The Hubble tension

October 21st, 2025
UK HEP Forum 2025: "Wandering in the Dark"
Abingdon, UK

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

University of Sheffield

THE ROYAL SOCIETY

What is H0?

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

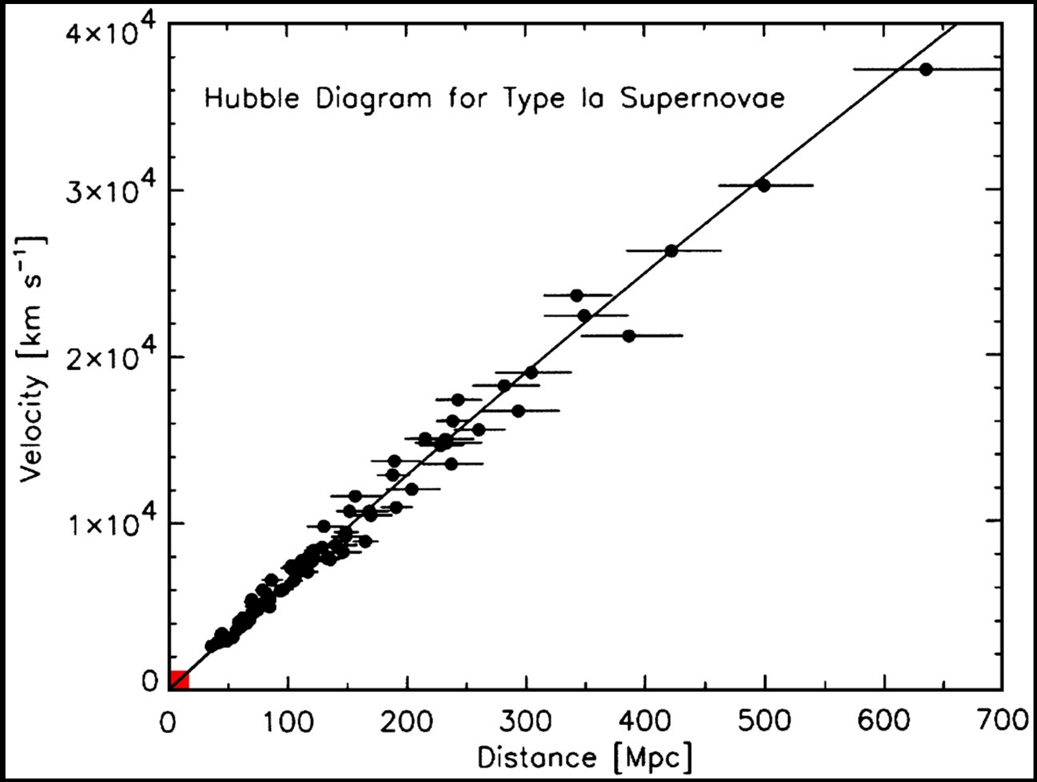
This can be obtained in two ways:

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.

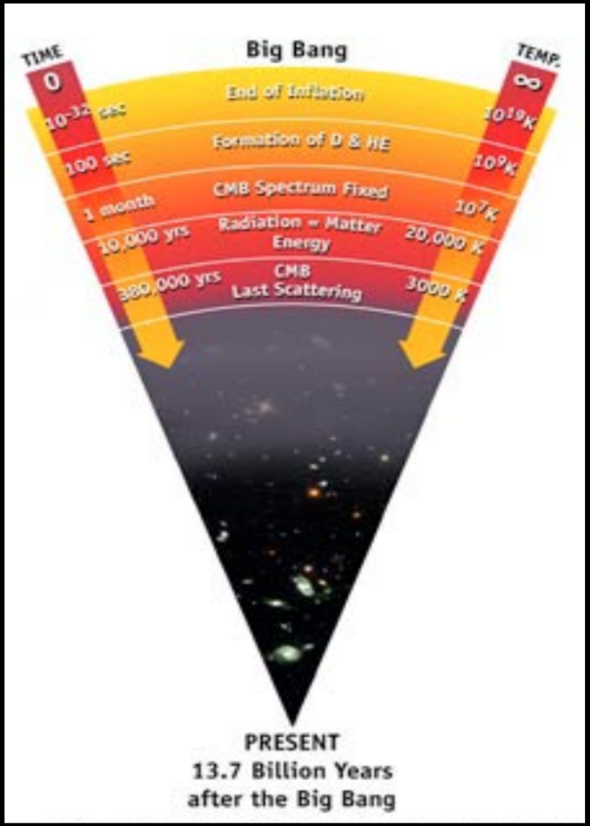
This can be obtained in two ways:

