

# Overview of recent results from cosmological observations and implications for particle physics

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# The $\Lambda$ CDM model

Among the various cosmological models proposed in literature, the  $\Lambda$ CDM 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.

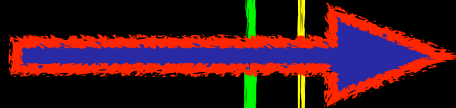
However, despite its incredible success,  $\Lambda$ CDM harbours large areas of phenomenology and ignorance. For example, it still cannot explain key concepts in our understanding of the structure and evolution of the Universe, at the moment based on unknown quantities, that are also its largest components.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



# The $\Lambda$ CDM 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 $\Lambda$ CDM:

- **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.

# The $\Lambda$ CDM model

## Three unknown pillars:

- an early stage of accelerated expansion (**Inflation**) which produces the initial, tiny, density perturbations needed for structure formation;

- a curvilinear factor (**Dark Energy**);

- an energy component to explain the current stage of accelerated expansion (**Dark Energy**).

## Specific solutions for $\Lambda$ CDM:

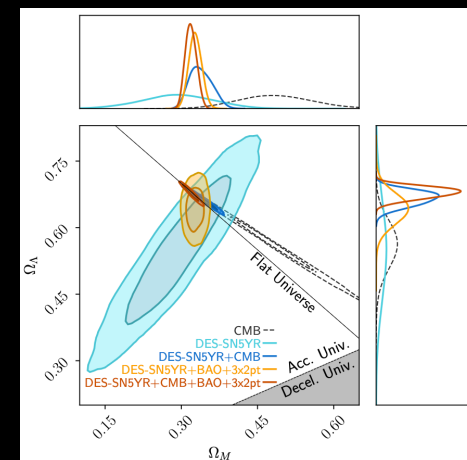
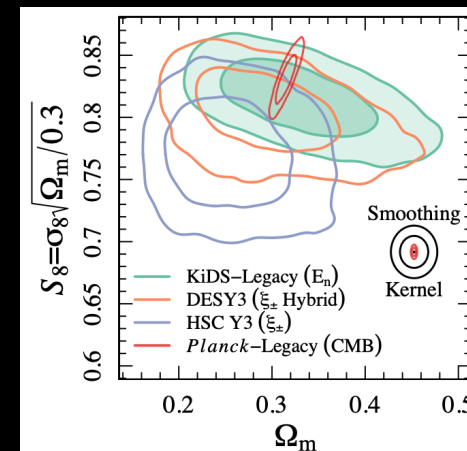
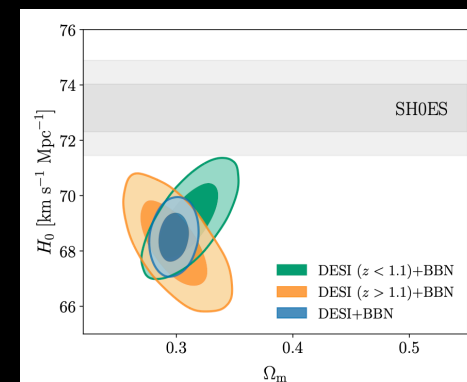
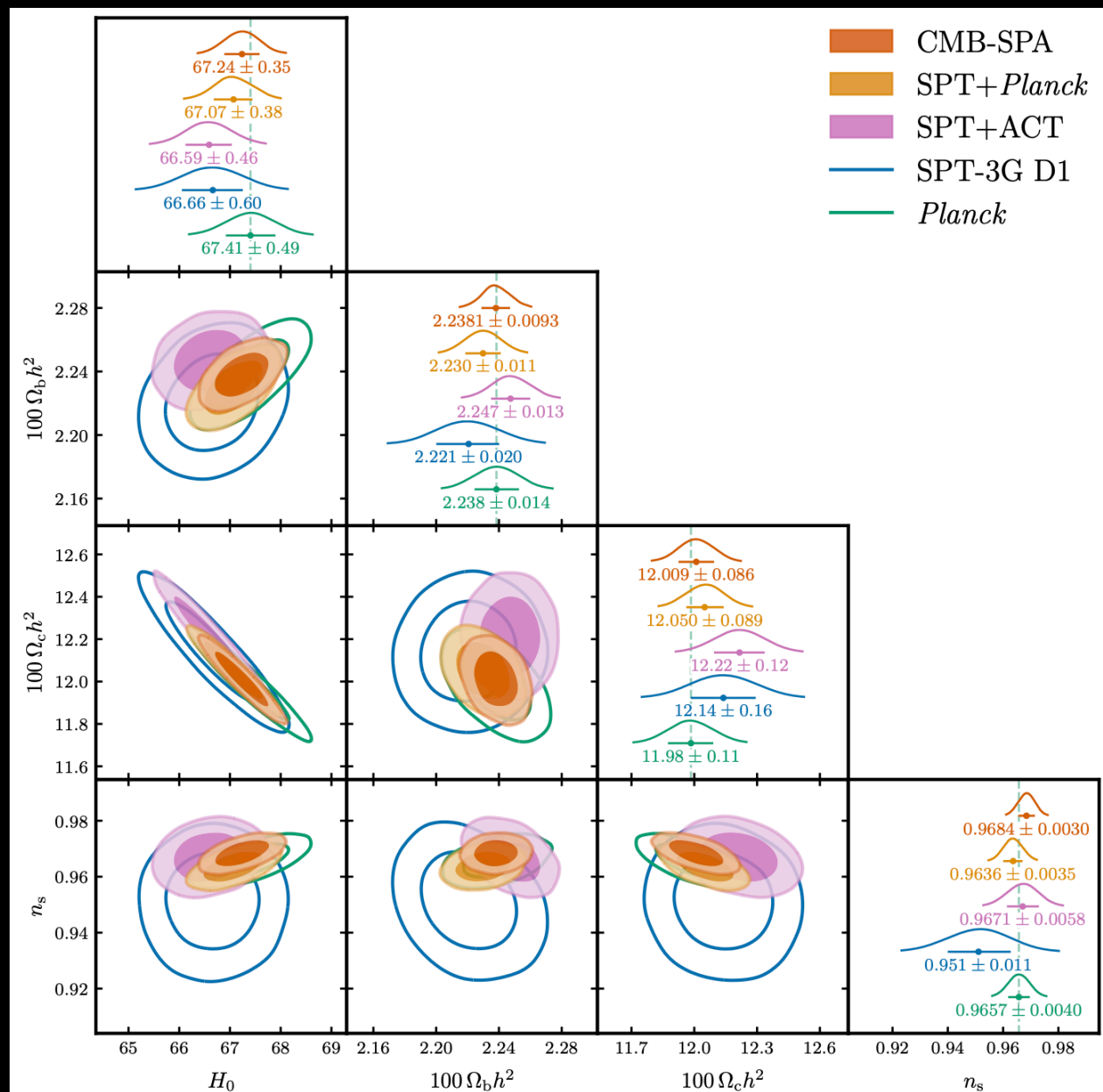
- **Inflation** is given by a single, minimally coupled, slow-rolling scalar field;

However, despite its **theoretical shortcomings**,  $\Lambda$ CDM remains the preferred model due to its ability to accurately describe observed phenomena.

- **Dark Energy** is a cosmological constant term.

fluid

# 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.

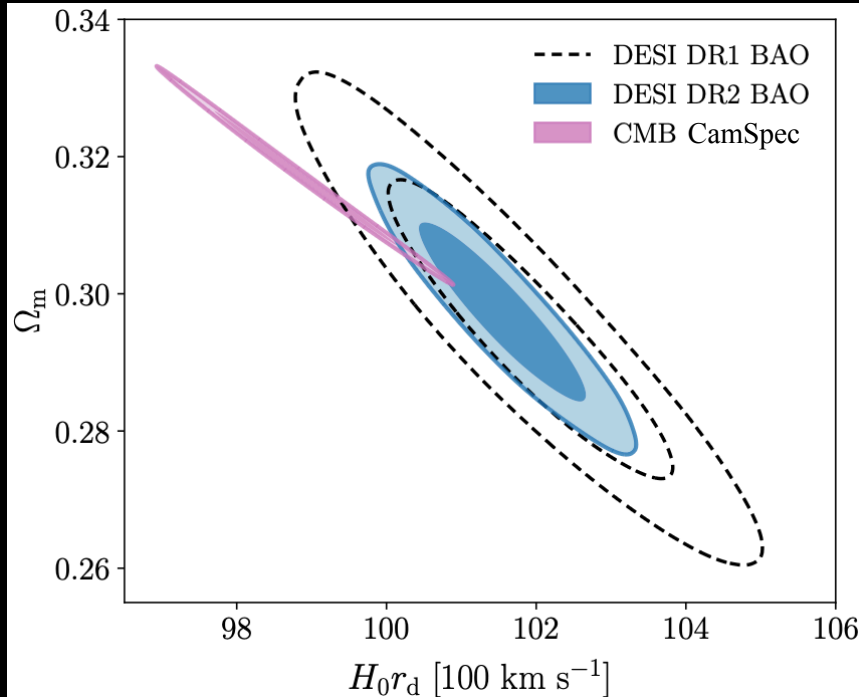
Therefore, to me, this means that LCDM provides a good fit to the data  
and shows no clear signs of deviation, even when extended.

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

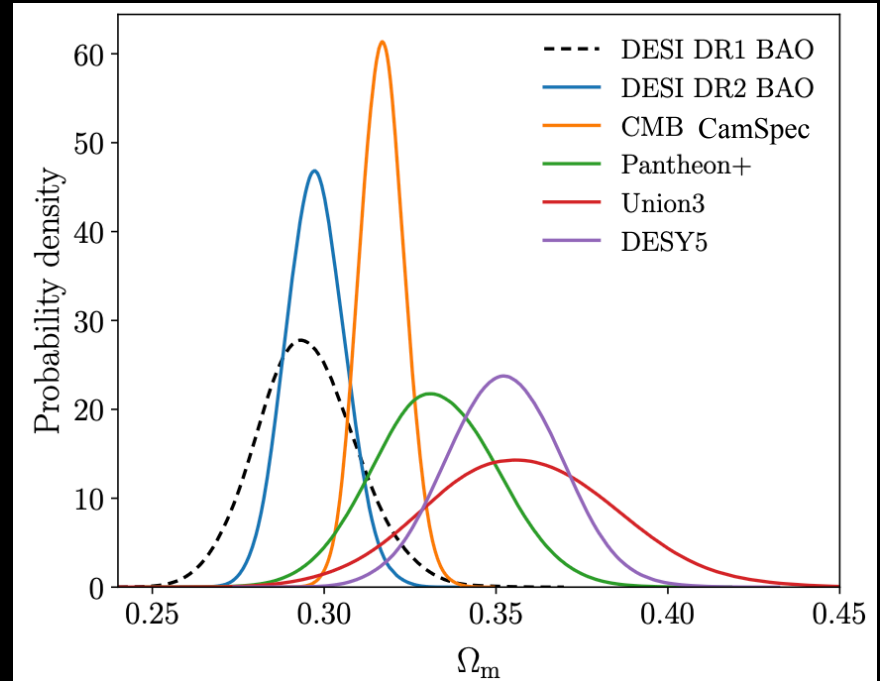
So LCDM appears different for the different data!

# Tensions and Disagreements in LCDM

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



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

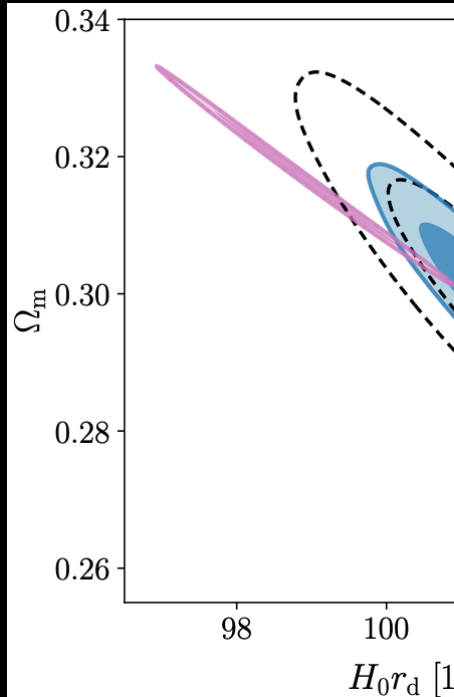


Finally, as in [38], we note a mild to moderate discrepancy between the recovered values of  $\Omega_m$  from DESI and SNe in the context of the  $\Lambda$ CDM model. This is shown in the marginalized posteriors in Figure 10: the discrepancy is  $1.7\sigma$  for Pantheon+,  $2.1\sigma$  for Union3, and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

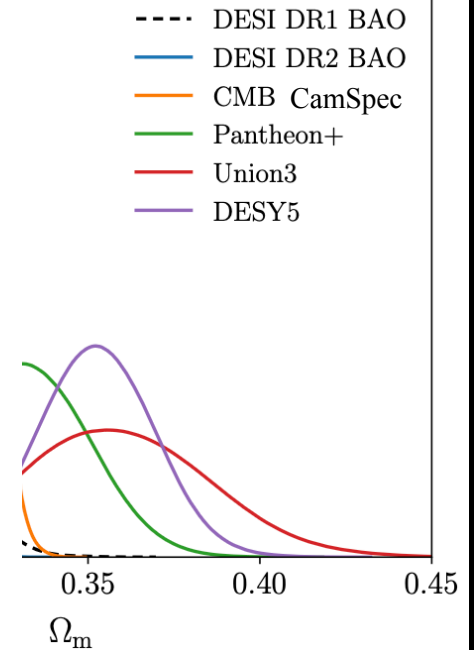
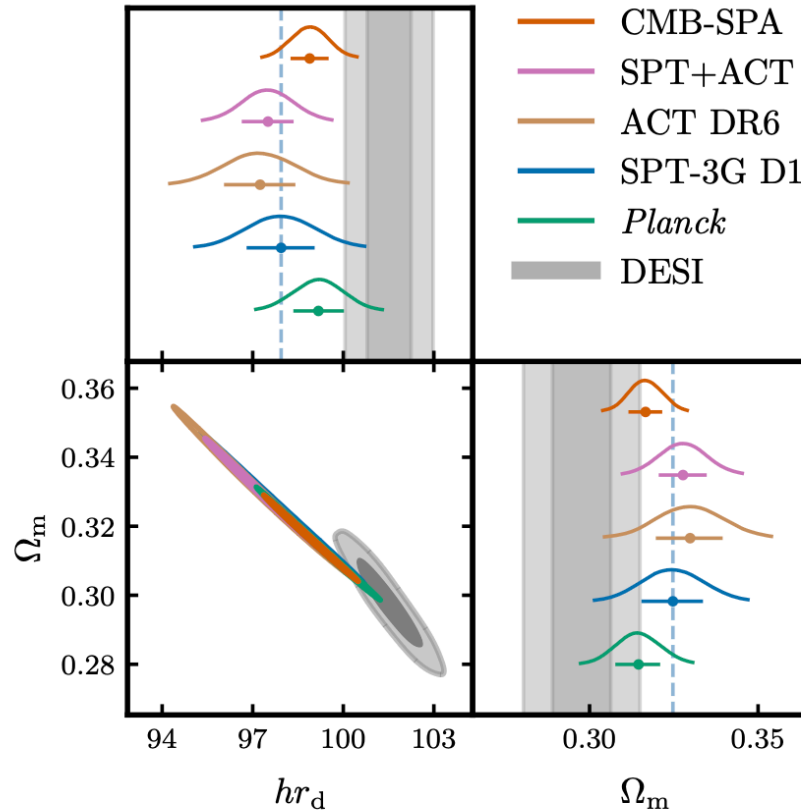
The same LCDM cannot fit 2 datasets together!

# Tensions and Disagreements in LCDM

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



the corresponding  $2 \times 2$  posteriors. Converting this  $\chi^2$  into a p-value, we find it is equivalent between BAO and CMB in  $\Lambda$ CDM in DR1. However, we note that CMB lensing is excluded. The reason why more models with expansion history than  $\Lambda$ CDM

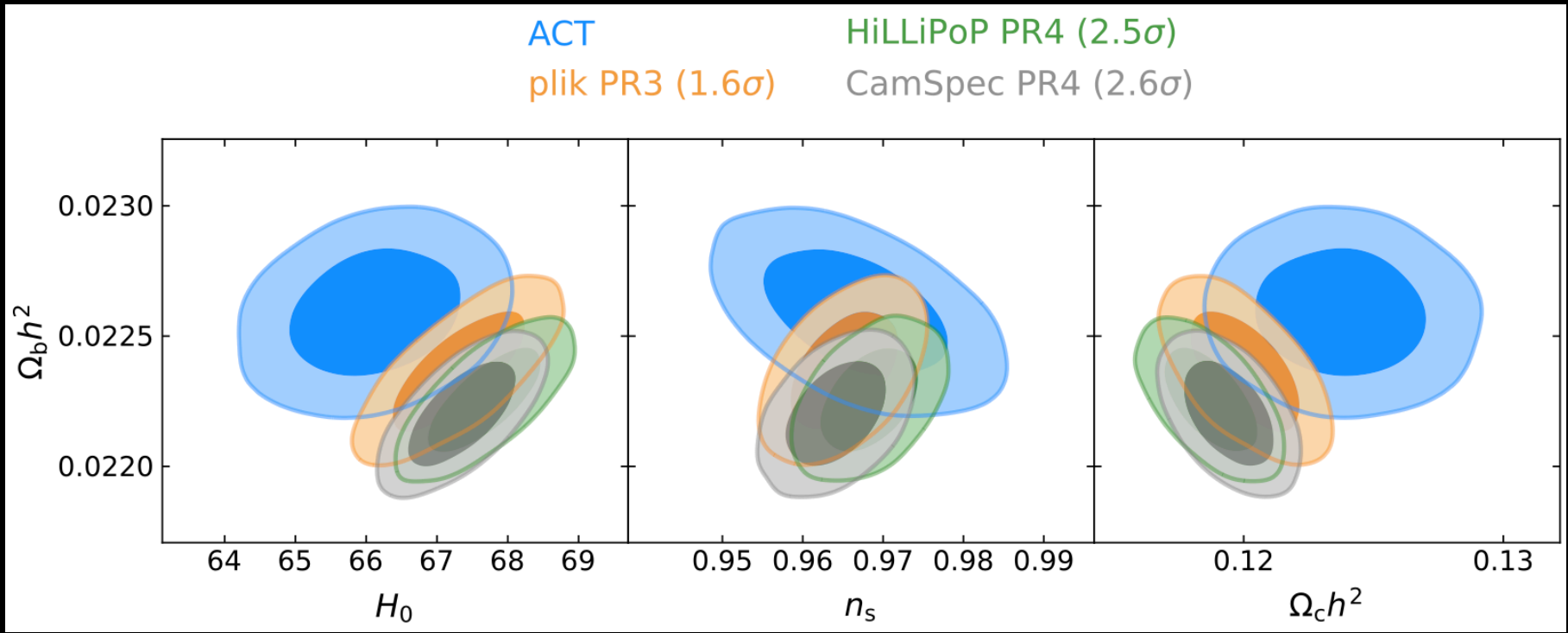


	$100 \Omega_m$	$hr_d$ [Mpc]	Distance to DESI
CMB-SPA	$31.66 \pm 0.50$	$98.89 \pm 0.63$	$2.8 \sigma$
SPT+ACT	$32.77 \pm 0.72$	$97.51 \pm 0.87$	$3.7 \sigma$
SPT+Planck	$31.89 \pm 0.54$	$98.63 \pm 0.67$	$3.0 \sigma$
ACT DR6	$33.0 \pm 1.0$	$97.2 \pm 1.2$	$3.1 \sigma$
SPT-3G D1	$32.47 \pm 0.91$	$97.9 \pm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

e a mild to moderate discrepancy values of  $\Omega_m$  from DESI and  $\Lambda$ CDM model. This is shown in Figure 10: the discrepancy,  $2.1\sigma$  for Union3, and  $2.9\sigma$  for samples preferring higher values of  $\Omega_m$  uncertainties. For  $\Lambda$ CDM we find constraints on parameters from any SNe data. However, as with

The same LCDM cannot fit 2 datasets together!

