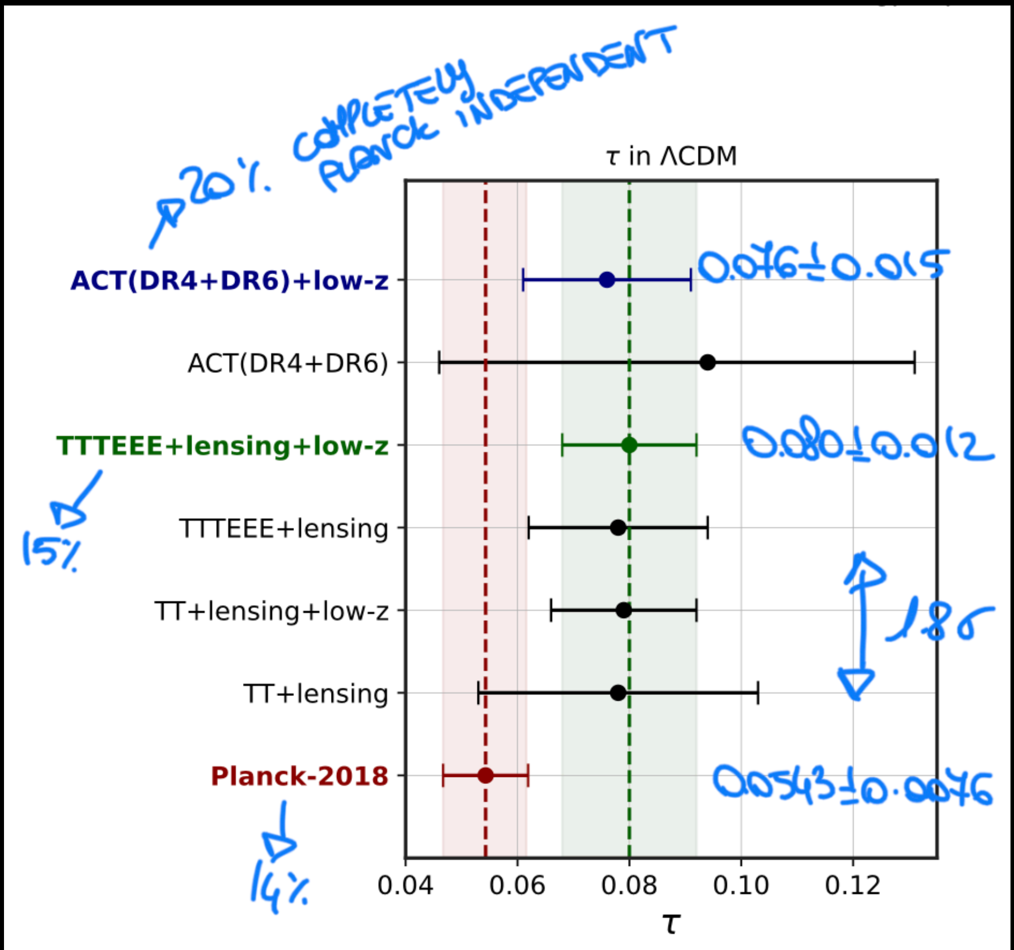
lowE independent optical depth



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

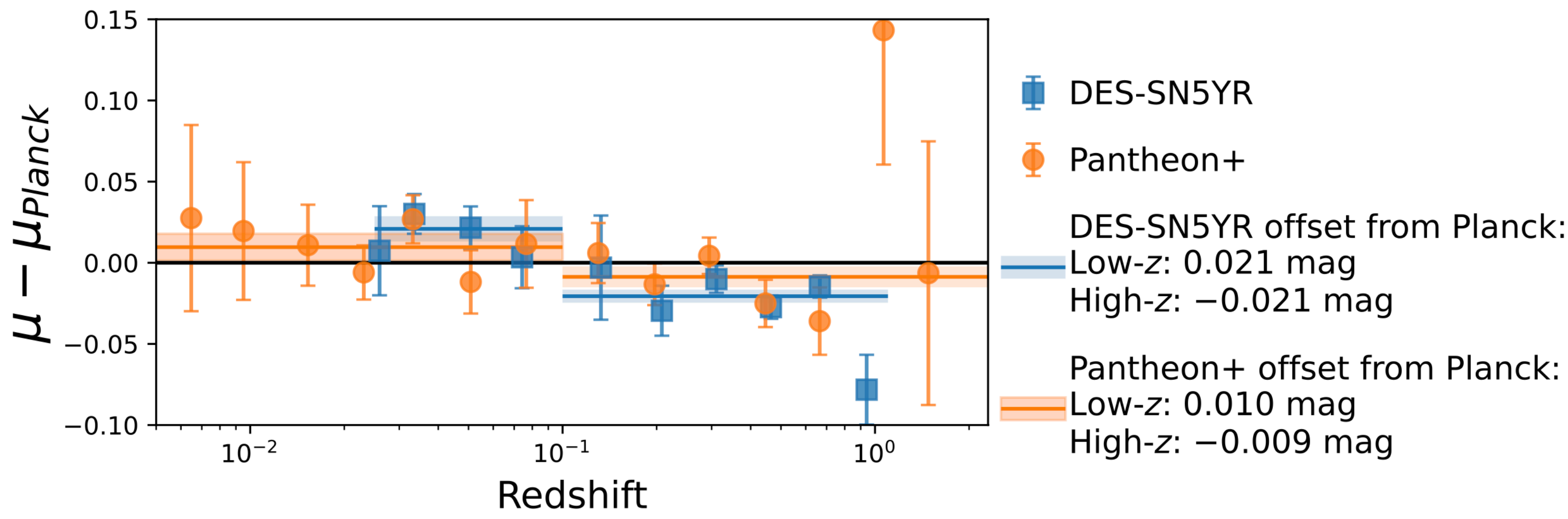


Figure 1. Pantheon+ and DES-SN5YR binned Hubble residuals calculated w.r.t. a FlatΛCDM cosmology assuming $\Omega_M = 0.315$ from *Planck*. In each redshift bin we show the weighted mean of the Hubble residual and statistical-only uncertainties. The horizontal bands show the weighted mean of the Hubble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