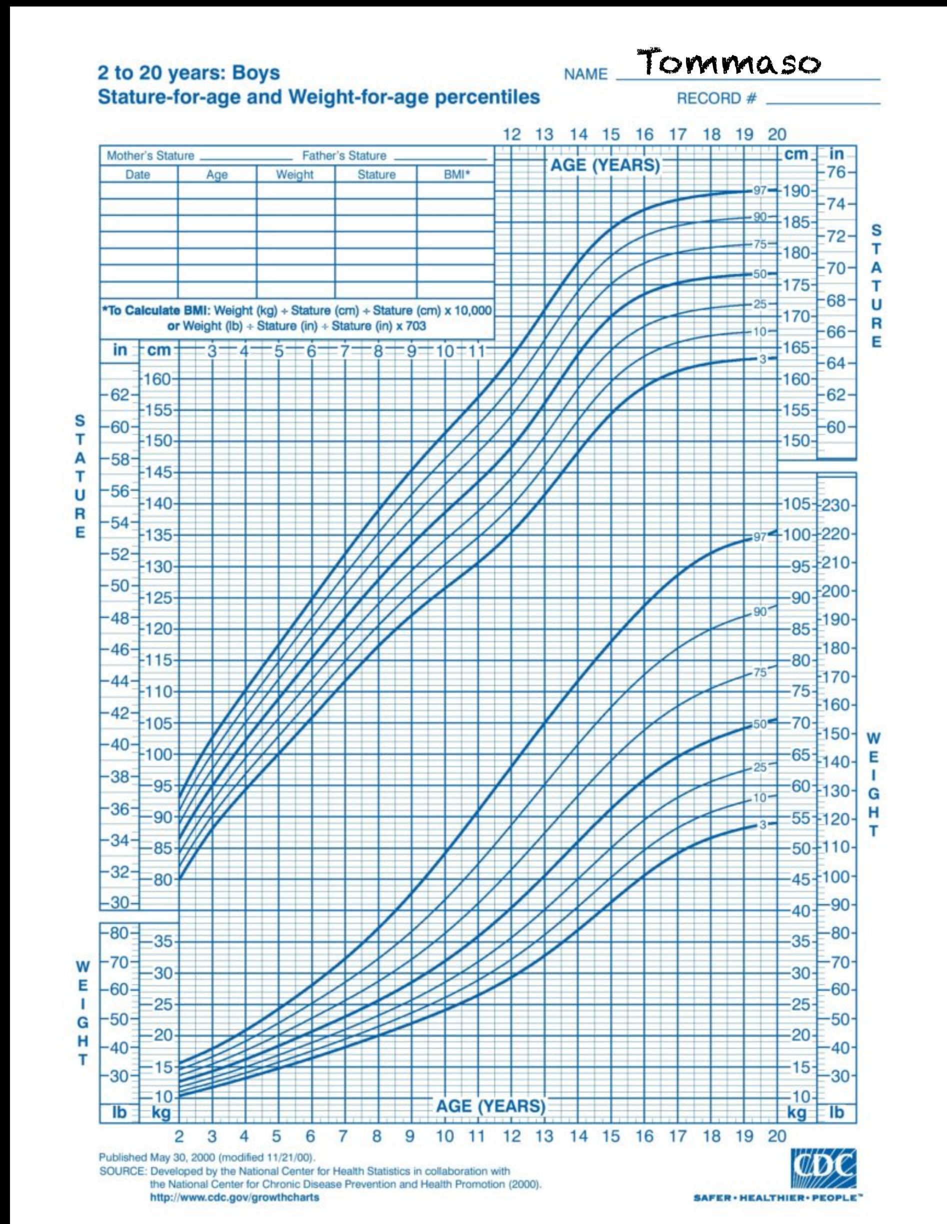
1. measuring the luminosity distance and the recessional velocity of known galaxies, and computing the proportionality factor.
2. considering early universe measurements, and assuming a model for the expansion history of the universe.