# CMB tension in LCDM

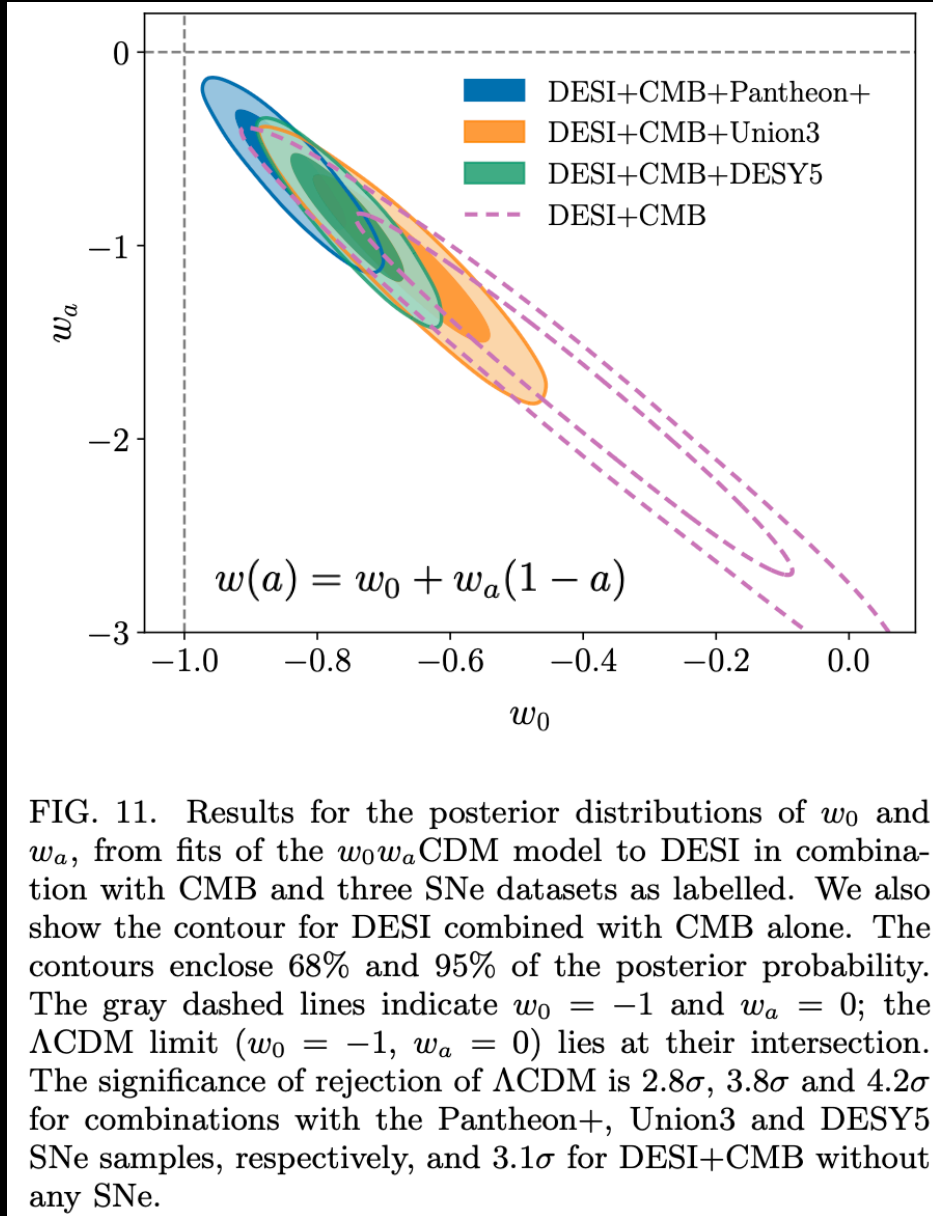


In Figure 37 we show the comparison of the ACT DR6 results with those from different versions of the *Planck* likelihoods, as discussed in §8. The agreement between ACT and *Planck* is closest for the Plik PR3 at  $1.6\sigma$ , neglecting correlations between the data and using the four-dimensional parameter 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  $2.6\sigma$  separation in the four-dimensional parameter space.

ACT collaboration, Louis et al., arXiv:2503.14452



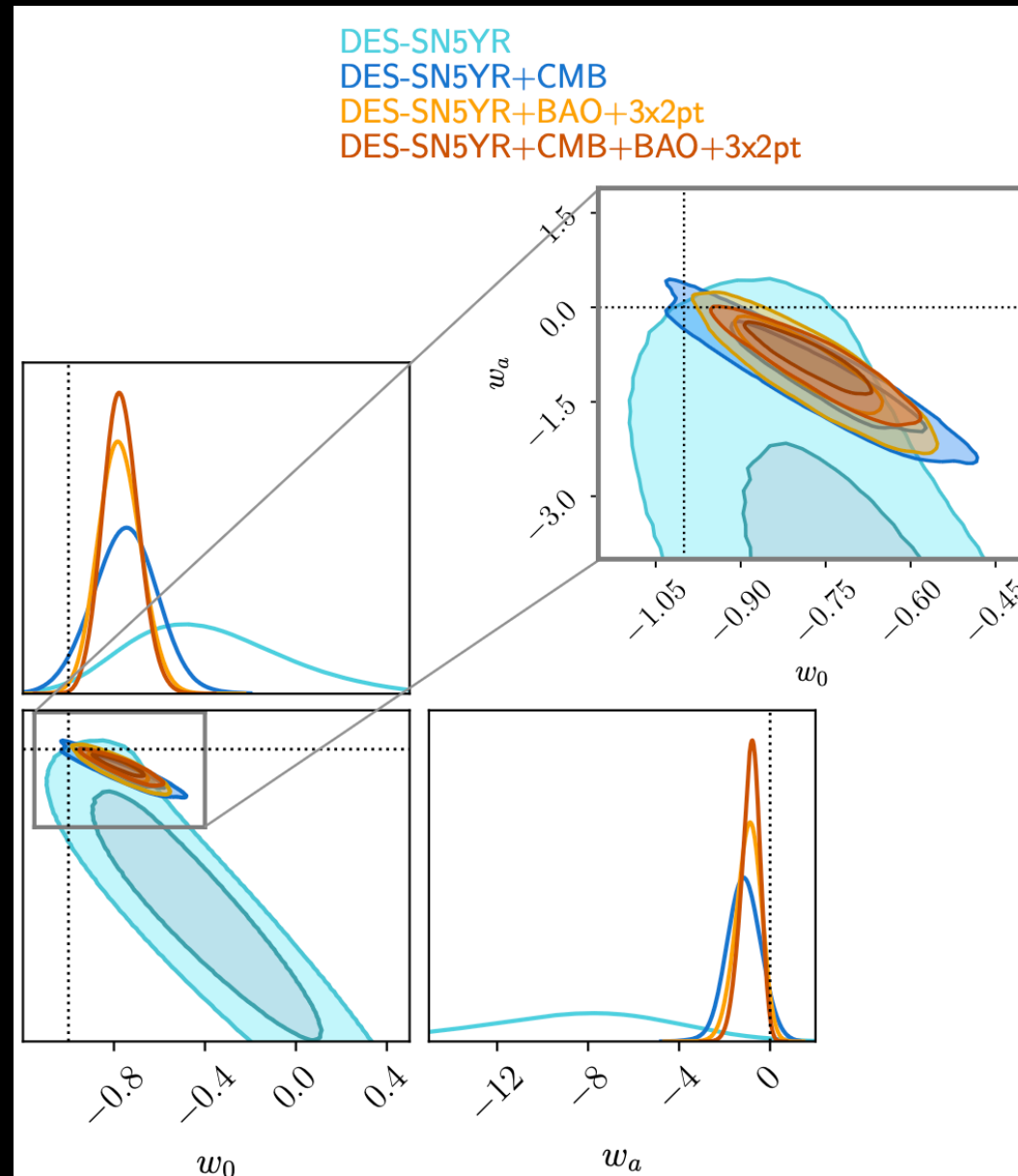
# Consequences? Indication for DDE



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

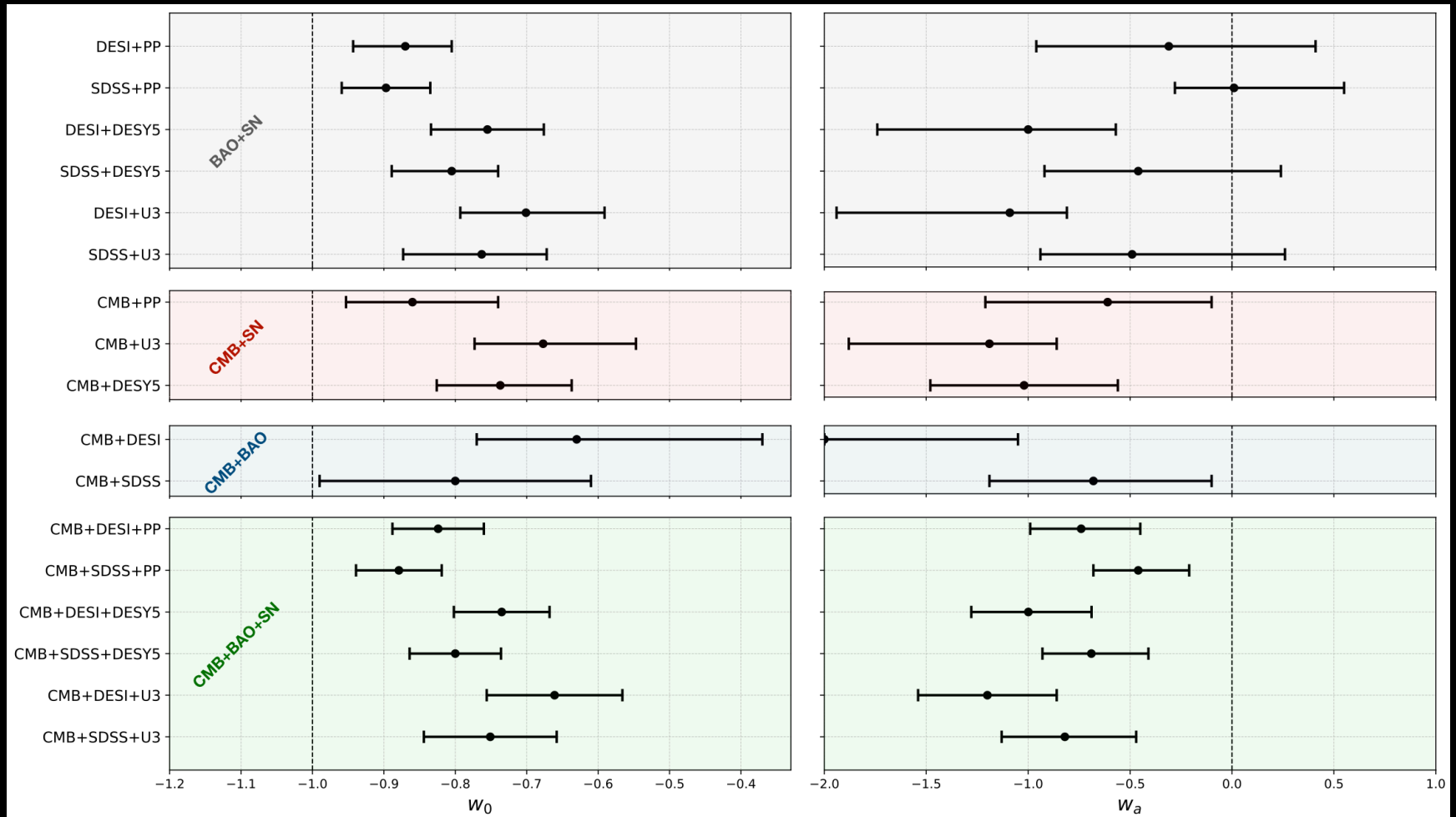


# Consequences? Indication for DDE



DESY5 collaboration: Abbott et al., arXiv:2401.02929

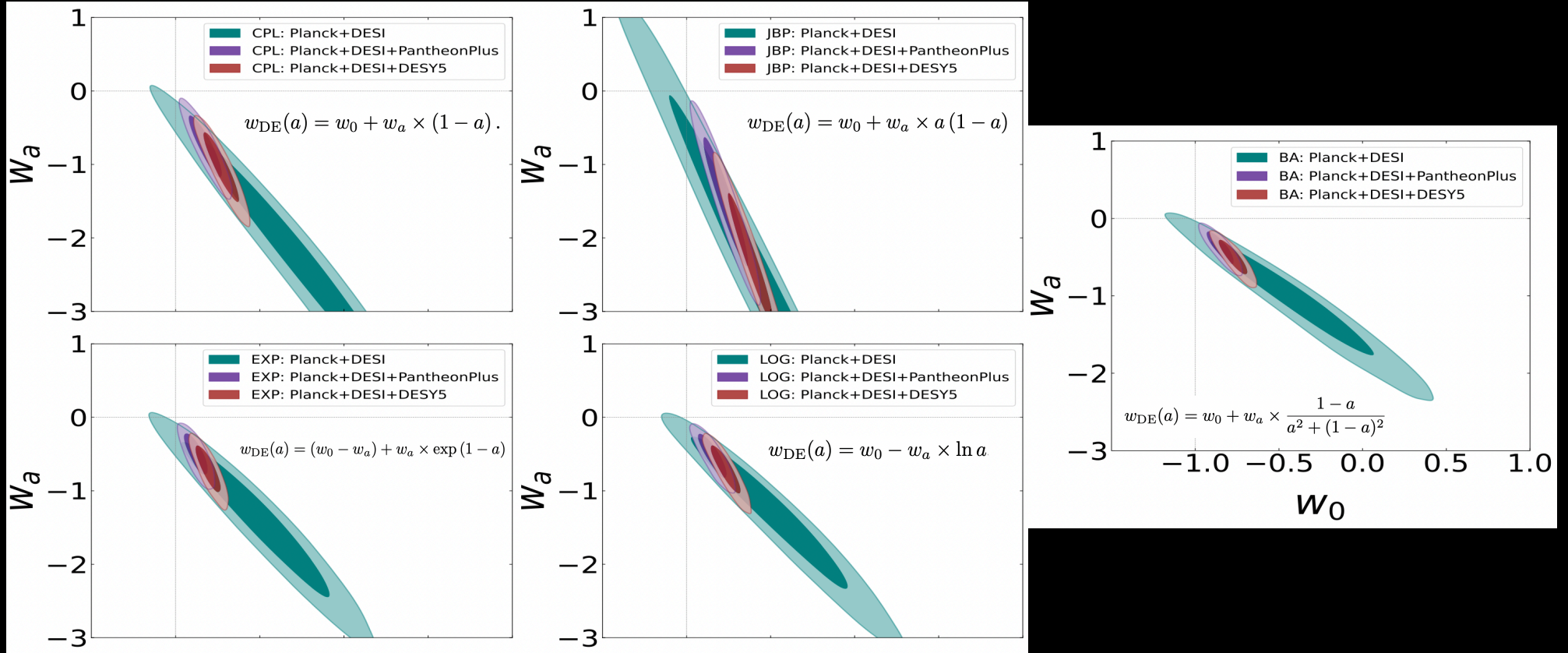
# Hints for DDE robust changing datasets



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.