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

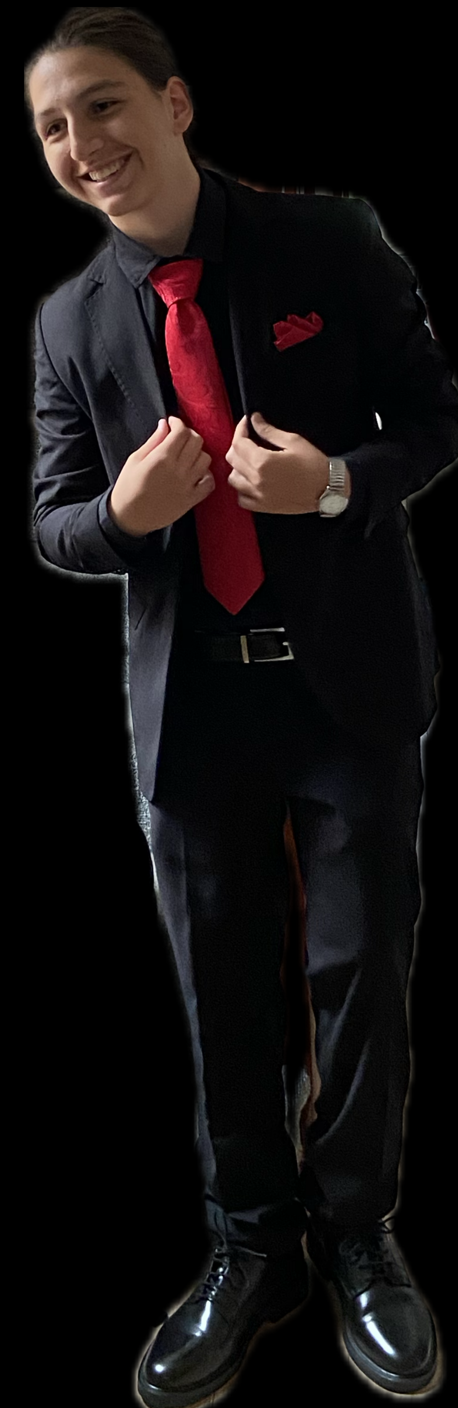
1st Friedmann equation describes the expansion history of the universe:

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





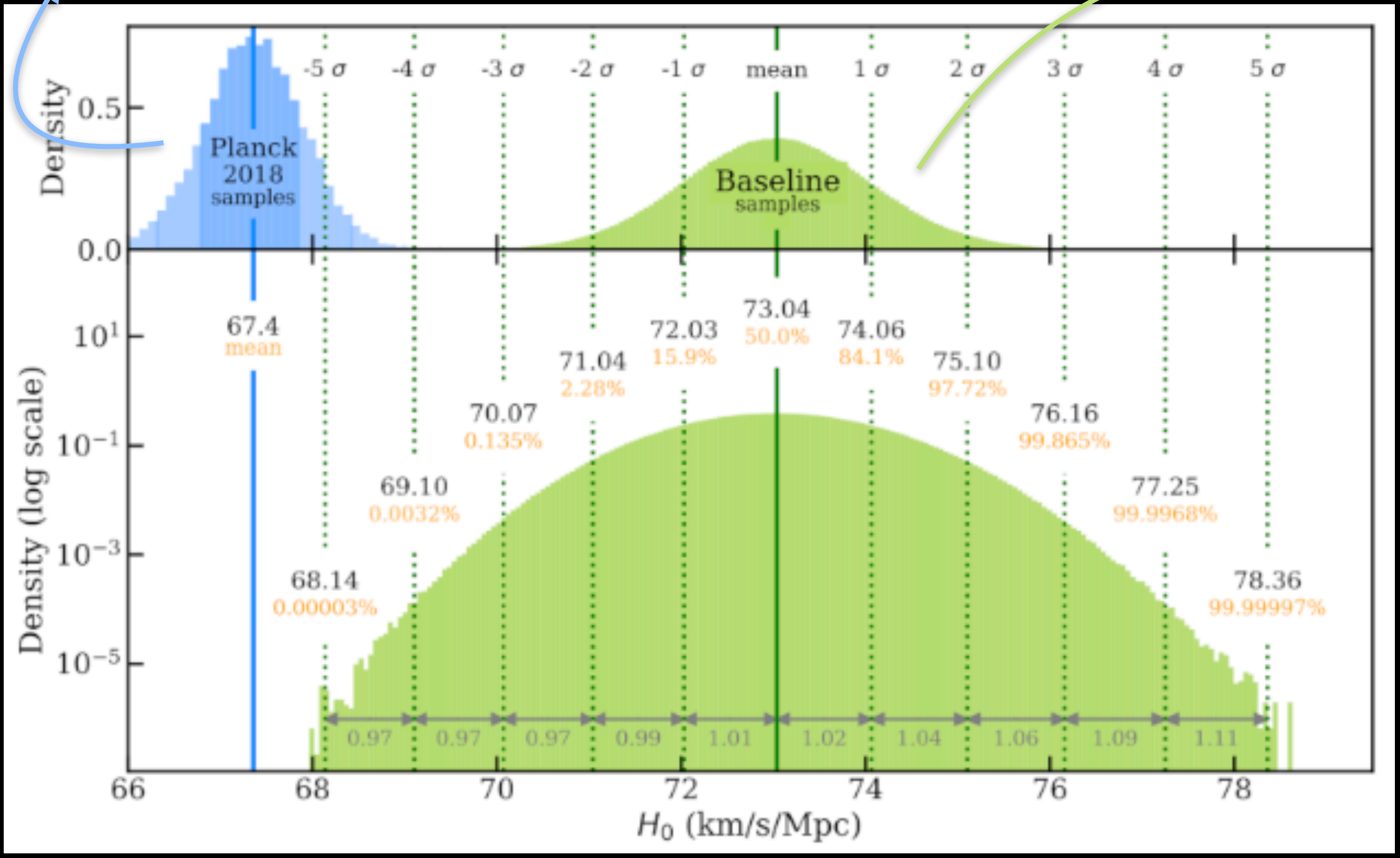
2 to 20 years: Boys
Stature-for-age and Weight-for-age percentiles
NAME Tommaso
RECORD #
Mother's Stature
Father's Stature
Date
Age
Weight
Stature
BMI*
*To Calculate BMI: Weight (kg) ÷ Stature (cm) ÷ Stature (cm) x 10,000
or Weight (lb) ÷ Stature (in) ÷ Stature (in) x 703
AGE (YEARS)
STATURE
WEIGHT
Published 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

We thought we had a consistent picture of the cosmos.
Yet today, these two independent methods for measuring the expansion rate of the Universe give conflicting results. This is the Hubble tension.

The Planck estimate assuming a “vanilla" ΛCDM cosmological model:
$H0 = 67.36 \pm 0.54$ km/s/Mpc
Planck 2018, Astron.Astrophys. 641 (2020) A6