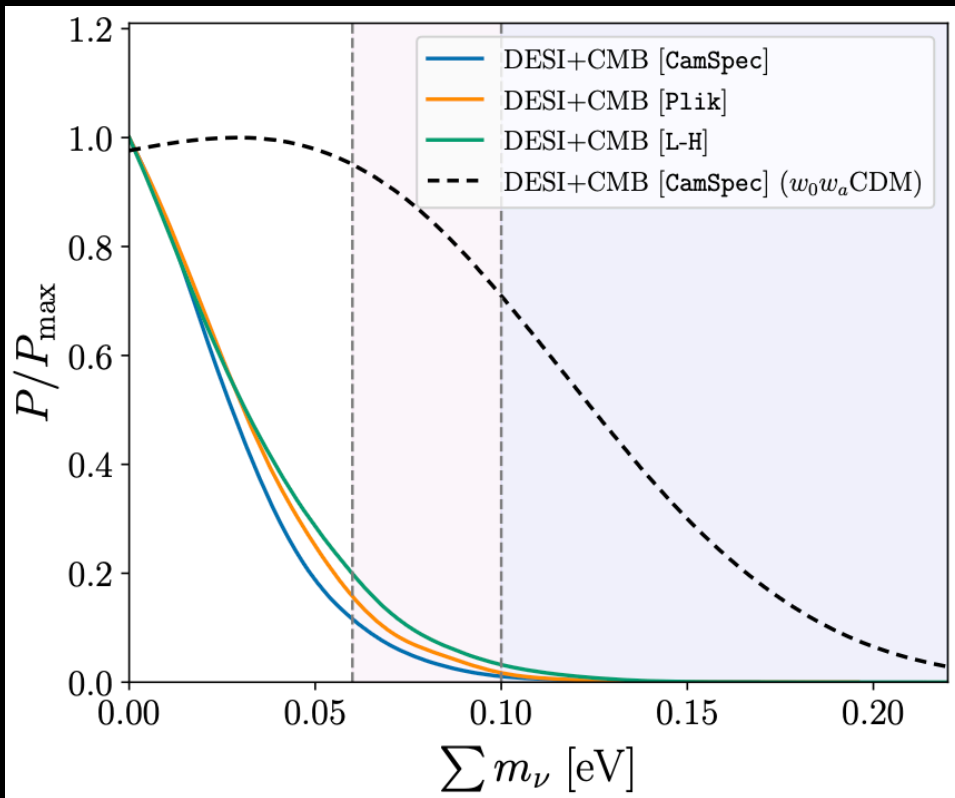
# Hint for DDE robust changing $w(z)$ parametrizations

Giare, 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  $\chi^2$  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.

# Consequences? Neutrino mass tension

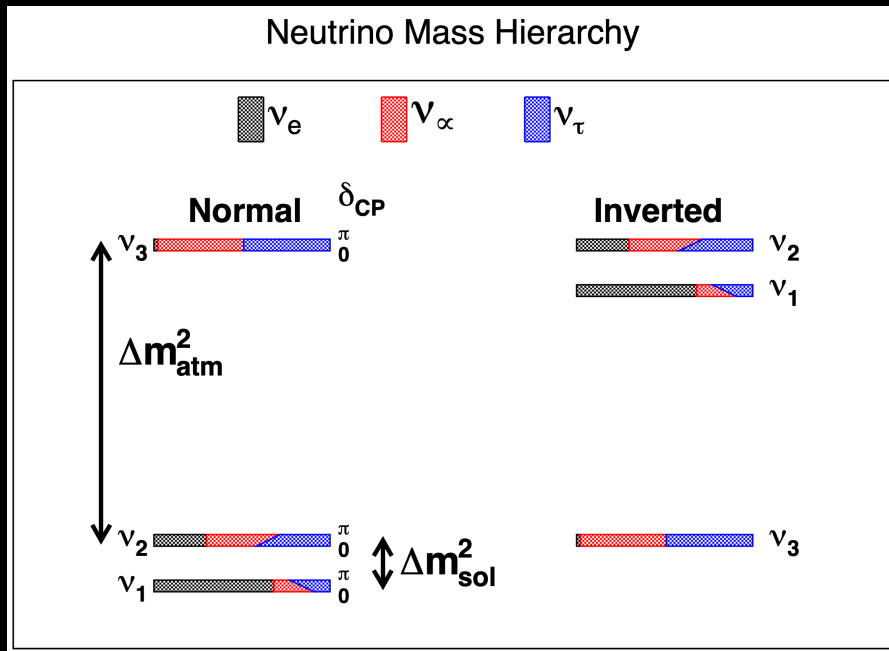


Model/Dataset	$\Omega_m$	$H_0$ [km s <sup>-1</sup> Mpc <sup>-1</sup> ]	$H_0 r_d$ [100 km s <sup>-1</sup> ]	$\sum m_\nu$ [eV]
<b><math>\Lambda</math>CDM + <math>\sum m_\nu</math></b>				
DESI BAO+CMB [Camspec]	$0.3009 \pm 0.0037$	$68.36 \pm 0.29$	$100.96 \pm 0.48$	$< 0.0642$
DESI BAO+CMB [L-H]	$0.2995 \pm 0.0037$	$68.48 \pm 0.30$	$101.16 \pm 0.49$	$< 0.0774$
DESI BAO+CMB [Planck]	$0.2998 \pm 0.0038$	$68.56 \pm 0.31$	$101.09 \pm 0.50$	$< 0.0691$

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

# Consequences? Neutrino mass tension

Even though the absolute masses of neutrinos  $\nu$  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.



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:

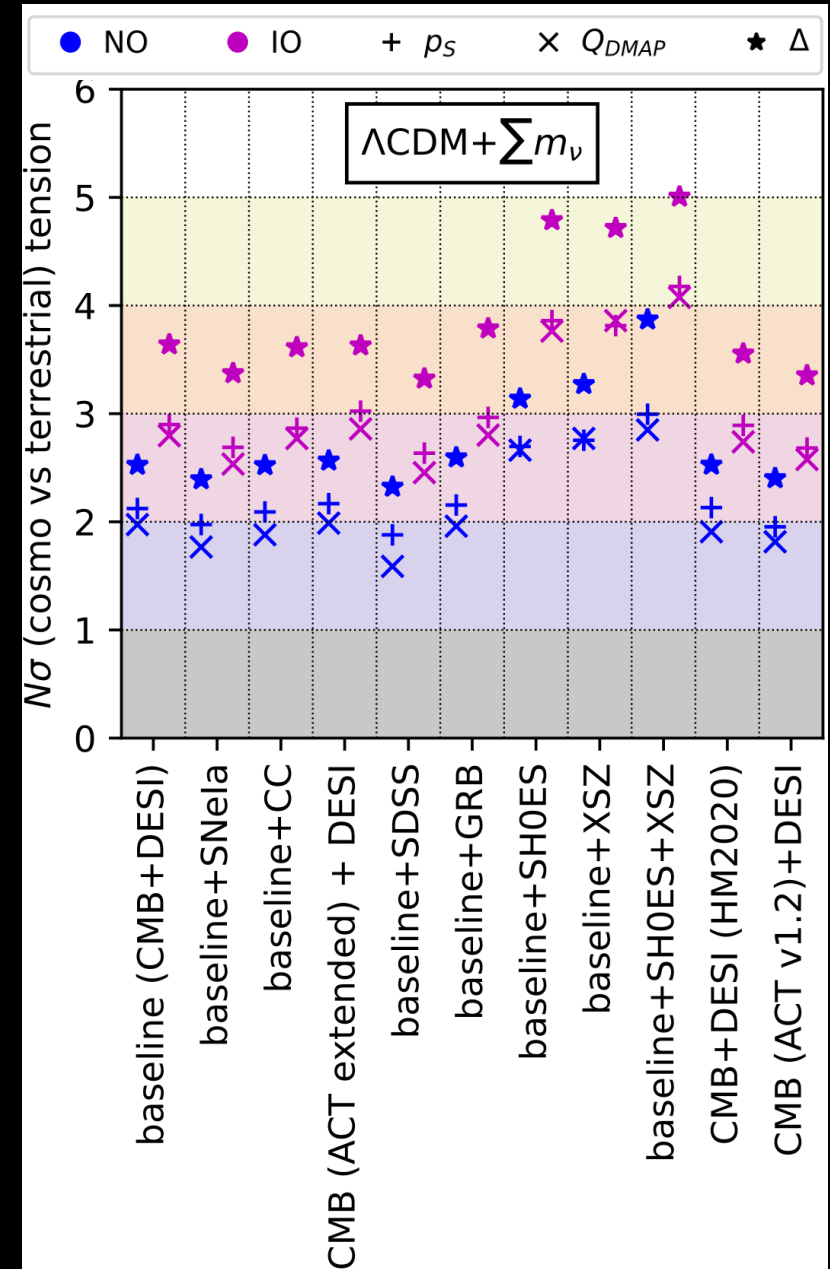
$$\sum m_\nu > \begin{cases} (0.0591 \pm 0.00027) \text{ eV} & (\text{NO}) \\ (0.0997 \pm 0.00051) \text{ eV} & (\text{IO}) \end{cases}$$

# Consequences? Neutrino mass tension

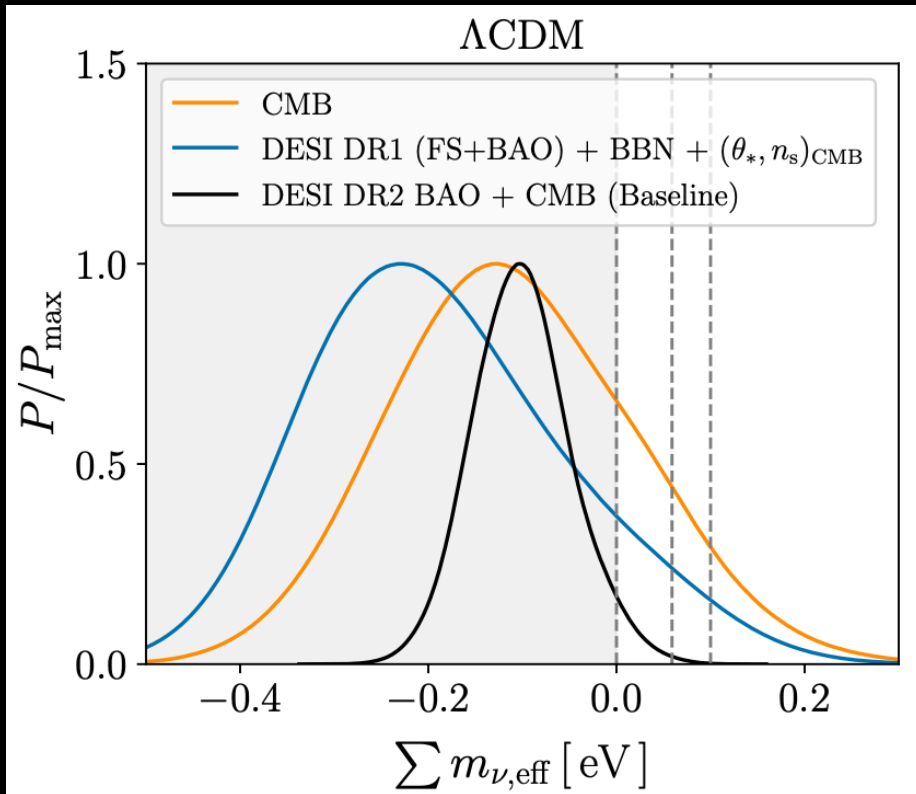
Dataset combination	$\Lambda\text{CDM} + \sum m_\nu$	
	$\sum m_\nu$ (eV)	$B_{\text{NO}, \text{IO}}$
baseline (CMB + DESI)	$< 0.072$	8.1
baseline + SNeIa	$< 0.081$	7.0
baseline + CC	$< 0.073$	7.3
baseline + SDSS	$< 0.083$	6.8
baseline + SH0ES	$< 0.048$	47.8
baseline + XSZ	$< 0.050$	46.5
baseline + GRB	$< 0.072$	8.7
aggressive combination (baseline + SH0ES + XSZ)	$< 0.042 \text{ eV}$	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  $2.5\sigma$ , and increases to approximately  $3.5\sigma$  for IO, when excluding the most extreme cases involving SH0ES and XSZ.



# Consequences? Indication for negative neutrino mass



Model/Dataset	$\Omega_m$	$H_0 [\text{km s}^{-1} \text{Mpc}^{-1}]$	$\sum m_{\nu, \text{eff}} [\text{eV}]$
<b><math>\Lambda</math>CDM + <math>\sum \mathbf{m}_{\nu, \text{eff}}</math></b>			
DESI BAO+CMB (Baseline)	$0.2953 \pm 0.0043$	$68.92 \pm 0.38$	$-0.101^{+0.047}_{-0.056}$
DESI BAO+CMB (plik)	$0.2948 \pm 0.0043$	$69.06 \pm 0.39$	$-0.099^{+0.050}_{-0.061}$
DESI BAO+CMB (L-H)	$0.2953 \pm 0.0044$	$68.89 \pm 0.39$	$-0.067^{+0.054}_{-0.064}$

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  $\sim 3.9$  sigma for the Dark Energy 5 year (DESSY) SN sample to  $\sim 2.5$  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 DESSY 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 DESSY and Pantheon+ compilations shows evidence for an offset of  $\sim 0.04$  mag. between low and high redshifts. Systematics of this order can bring the DESSY 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  $D_{\text{perp}}$  and  $D_{\text{par}}$ . These quantities allow simple tests of consistency with the Planck LCDM cosmology. The parameter  $D_{\text{perp}}$  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  $D_{\text{perp}}$  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  $D_{\text{par}}$  provides a measure of the physical matter density  $\omega_m$  in the LCDM cosmology. The DR2 measurements of  $D_{\text{par}}$  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.

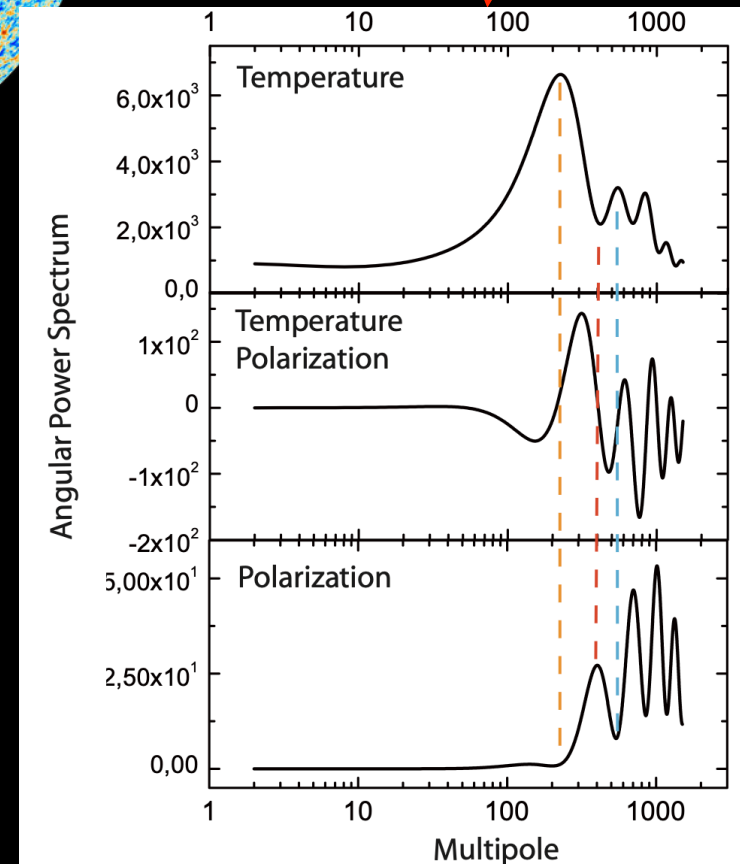
What about the CMB problems?



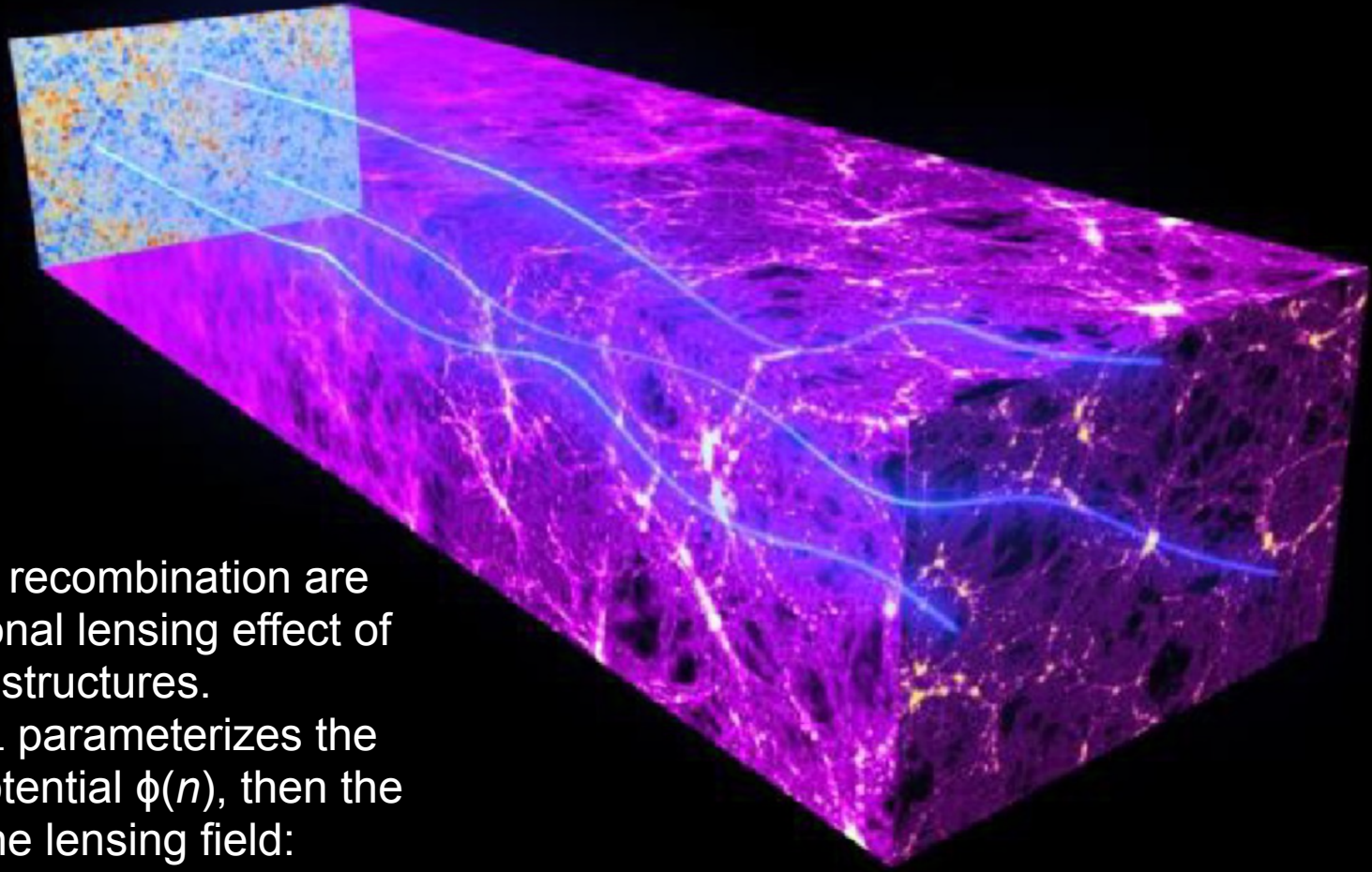
$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1) \frac{\Delta T}{T}(\vec{\gamma}_2) \right\rangle = \frac{1}{2\pi} \sum_{\ell} (2\ell+1) C_{\ell} P_{\ell}(\vec{\gamma}_1 \cdot \vec{\gamma}_2)$$