The latest local measurements obtained by the SH0ES collaboration

$H0 = 73.04 \pm 1.04$ km/s/Mpc

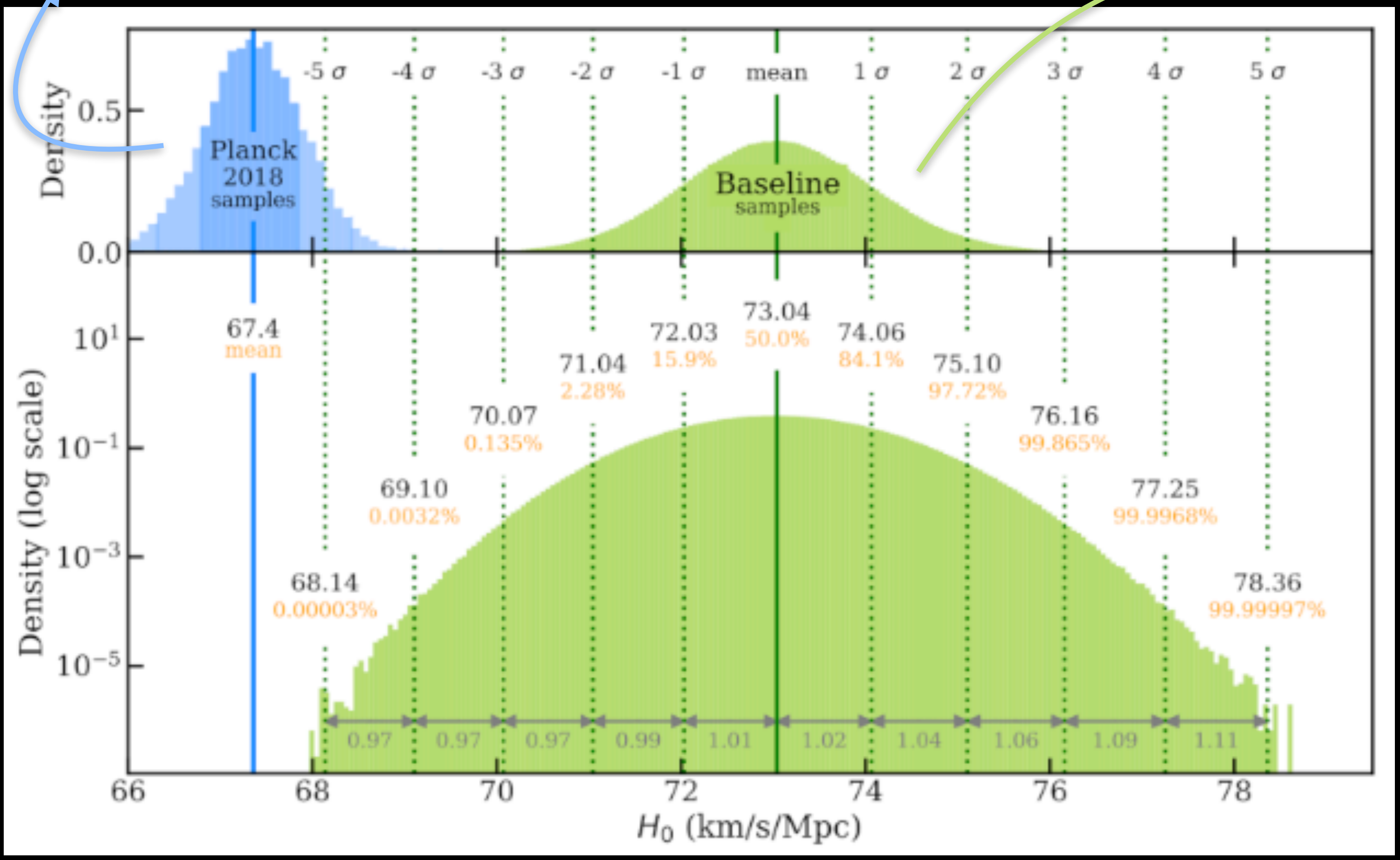
Riess et al. arXiv:*2112.04510*

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

Distance Ladder

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

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