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  $\phi(n)$ , then the power spectrum of the lensing field:

$$C_{\ell}^{\phi\phi} \rightarrow A_L C_{\ell}^{\phi\phi}$$

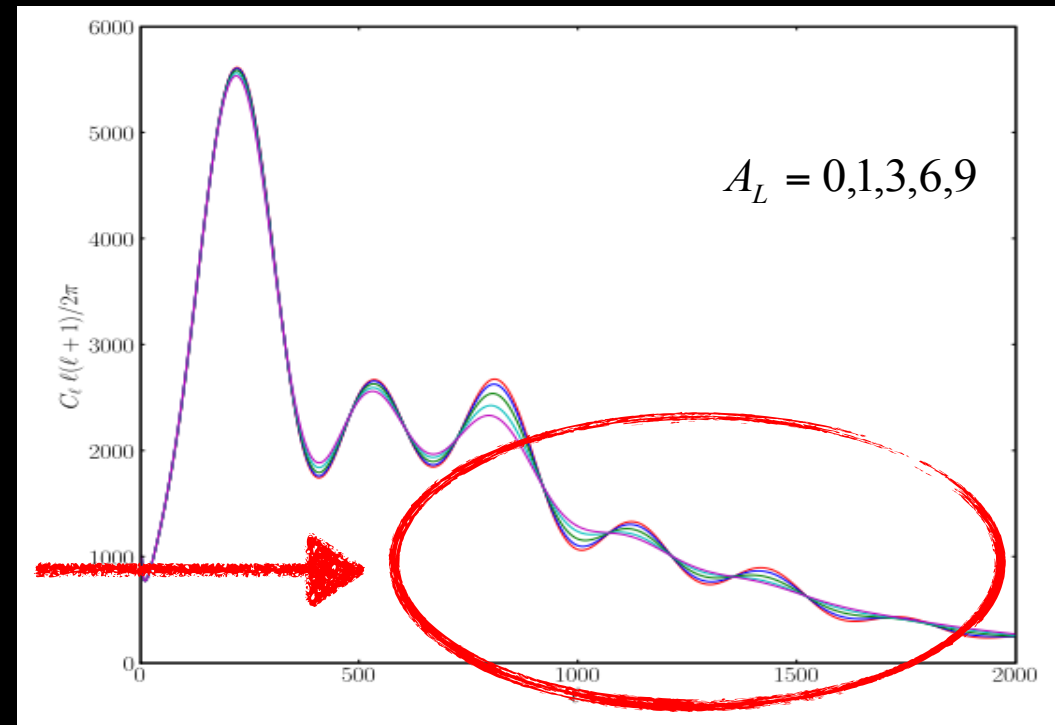
The gravitational lensing deflects the photon path by a quantity defined by the gradient of the lensing potential  $\phi(n)$ , integrated along the line of sight  $n$ , remapping the temperature field.

# Plik PR3 $A_L$ problem

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

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

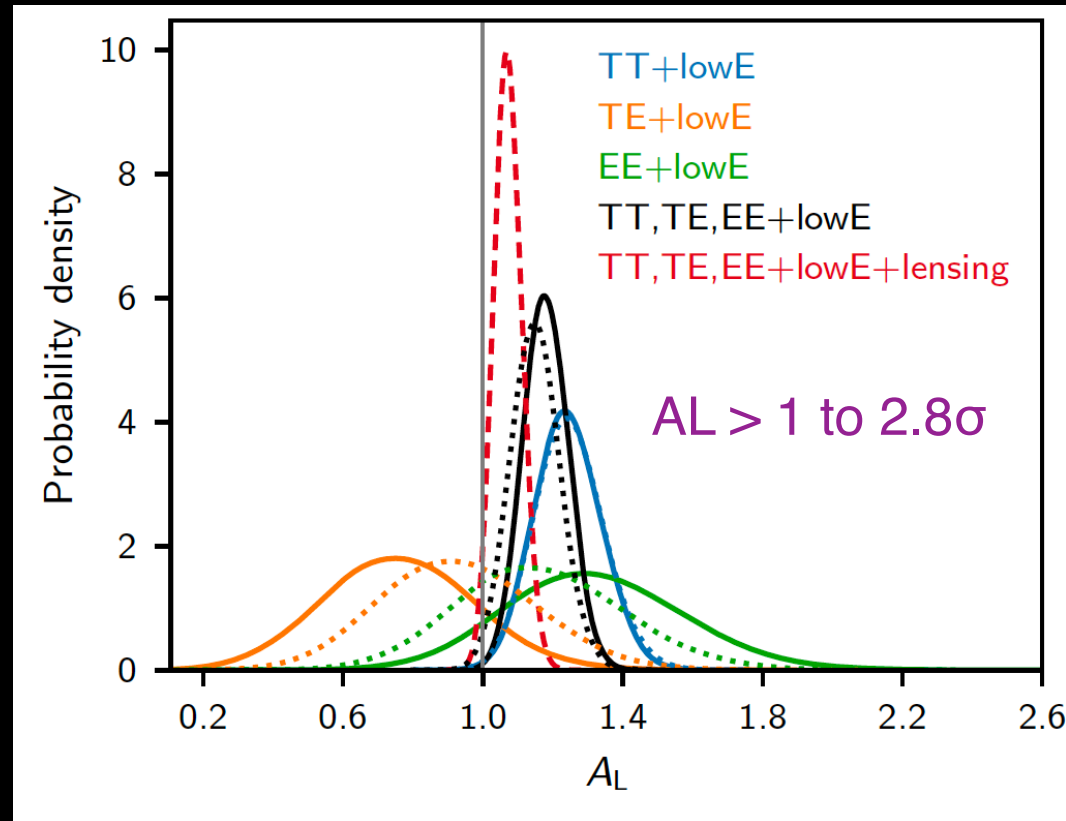
If  $A_L = 1$  then the theory is correct, otherwise we have a new physics or systematics.



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

# Plik PR3 $A_L$ problem

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



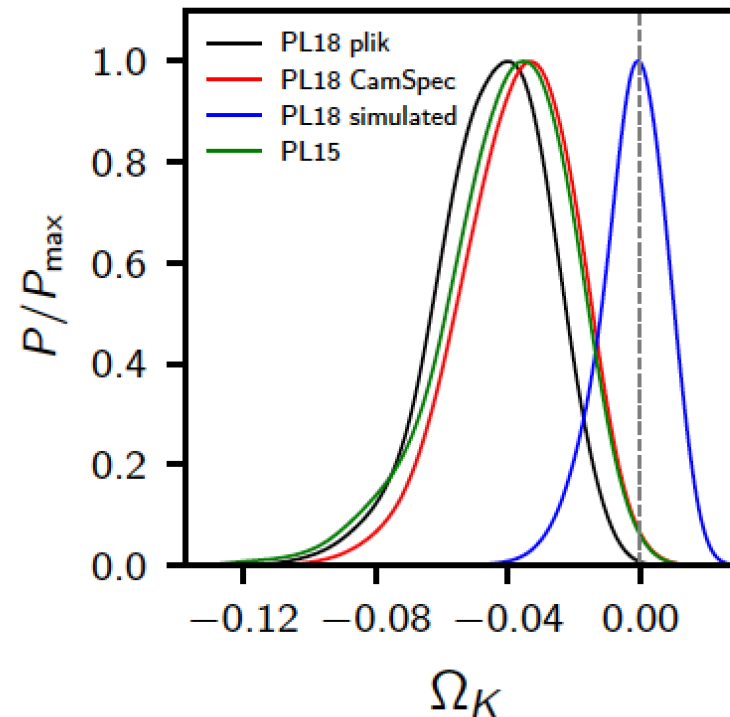
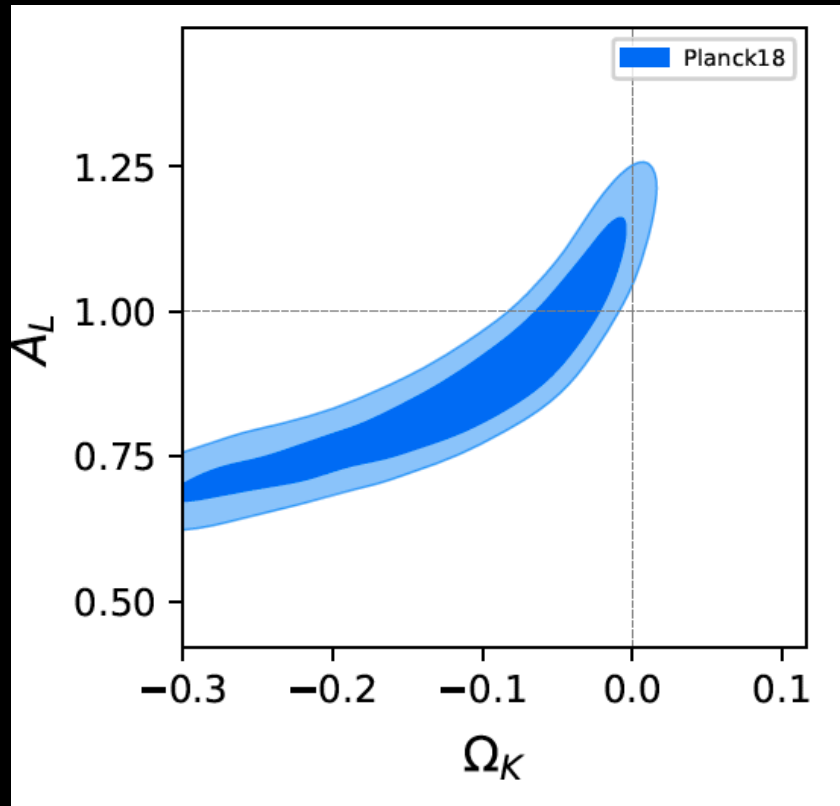
$$A_L = 1.243 \pm 0.096 \quad (68\%, \text{Planck TT+lowE}),$$

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

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



# Plik PR3 $\Omega_K$ problem



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

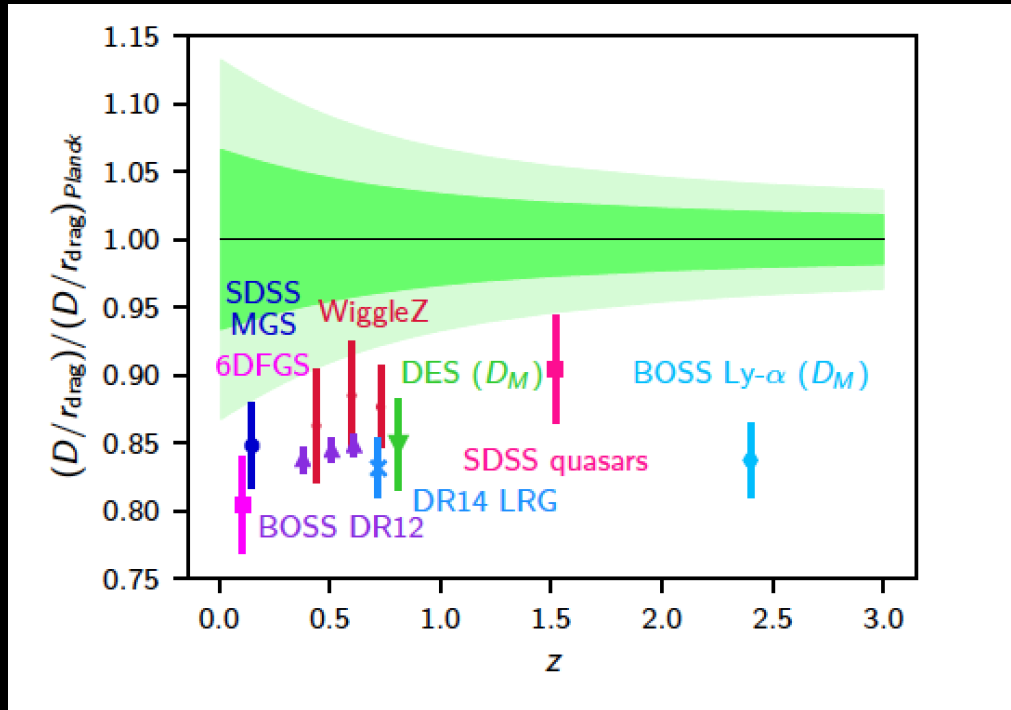
This excess of lensing affects the constraints on the curvature of the universe:

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

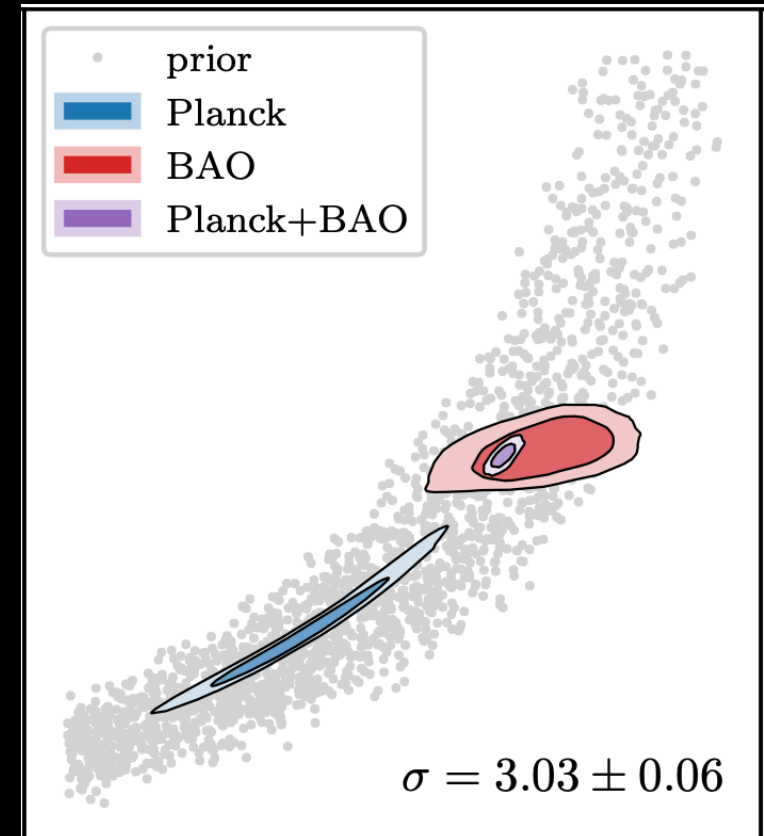
Planck 2018, *Astron.Astrophys.* 641 (2020) A6

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 $\Lambda$ CDM



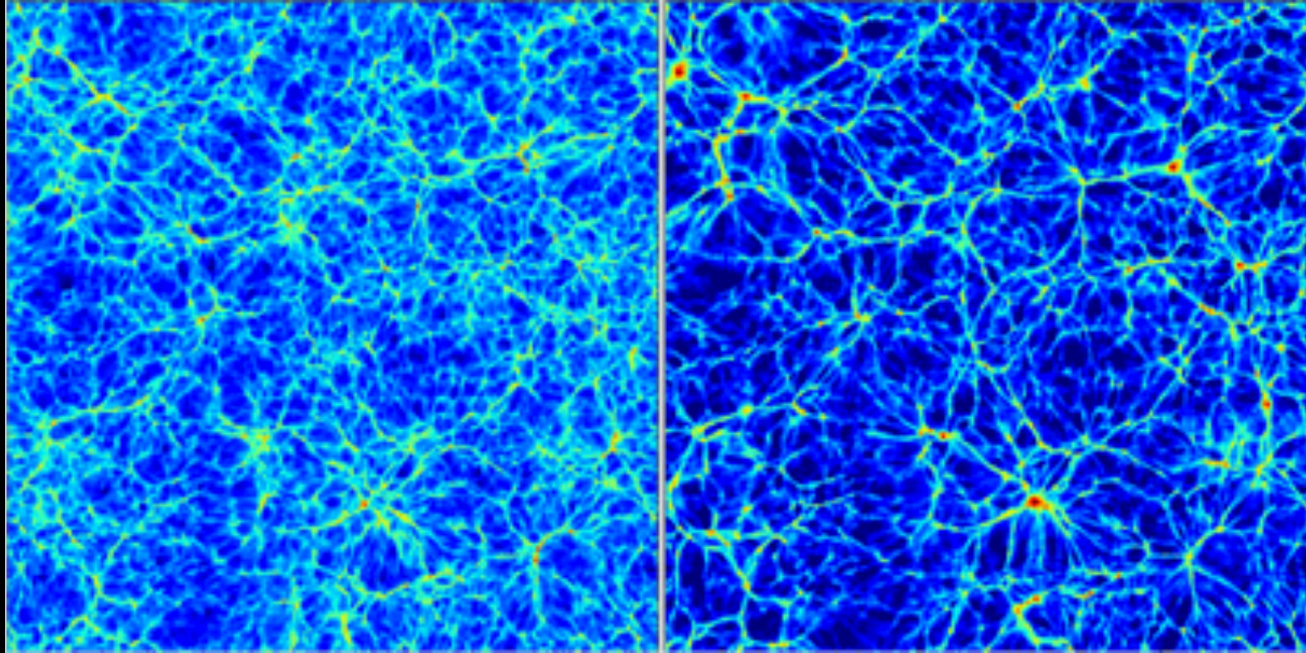
Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203



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

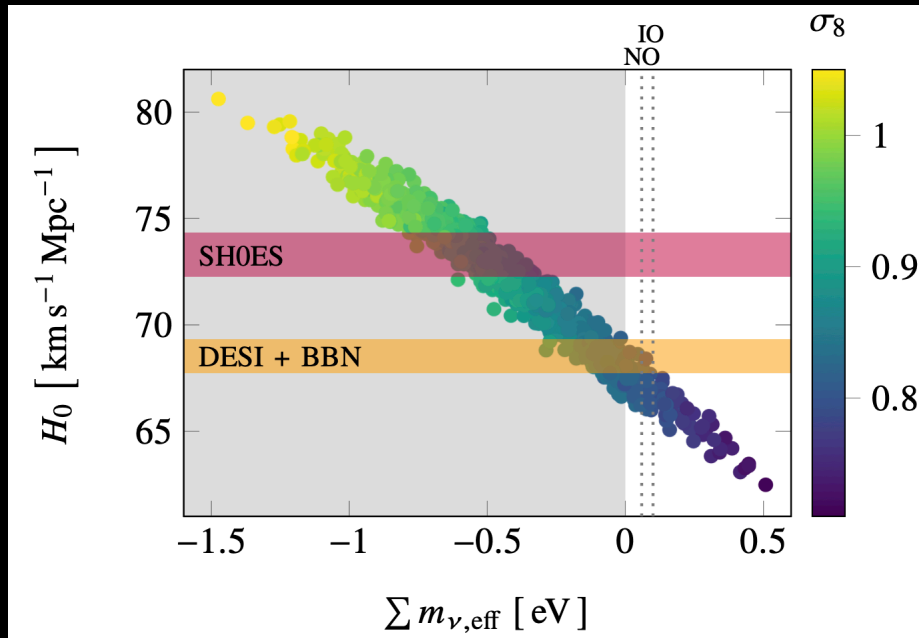
Allowing curvature to vary reveals a significant disagreement between the Planck spectra and BAO data.

# The total neutrino mass and CMB lensing

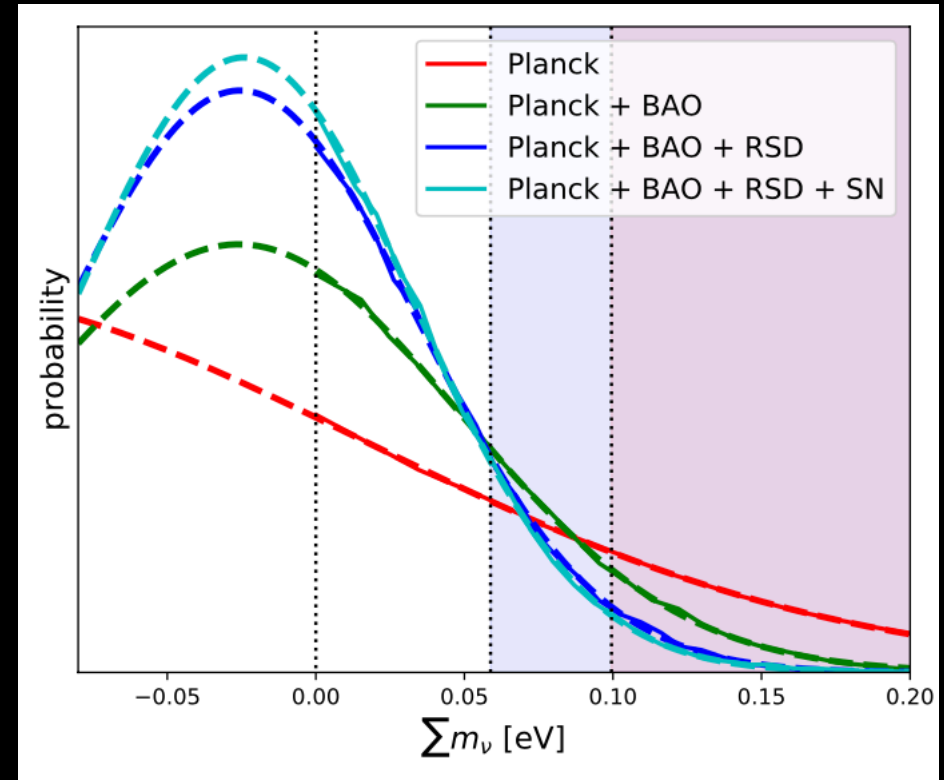


Given that massive neutrinos practically do not form structure, more massive the neutrino is less structure we have, less the CMB lensing will be. So a larger signal of lensing means a smaller neutrino mass.

# Negative total neutrino mass



Elbers et al., arXiv: 2407.10965

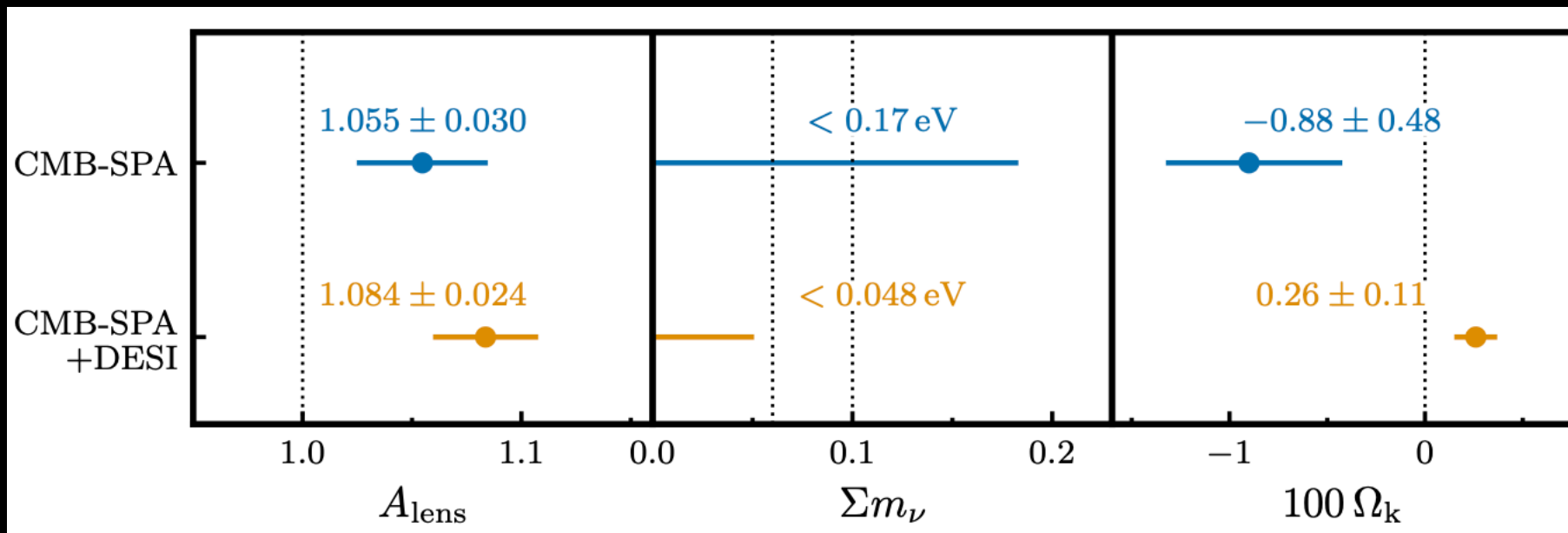


eBOSS collaboration, Alam et al.,  
*Phys.Rev.D* 103 (2021) 8, 083533

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



$$A_{\text{lens}} = 1.084 \pm 0.035 \text{ for SPT-3G D1 + DESI,} \quad (74)$$

$$A_{\text{lens}} = 1.092 \pm 0.026 \text{ for SPT+ACT + DESI,} \quad (75)$$

$$A_{\text{lens}} = 1.084 \pm 0.024 \text{ for CMB-SPA + DESI.} \quad (76)$$

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:

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

$$\Sigma m_\nu < 0.048 \text{ eV for CMB-SPA + DESI.} \quad (97)$$

The preference for a high  $A_L$  is at the  $3.5\sigma$  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. <sup>27</sup>

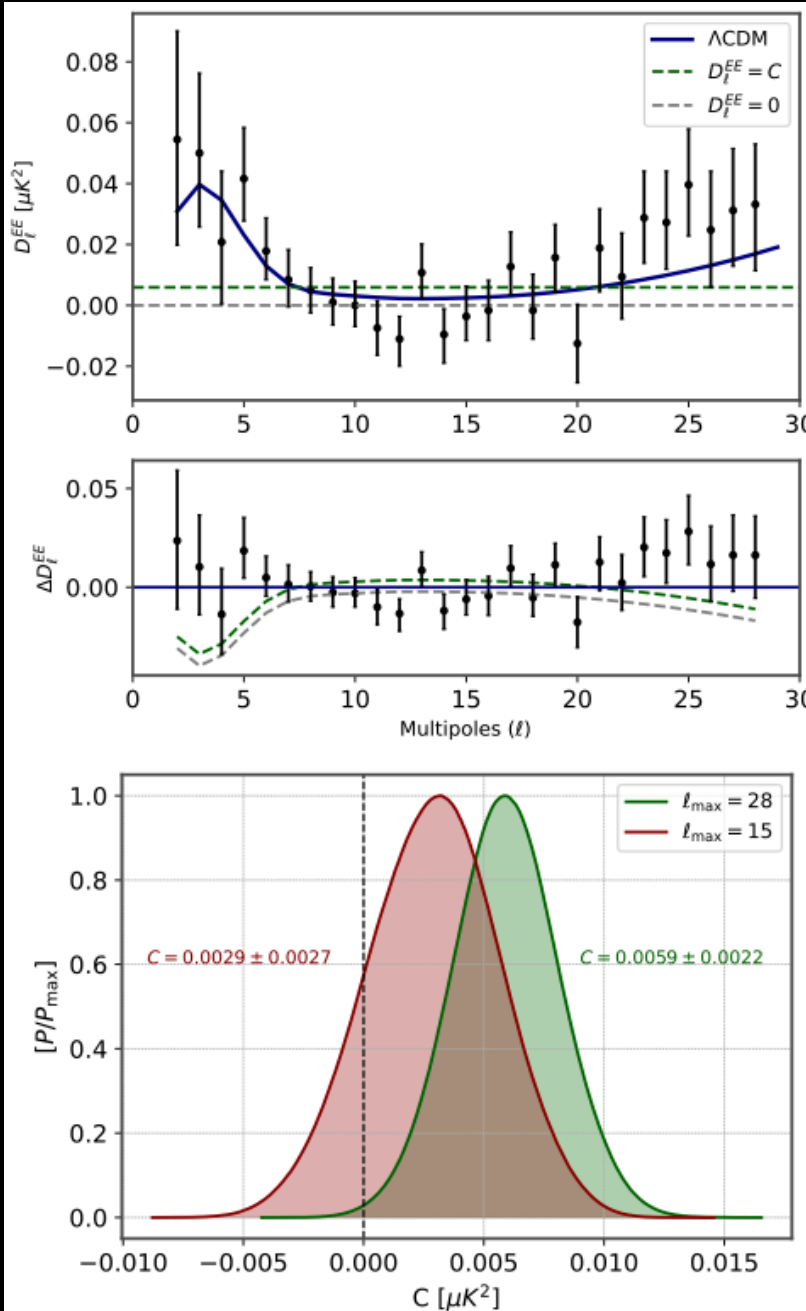
# The optical depth

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

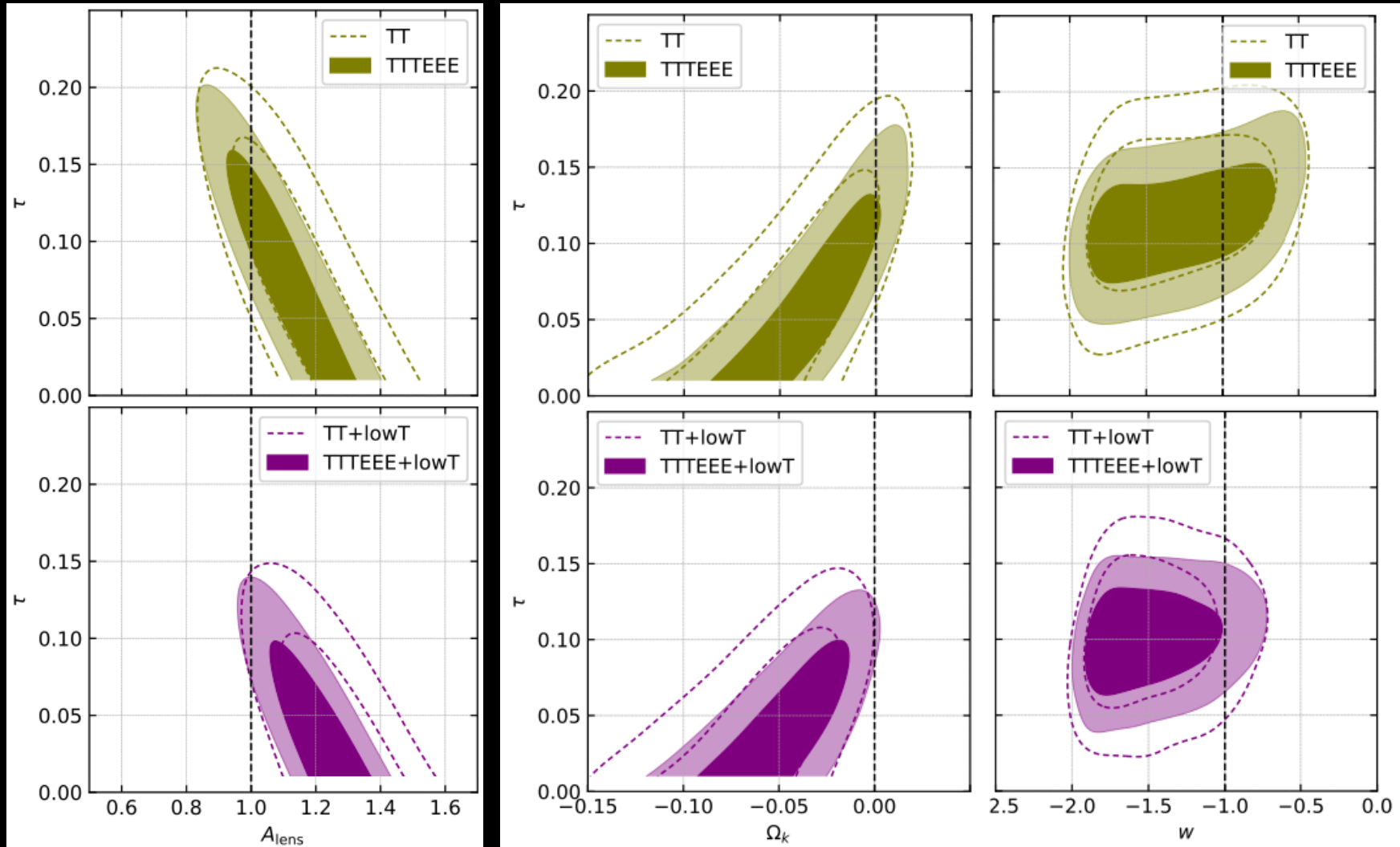
Reionization leaves an imprint on the large-scale CMB E-mode polarization (EE) and causes a suppression of temperature anisotropies at smaller scales (proportional to  $A_s e^{-2\tau}$ ). Planck measured  $\tau = 0.054 \pm 0.008$  at 68% CL, a significant improvement over the WMAP9 value of  $\tau = 0.089 \pm 0.014$ . However, the low- $\ell$  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  $2 \leq \ell \leq 15$ , the case  $C=0$  (no signal) falls within the  $1\sigma$  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  $\tau$ .

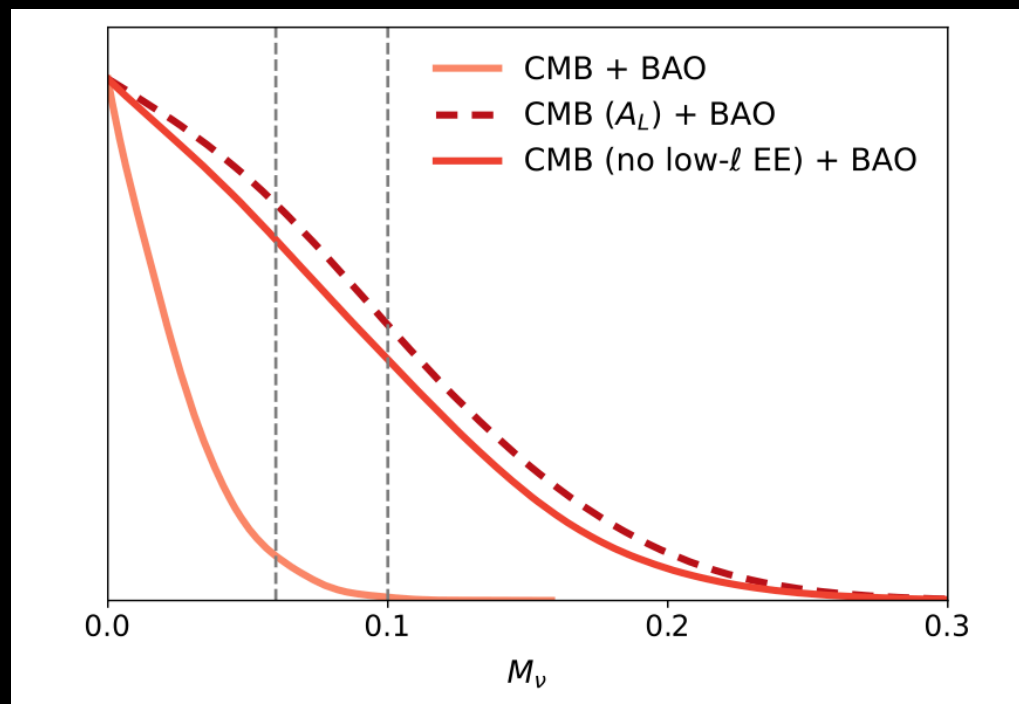


# The role of the optical depth



When the lowE data are excluded, the results become consistent with  $\Lambda$ CDM, and the Planck anomalies disappear.