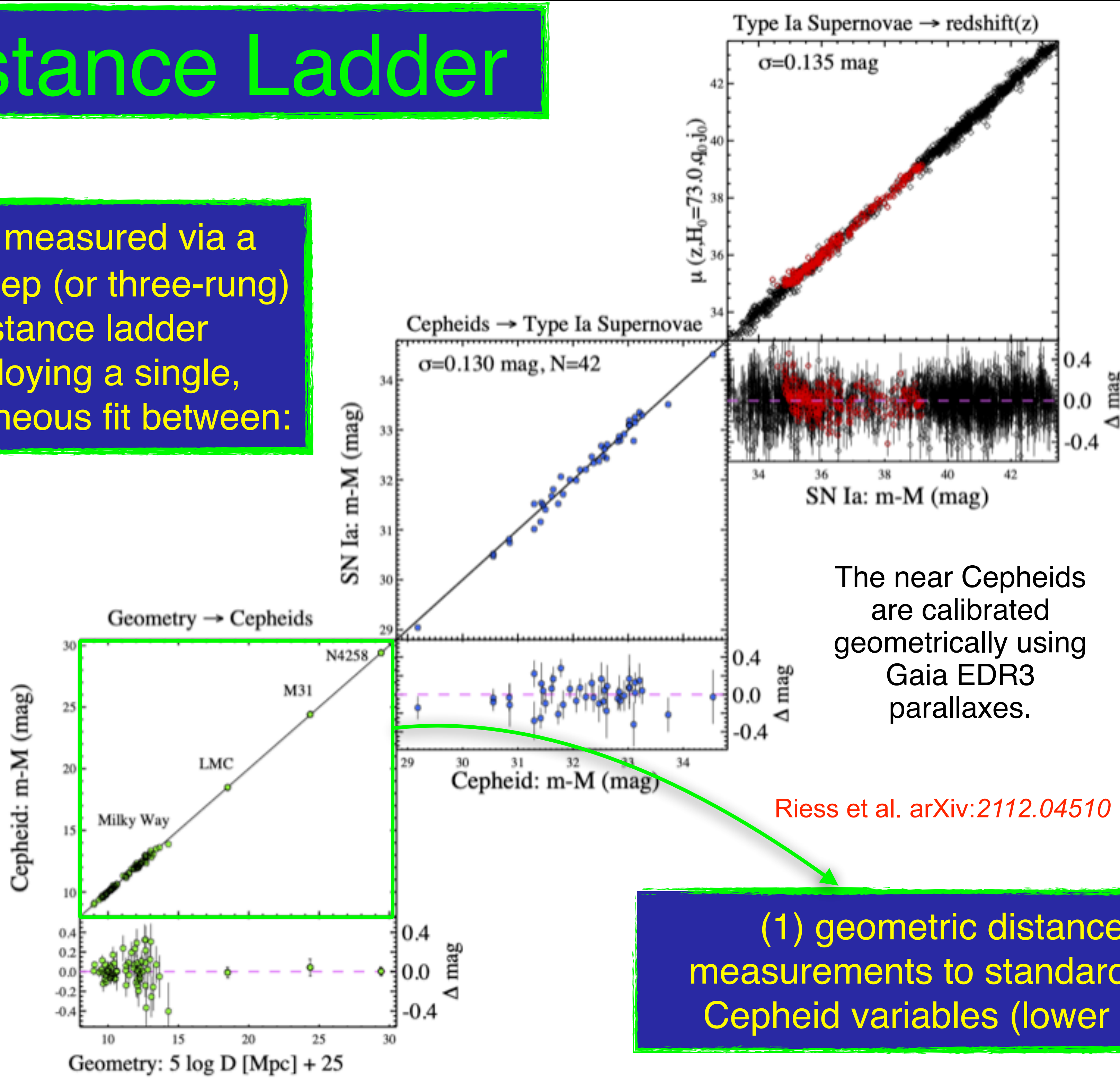
The latest local measurements obtained by the SH0ES collaboration

$H0 = 73.04 \pm 1.04$ km/s/Mpc

Riess et al. arXiv:*2112.04510*

Distance Ladder

H0 is measured via a three-step (or three-rung) distance ladder employing a single, simultaneous fit between:



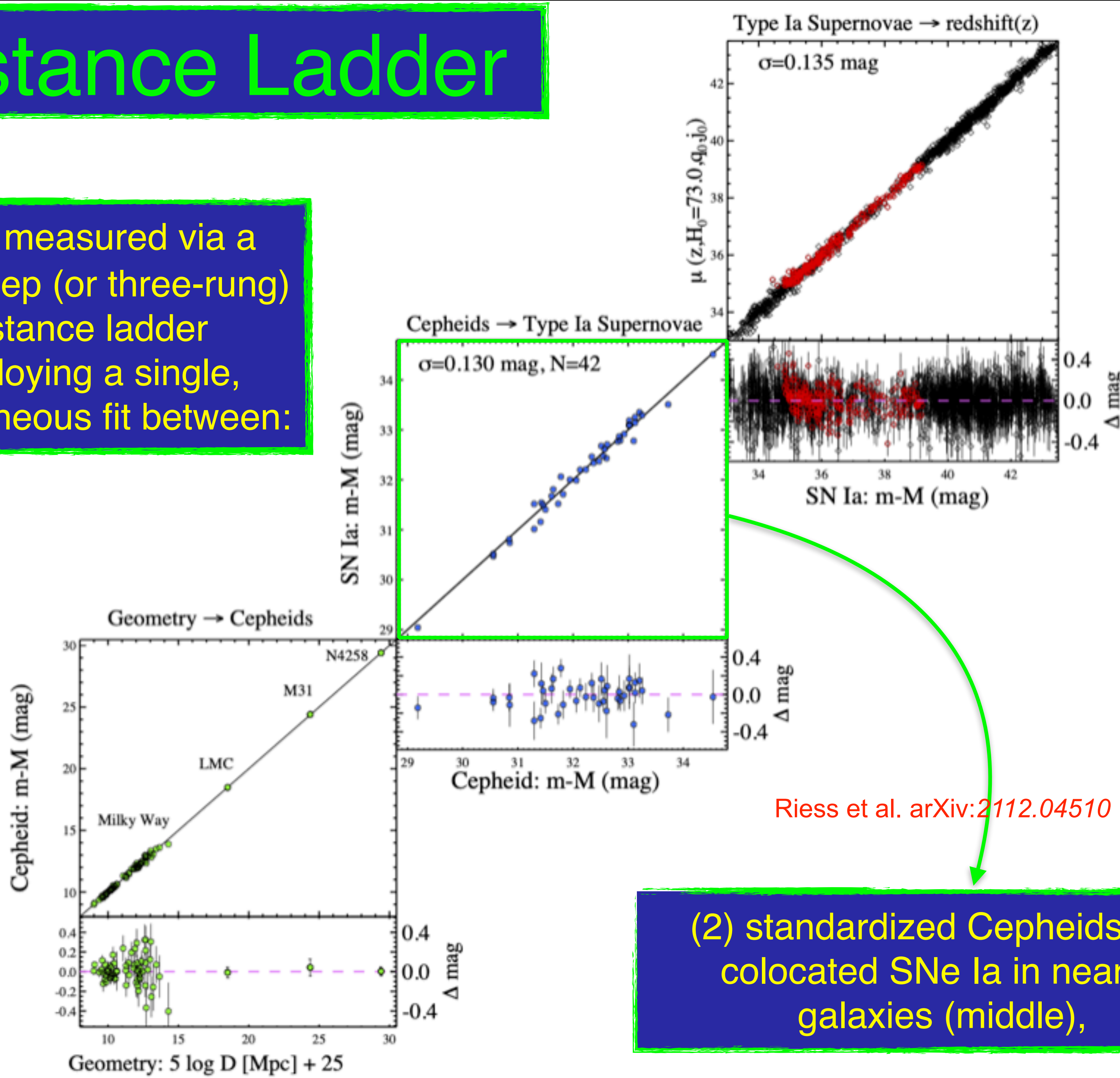
The near Cepheids are calibrated geometrically using Gaia EDR3 parallaxes.