# 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  $\tau$ .

Since TT measures  $A_s e^{-2\tau}$ , raising  $\tau$  requires raising  $A_s$ , but  $A_s$  also controls structure growth, that is entangled with  $\Sigma m_\nu$  effects.

This degeneracy means CMB-only data allow biased  $\Sigma m_\nu$  values; low- $\ell$  polarization is essential to pin down  $\tau$  and break the degeneracy.

The apparent CMB+BAO preference for negative neutrino masses could be an artifact of the  $\tau$ – $\Sigma m_\nu$  degeneracy.

Allowing either a free lensing amplitude  $A_L$  or dropping low- $\ell$  EE  $\tau$  constraints both restore consistency with minimal neutrino masses.

In other words: the “negative neutrino mass” problem disappears if  $\tau$  is allowed to rise, highlighting that  $\tau$  systematics strongly impact cosmological neutrino mass bounds.

# All the models are wrong, but some are useful

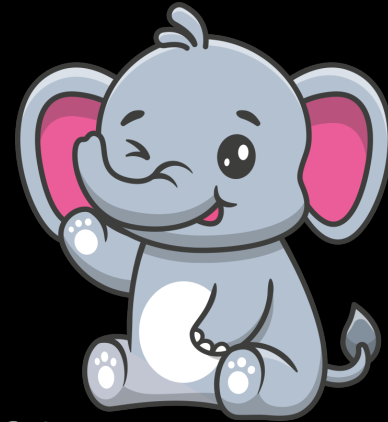
We shouldn't interpret observations through personal, theoretical, or historical priors.

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  $H_0$ .

# What is H0?

The Hubble constant  $H_0$  describes the expansion rate of the Universe today.

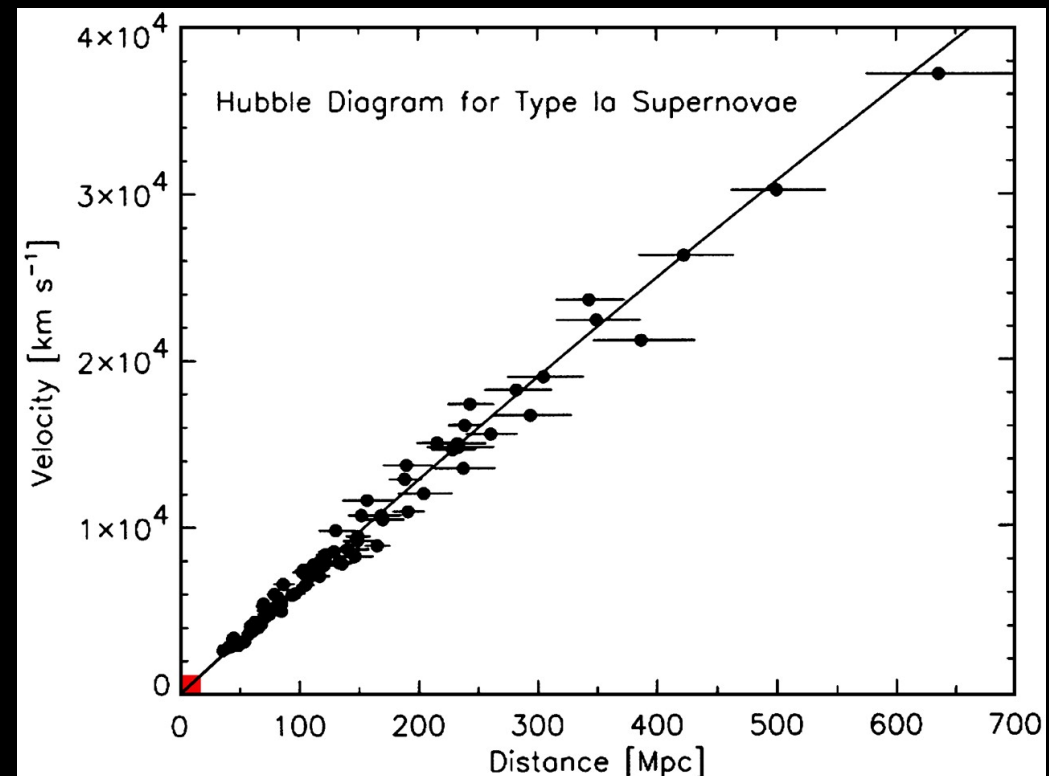
This can be obtained in two ways:

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  $H_0$  describes the expansion rate of the Universe today.

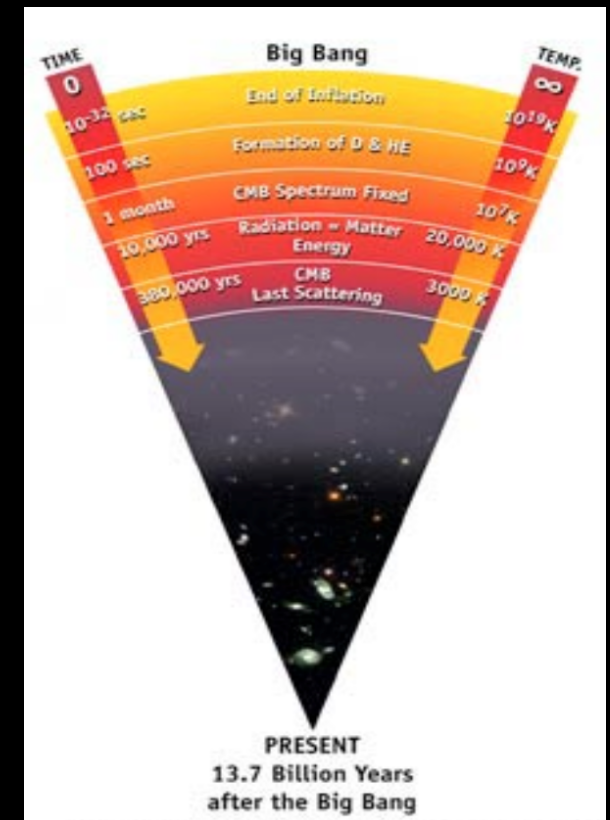
This can be obtained in **two ways**:

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.

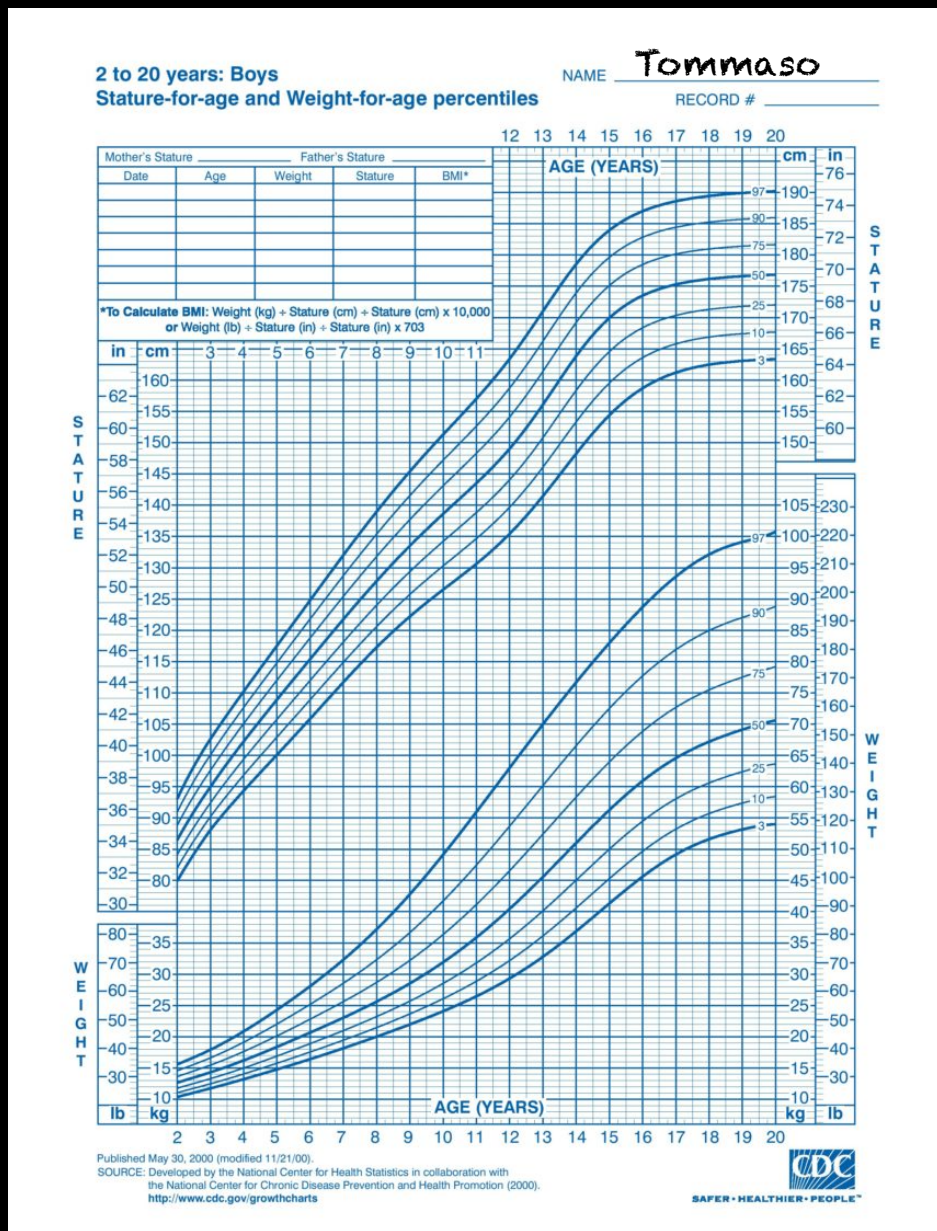
For example, we have **CMB measurements** and we assume the standard model of cosmology, i.e. the  **$\Lambda$ CDM scenario**.

**1<sup>st</sup> Friedmann equation describes the expansion history of the universe:**

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









# H0 tension

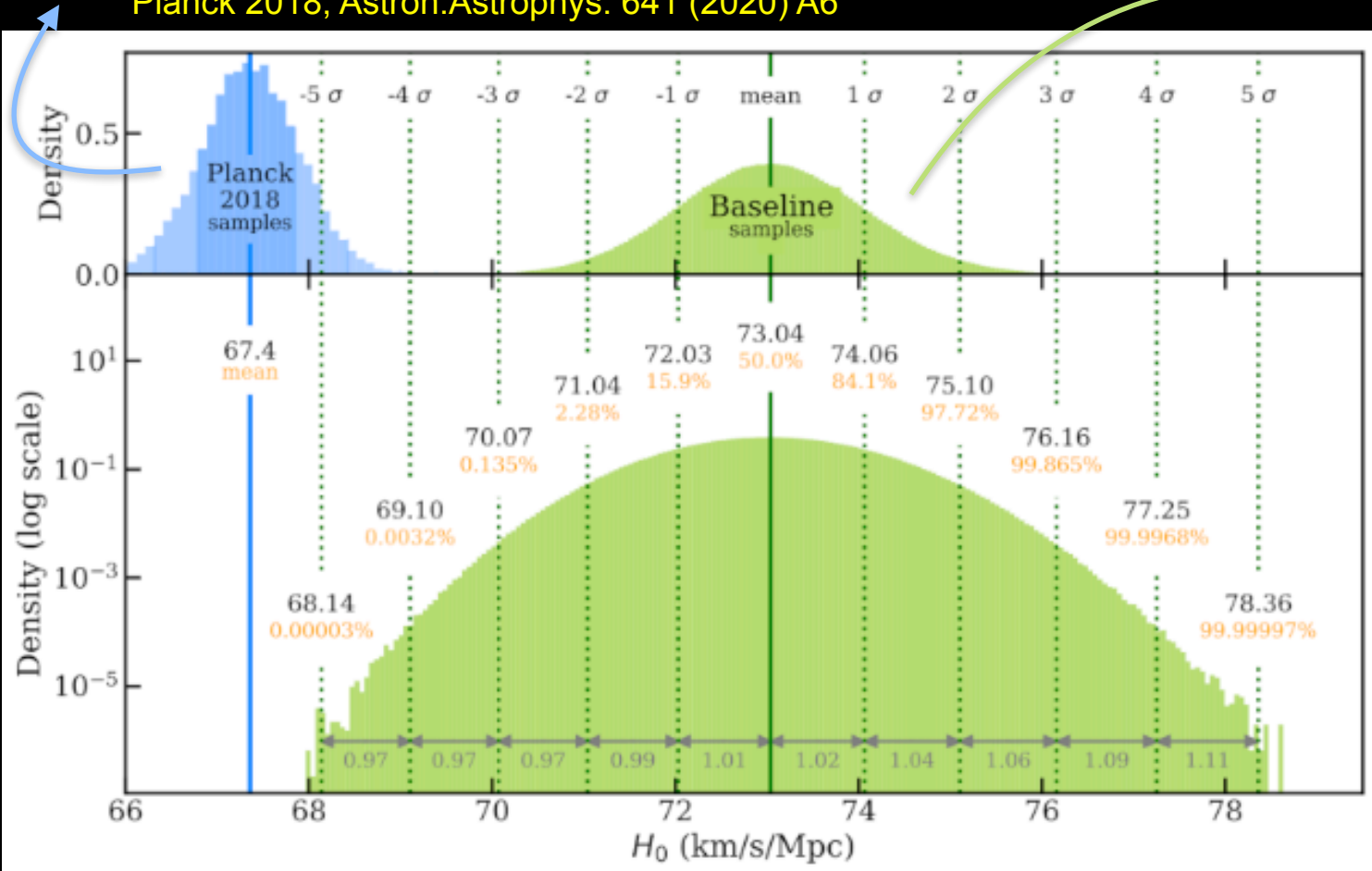
If we compare the H0 estimates using these 2 methods they disagree.

The Planck estimate assuming a “vanilla”

$\Lambda$ CDM cosmological model:

$$H_0 = 67.36 \pm 0.54 \text{ km/s/Mpc}$$

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



The latest local measurements obtained by the SH0ES collaboration

$$H_0 = 73.04 \pm 1.04 \text{ km/s/Mpc}$$

Riess et al. *arXiv:2112.04510*

5 $\sigma$  = 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...

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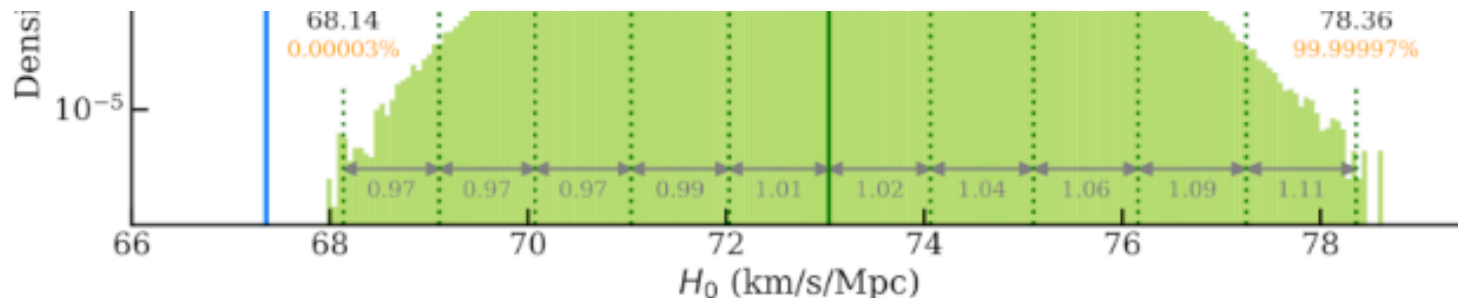
Astrophysics > Cosmology and Nongalactic Astrophysics

[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  $H_0 = 74.1 \pm 2.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . Combining these four geometric distances with our HST photometry of SMC Cepheids, we obtain  $H_0 = 73.17 \pm 0.86 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . 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  $\gamma = -0.22 \pm 0.05 \text{ mag dex}^{-1}$ . Our local measurement of  $H_0$  based on Cepheids and Type Ia supernovae shows a  $5.8\sigma$  tension with the value inferred from the CMB assuming a  $\Lambda$ CDM cosmology, reinforcing the possibility of physics beyond  $\Lambda$ CDM.



implausible to reconcile  
the two by chance

# H0 tension

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. Korneelje, 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  $\Lambda$ CDM 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 power.

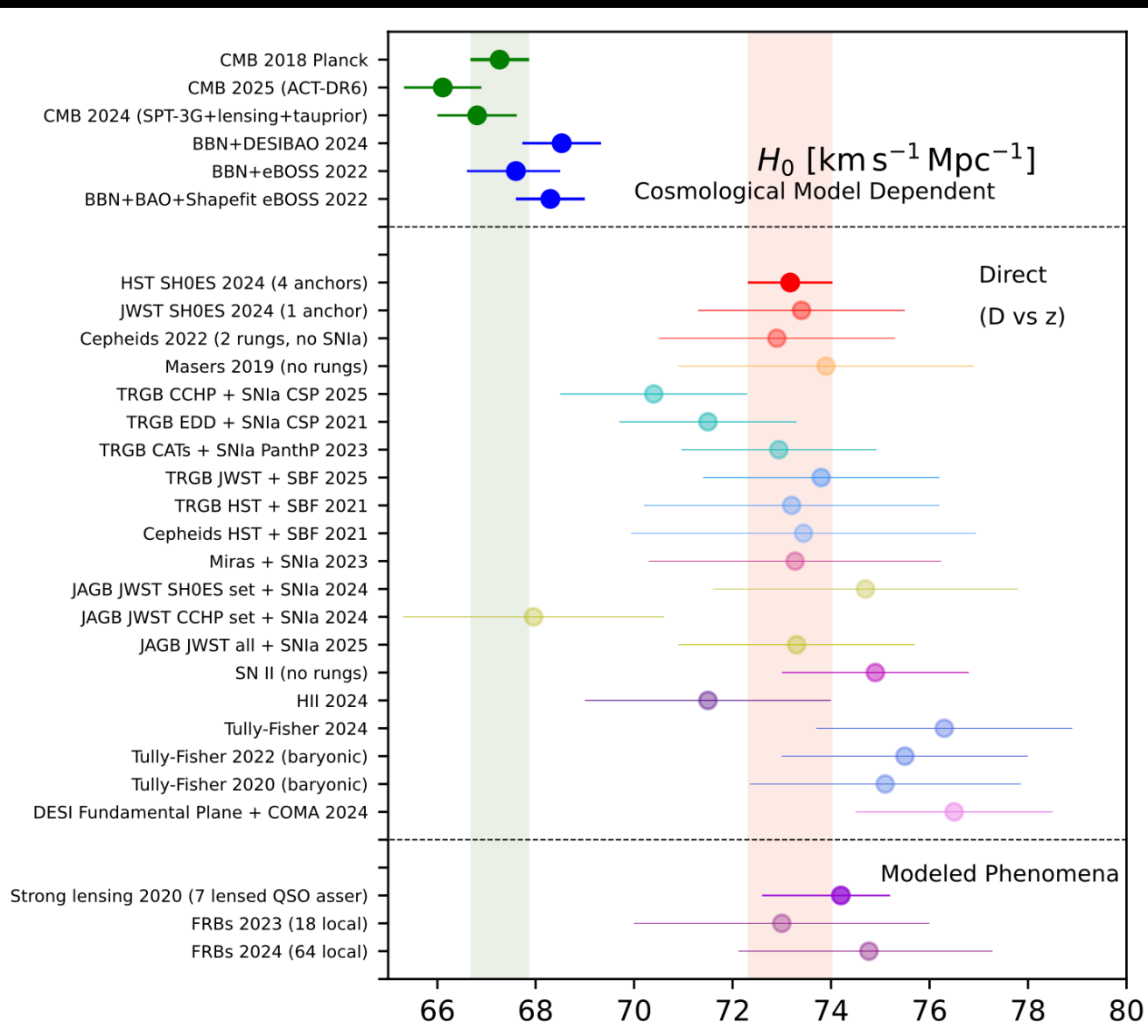
Parameter	Planck	SPT-3G D1	ACT DR6	SPT+ACT	SPT+Planck	CMB-SPA
<i>Sampled</i>						
$10^4 \theta_s^*$	$104.184 \pm 0.029$	$104.171 \pm 0.060$	$104.157 \pm 0.030$	$104.158 \pm 0.025$	$104.176 \pm 0.026$	$104.162 \pm 0.023$
$100 \Omega_b h^2$	$2.238 \pm 0.014$	$2.221 \pm 0.020$	$2.257 \pm 0.016$	$2.247 \pm 0.015$	$2.230 \pm 0.011$	$2.2381 \pm 0.0093$
$100 \Omega_c h^2$	$11.98 \pm 0.11$	$12.14 \pm 0.16$	$12.26 \pm 0.17$	$12.15 \pm 0.15$	$12.05 \pm 0.089$	$12.009 \pm 0.086$
$n_s$	$0.9657 \pm 0.0040$	$0.951 \pm 0.011$	$0.9682 \pm 0.005$	$0.965 \pm 0.005$	$0.9636 \pm 0.0035$	$0.9684 \pm 0.0030$
$\log(10^{10} A_s)$	$3.042 \pm 0.011$	$3.054 \pm 0.015$	$3.038 \pm 0.012$	$3.042 \pm 0.011$	$3.046 \pm 0.010$	$3.0479 \pm 0.0099$
$\tau_{\text{reio}}$	$0.0535 \pm 0.0056$	$0.0506 \pm 0.0059$	$0.0513 \pm 0.0060$	$0.0514 \pm 0.0059$	$0.0538 \pm 0.0054$	$0.0559 \pm 0.0055$
<i>Derived</i>						
$H_0$ [km/s/Mpc]	$67.41 \pm 0.49$	$66.66 \pm 0.60$	$66.51 \pm 0.64$	$66.59 \pm 0.46$	$67.07 \pm 0.38$	$67.24 \pm 0.35$

6.7 sigma

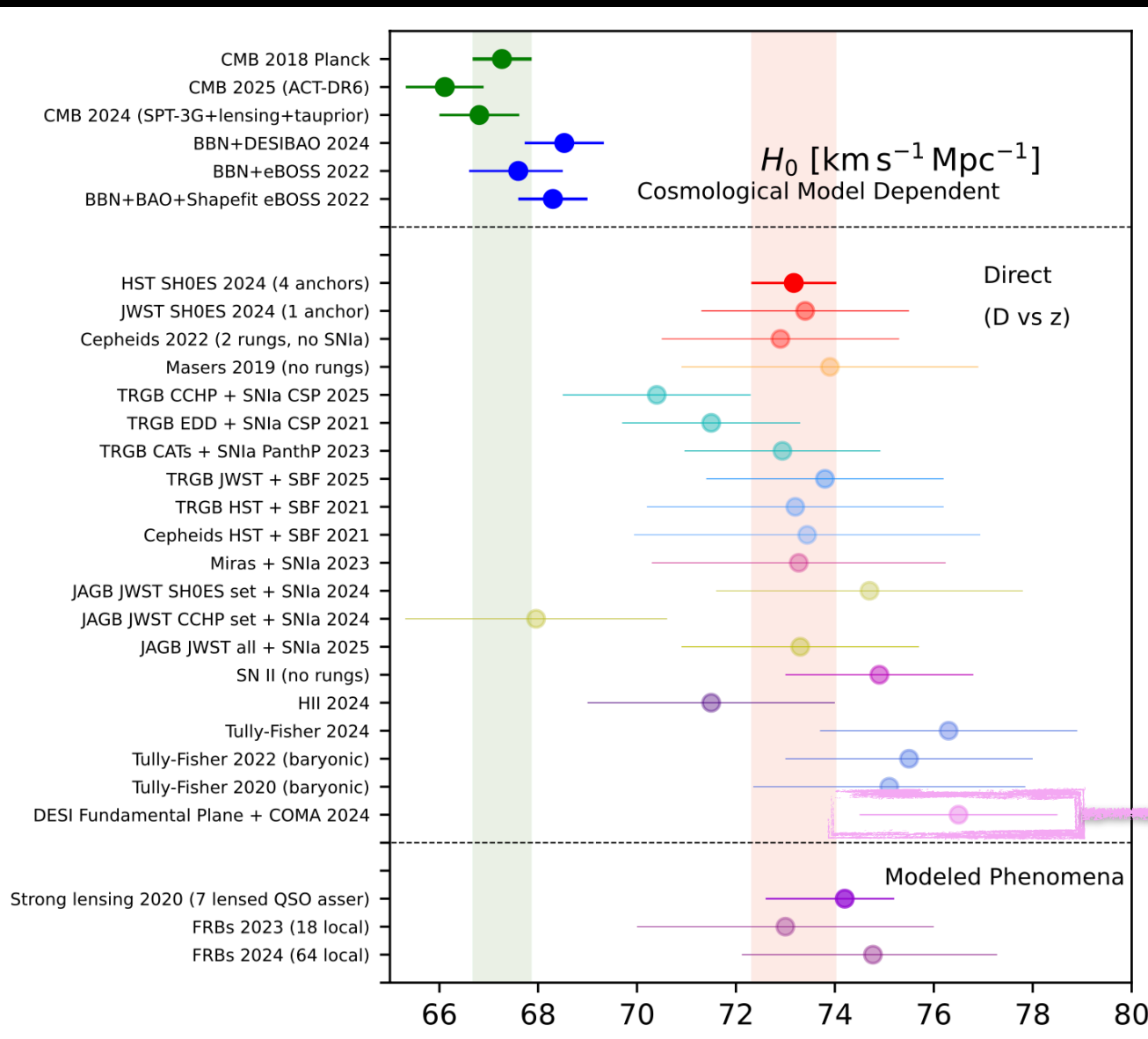
# Latest H0 measurements

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

The red vertical band corresponds to the  $H_0$  value from SH0ES Team and the grey vertical band corresponds to the  $H_0$  value as reported by Planck 2018 team within a  $\Lambda$ CDM scenario.



# Latest H0 measurements



DESI measured relation between  $H_0$  and the distance to the Coma cluster using the fundamental plane relation of early-type galaxies.

$$H_0 = 76.5 \pm 2.2 \text{ km/s/Mpc}$$

Scolnic et al., arXiv: 2409.14546

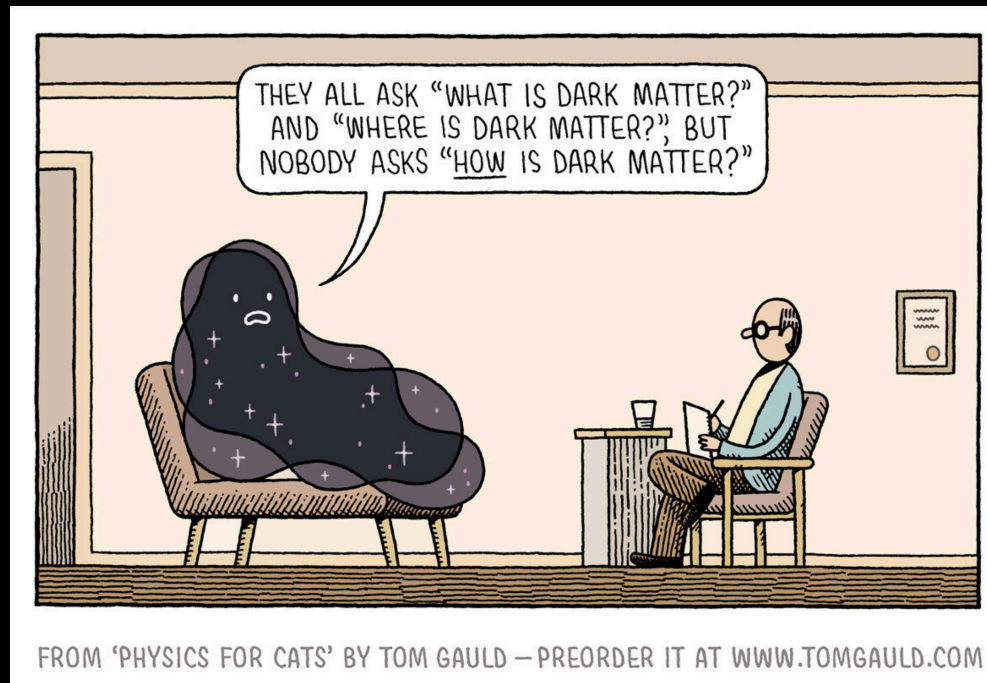


# Why Do We Care?

Dark Matter is at the heart of cosmological tensions and  $\Lambda$ CDM'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  $\Lambda$ CDM model, any particle-physics interpretation must wait.

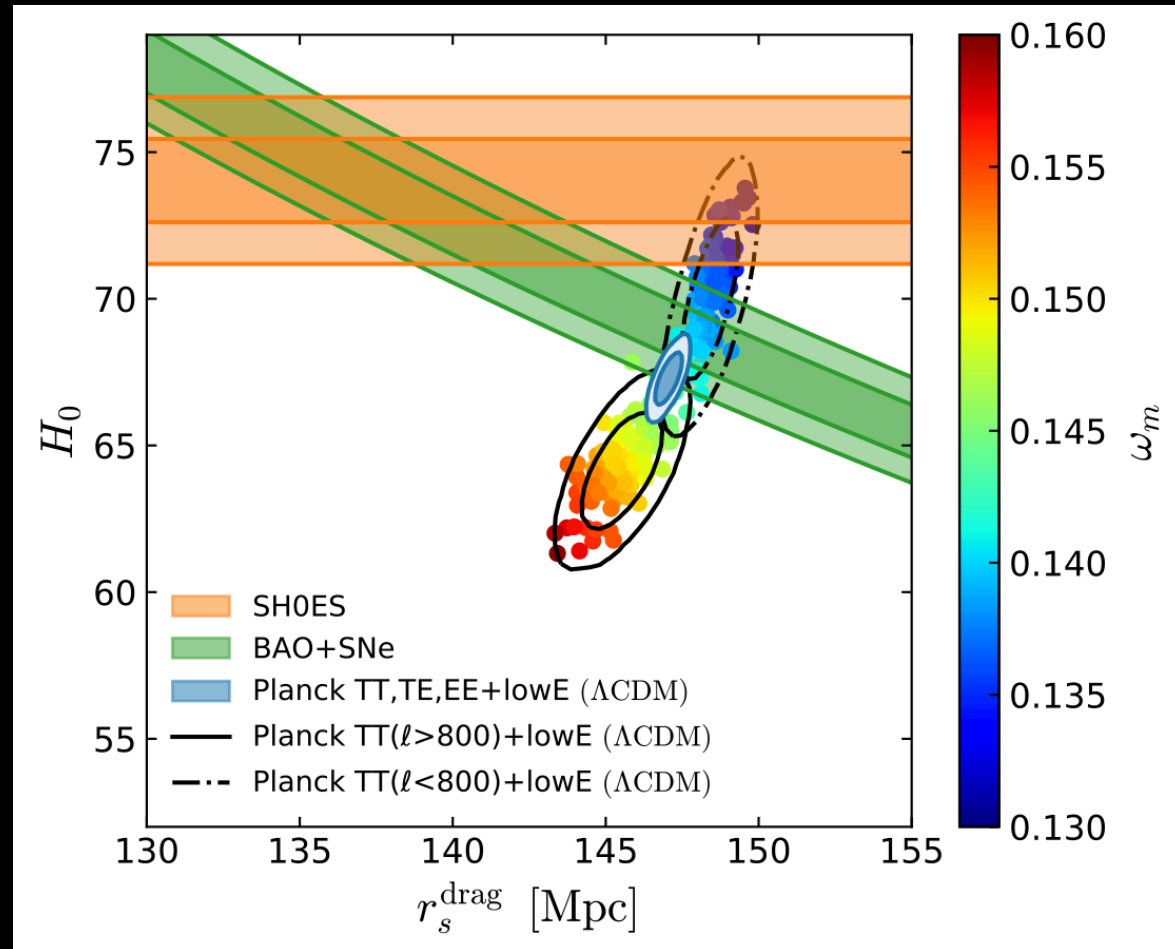




# Before DESI

BAO+Pantheon measurements  
constrain the product of  
 $H_0$  and the sound horizon  $r_s$ .

In order to have a higher  $H_0$  value  
in agreement with SH0ES,  
we need  $r_s$  near 137 Mpc.  
However, Planck by assuming  
 $\Lambda$ CDM, prefers  $r_s$  near 147 Mpc.  
Therefore, a cosmological  
solution that can increase  $H_0$  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.



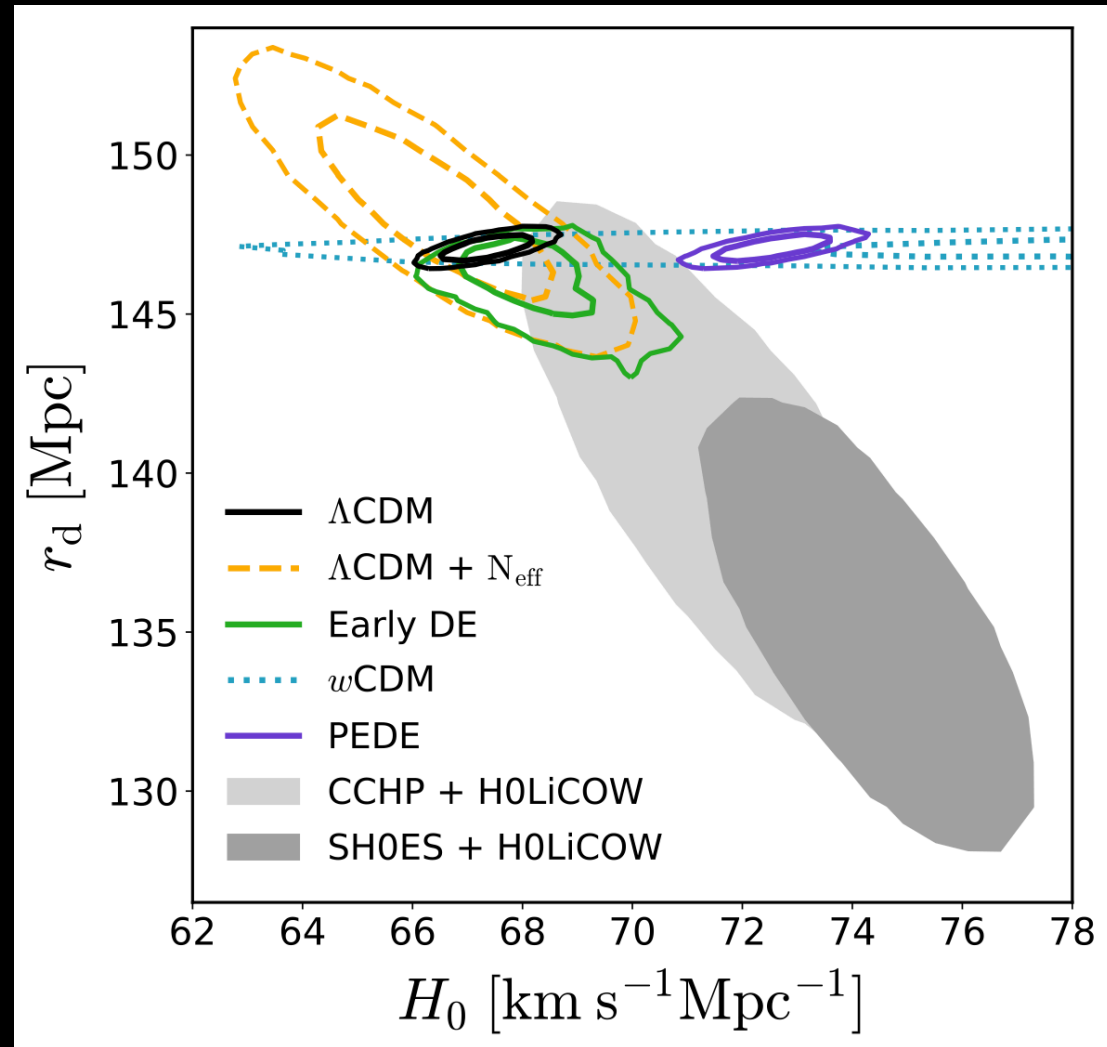
Knox and Millea, *Phys.Rev.D* 101 (2020) 4, 043533

# Early vs late time solutions

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

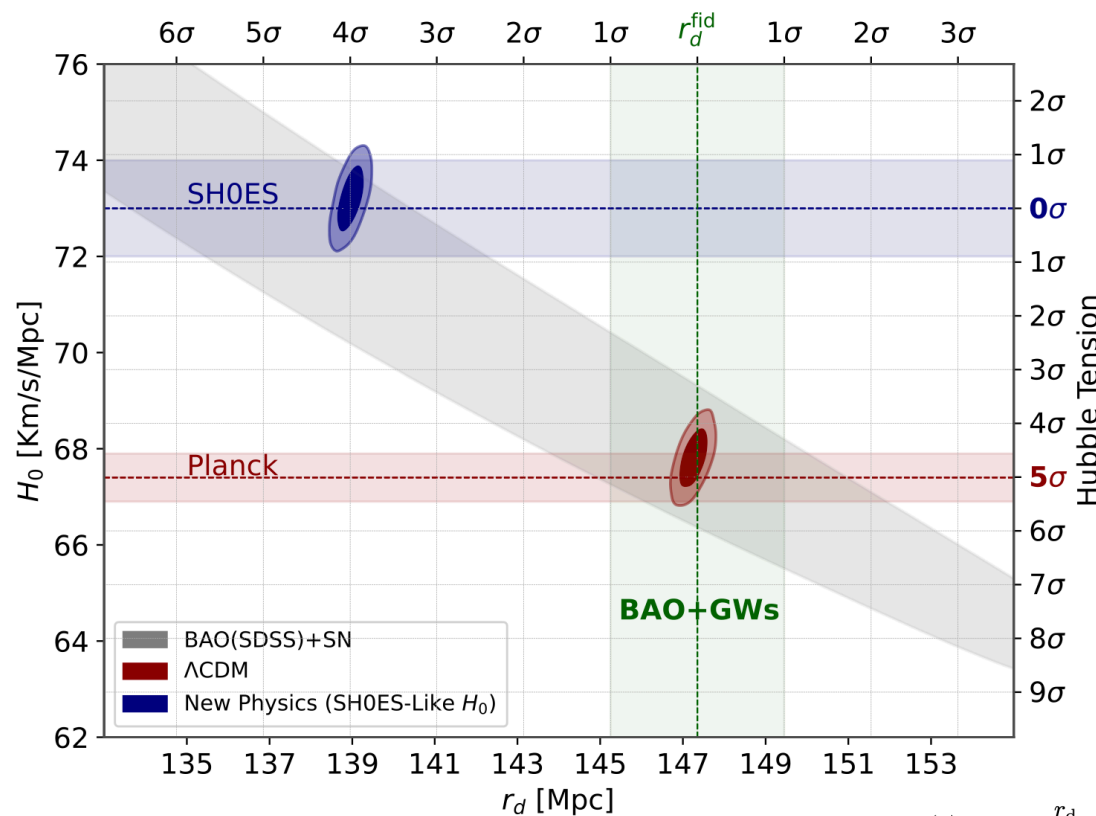
We see that the **late time solutions**, as  $w$ CDM, increase  $H_0$  because they decrease the expansion history at intermediate redshift, but leave  $r_s$  unaltered.

However, the **early time solutions**, as  $N_{\text{eff}}$  or Early Dark Energy, move in the right direction both the parameters, but can't solve completely the  $H_0$  tension between Planck and SH0ES.



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

# Sound Horizon from GWSS and 2D BAO



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

# 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  $\rho_x$  and the conformal Hubble rate  $\mathcal{H}$ , via a negative dimensionless parameter  $\xi$  quantifying the strength of the coupling, to avoid early-time instabilities.

# The IDE case

In this scenario of IDE the tension on  $H_0$  between the Planck satellite and SH0ES is completely solved.

The coupling could affect the value of the present matter energy density  $\Omega_m$ . Therefore, if within an interacting model  $\Omega_m$  is smaller (because for negative  $\xi$  the dark matter density will decay into the dark energy one), a larger value of  $H_0$  would be required in order to satisfy the peaks structure of CMB observations, which accurately determine the value of  $\Omega_m h^2$ .

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

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.



# The IDE case

Constraints at 68% cl.

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

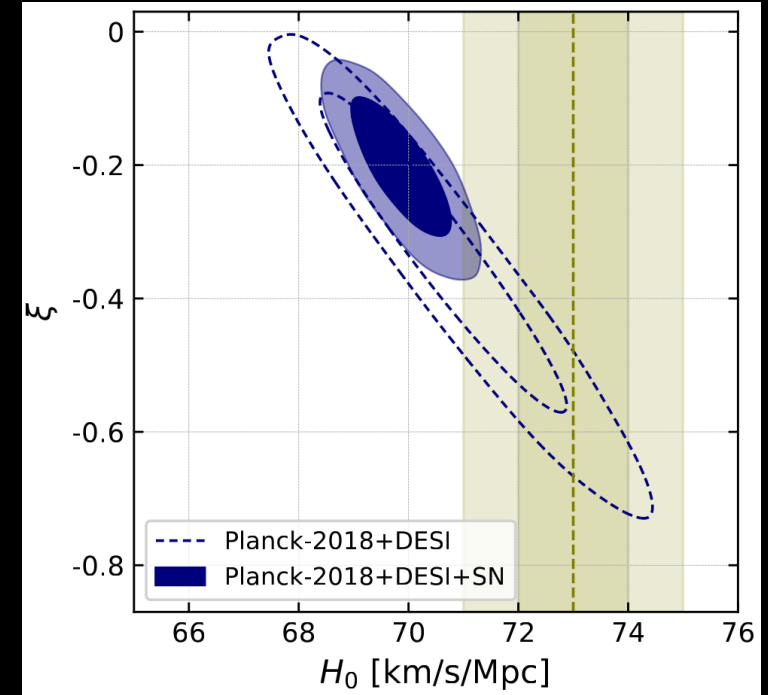
Nunes, Vagnozzi, Kumar, Di Valentino, and Mena, *Phys.Rev.D* 105 (2022) 12, 123506

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  $\Lambda$ CDM scenario, enough to bring the  $H_0$  tension at  $2.1\sigma$  with SH0ES.

# The IDE case

Constraints at 68% cl.

Parameter	Planck-2018+DESI	Planck-2018+DESI+SN
$\Omega_b h^2$	$0.02243 \pm 0.00014$ ( $0.02243^{+0.00028}_{-0.00026}$ )	$0.02254 \pm 0.00013$ ( $0.02254^{+0.00026}_{-0.00027}$ )
$\Omega_c h^2$	$0.079^{+0.025}_{-0.016}$ ( $0.079^{+0.037}_{-0.042}$ )	$0.0962^{+0.0085}_{-0.0074}$ ( $0.096^{+0.015}_{-0.015}$ )
$100\theta_s$	$1.04198 \pm 0.00029$ ( $1.04198^{+0.00056}_{-0.00056}$ )	$1.04211 \pm 0.00028$ ( $1.04211^{+0.00055}_{-0.00057}$ )
$\tau_{\text{reio}}$	$0.0555 \pm 0.0074$ ( $0.055^{+0.015}_{-0.014}$ )	$0.0592^{+0.0069}_{-0.0079}$ ( $0.059^{+0.016}_{-0.014}$ )
$n_s$	$0.9672 \pm 0.0037$ ( $0.9672^{+0.0073}_{-0.0072}$ )	$0.9696 \pm 0.0038$ ( $0.9696^{+0.0075}_{-0.0073}$ )
$\log(10^{10} A_s)$	$3.045 \pm 0.014$ ( $3.045^{+0.029}_{-0.028}$ )	$3.051 \pm 0.015$ ( $3.051^{+0.031}_{-0.028}$ )
$\xi$	$-0.32^{+0.18}_{-0.14}$ ( $-0.32^{+0.30}_{-0.29}$ )	$-0.186 \pm 0.068$ ( $-0.19^{+0.13}_{-0.14}$ )
$H_0$ [km/s/Mpc]	$70.8^{+1.4}_{-1.7}$ ( $70.8^{+2.8}_{-2.7}$ )	$69.87 \pm 0.60$ ( $69.9^{+1.2}_{-1.2}$ )
$\Omega_m$	$0.206^{+0.056}_{-0.044}$ ( $0.206^{+0.090}_{-0.096}$ )	$0.245 \pm 0.020$ ( $0.245^{+0.037}_{-0.039}$ )
$\sigma_8$	$1.23^{+0.14}_{-0.36}$ ( $1.23^{+0.74}_{-0.52}$ )	$0.974^{+0.059}_{-0.088}$ ( $0.97^{+0.15}_{-0.14}$ )
$r_{\text{drag}}$ [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  $H_0 = 70.8^{+1.4}_{-1.7}$  km/s/Mpc, in agreement with SH0ES at less than  $1.3\sigma$ . 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.

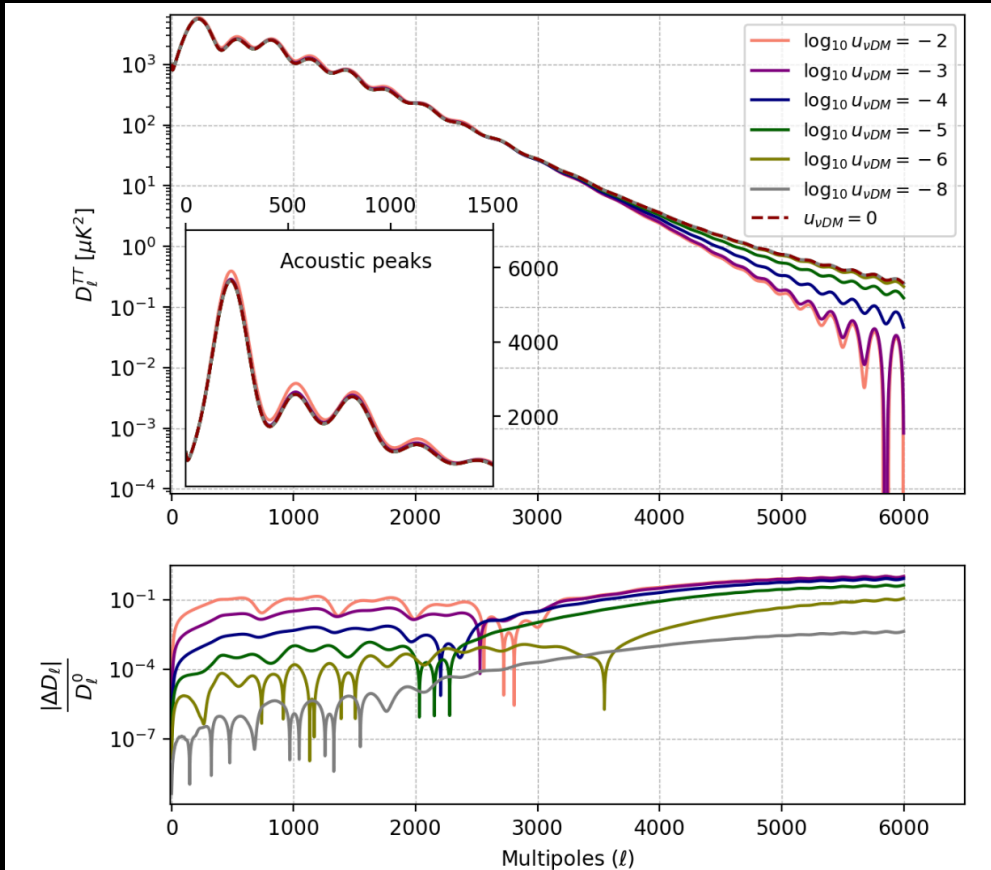
# v-DM scattering

This can be parameterized by a dimensionless coupling:

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

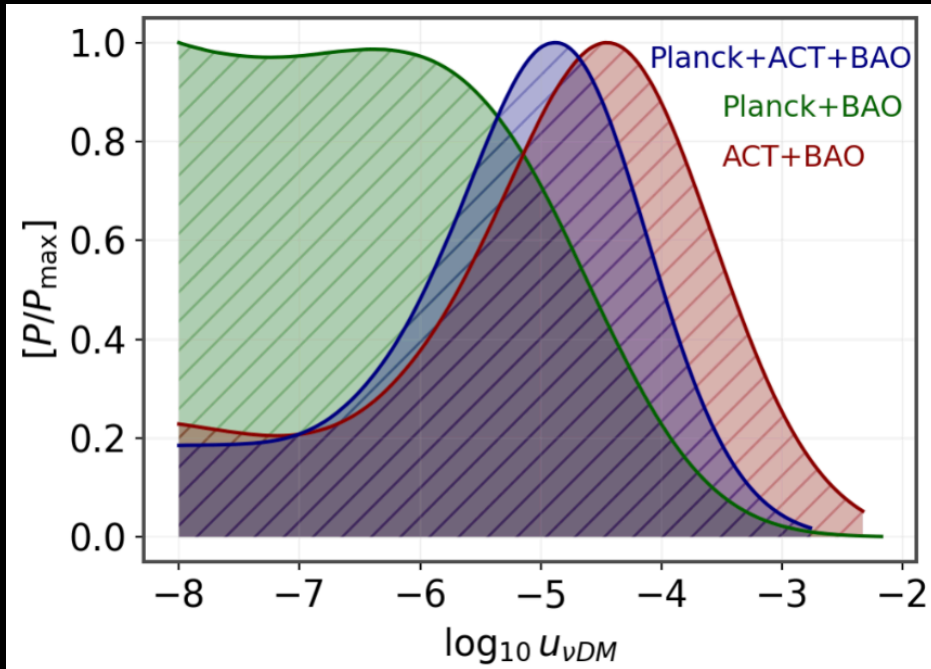
where  $\sigma_{\nu\text{DM}}$  and  $\sigma_T$  are the  $\nu\text{DM}$  and Thomson scattering cross sections and  $m_{\text{DM}}$  is the mass of the dark matter particle. Increasing  $u_{\nu\text{DM}}$ , the impact on the CMB temperature power spectrum is the suppression of the small-scale clustering 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- $\ell$  data are opening a new observational window on models that would otherwise be indistinguishable at lower multipoles.**



**Figure 1.** The top panel displays the theoretical  $D_\ell^{TT}$ , while the percentage difference  $|\Delta D_\ell|/D_\ell^0$  with respect to the non interacting case ( $D_\ell^0$ ) 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.

# $\nu$ -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  $\nu$ -DM scattering only through an upper limit  $\log_{10} U_{\nu\text{DM}} < -4.39$  at 95% CL, since for  $U_{\nu\text{DM}} \ll 10^{-5}$  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:

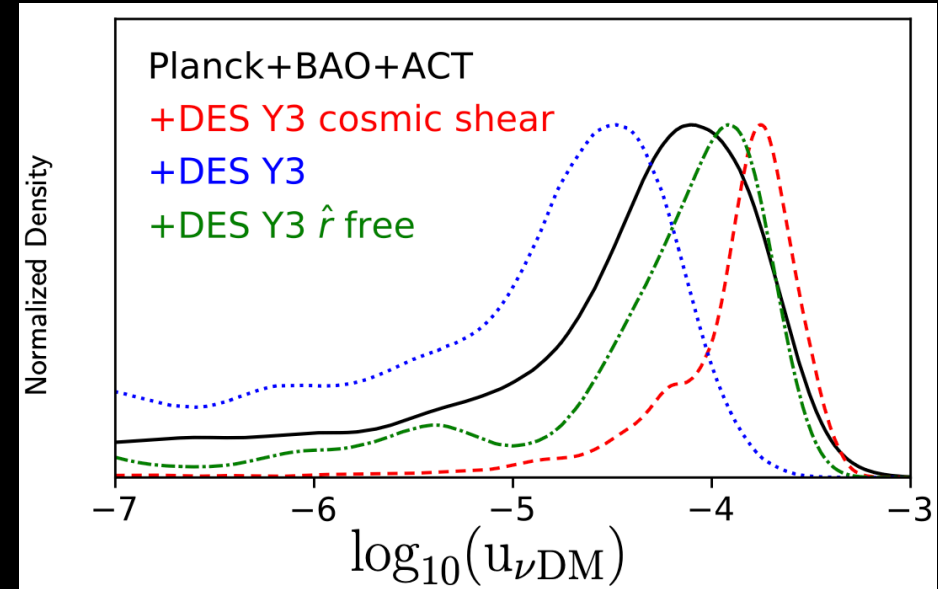
ACT+BAO gives

$$\log_{10} U_{\nu\text{DM}} \approx -4.86^{+1.5}_{-0.83} \text{ at 68\% CL.}$$

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

# v-DM scattering

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



Zu, Giarè, Zhang, Di Valentino, Sming Tsai and Trojanowski,  
arXiv:2501.13785, accepted in *Nature Astron.*

Combining Planck low- $\ell$  with high- $\ell$  ACT data shows a clear preference for non-zero  
v-DM coupling around  $\log_{10} u_{\nu\text{DM}} \approx -4.2$ .

Adding weak lensing (DES Y3) data strengthens the signal:  
using cosmic shear only, we find a  $\sim 3\sigma$  preference for v-DM scattering,  
with the central value shifting to  $\log_{10} u_{\nu\text{DM}} \approx -3.8$ .

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?

$\Lambda$ CDM 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  $> 6\sigma$  across multiple independent methods.
- The CMB lensing anomaly ( $AL > 1$ ), curvature hints ( $\Omega_k \neq 0$ ), and low  $\tau$ , 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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# 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](#)