Riess et al. arXiv:*2112.04510*

(1) geometric distance measurements to standardized Cepheid variables (lower left)

Distance Ladder

H0 is measured via a three-step (or three-rung) distance ladder employing a single, simultaneous fit between:

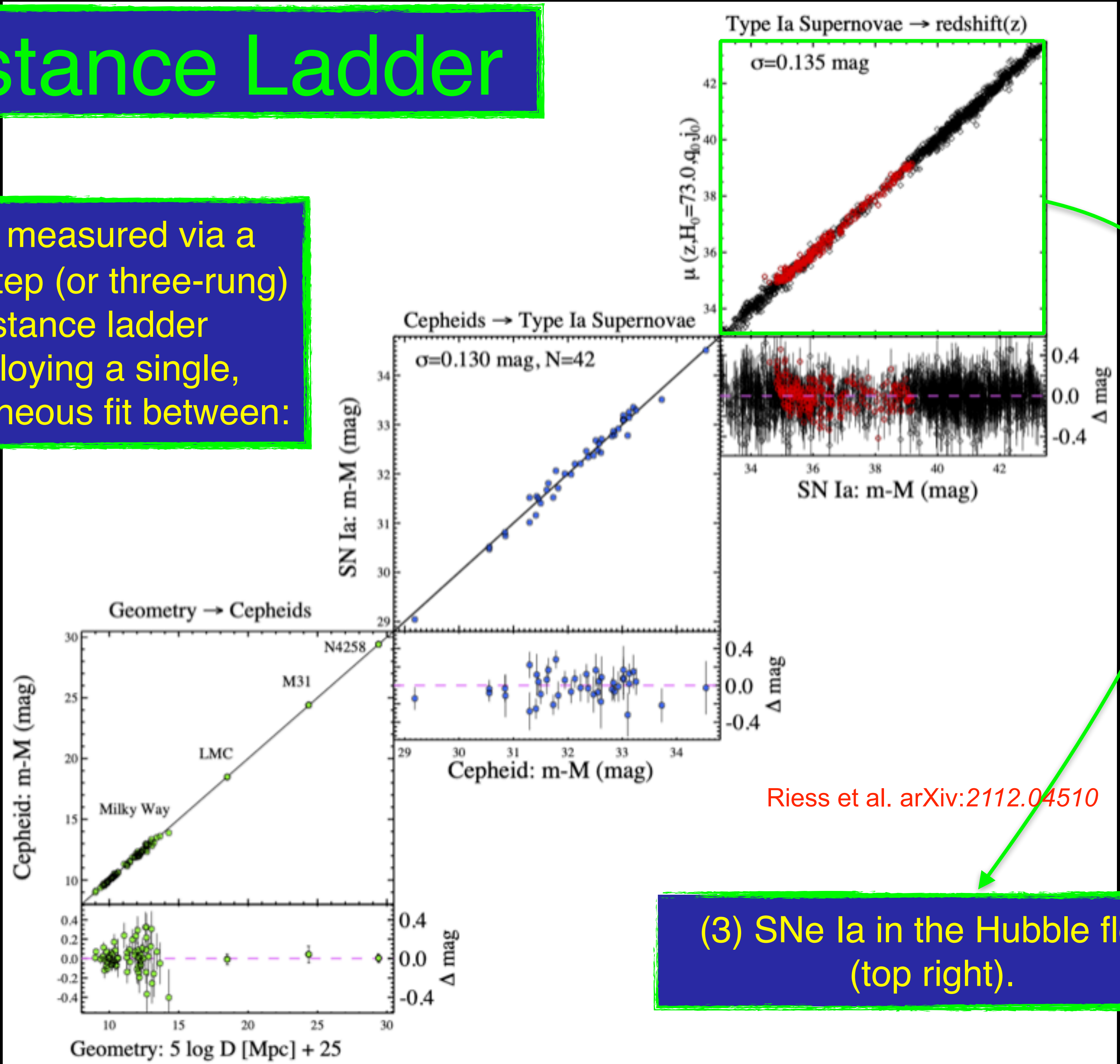


Riess et al. arXiv:2112.04510

(2) standardized Cepheids and colocated SNe Ia in nearby galaxies (middle),

Distance Ladder

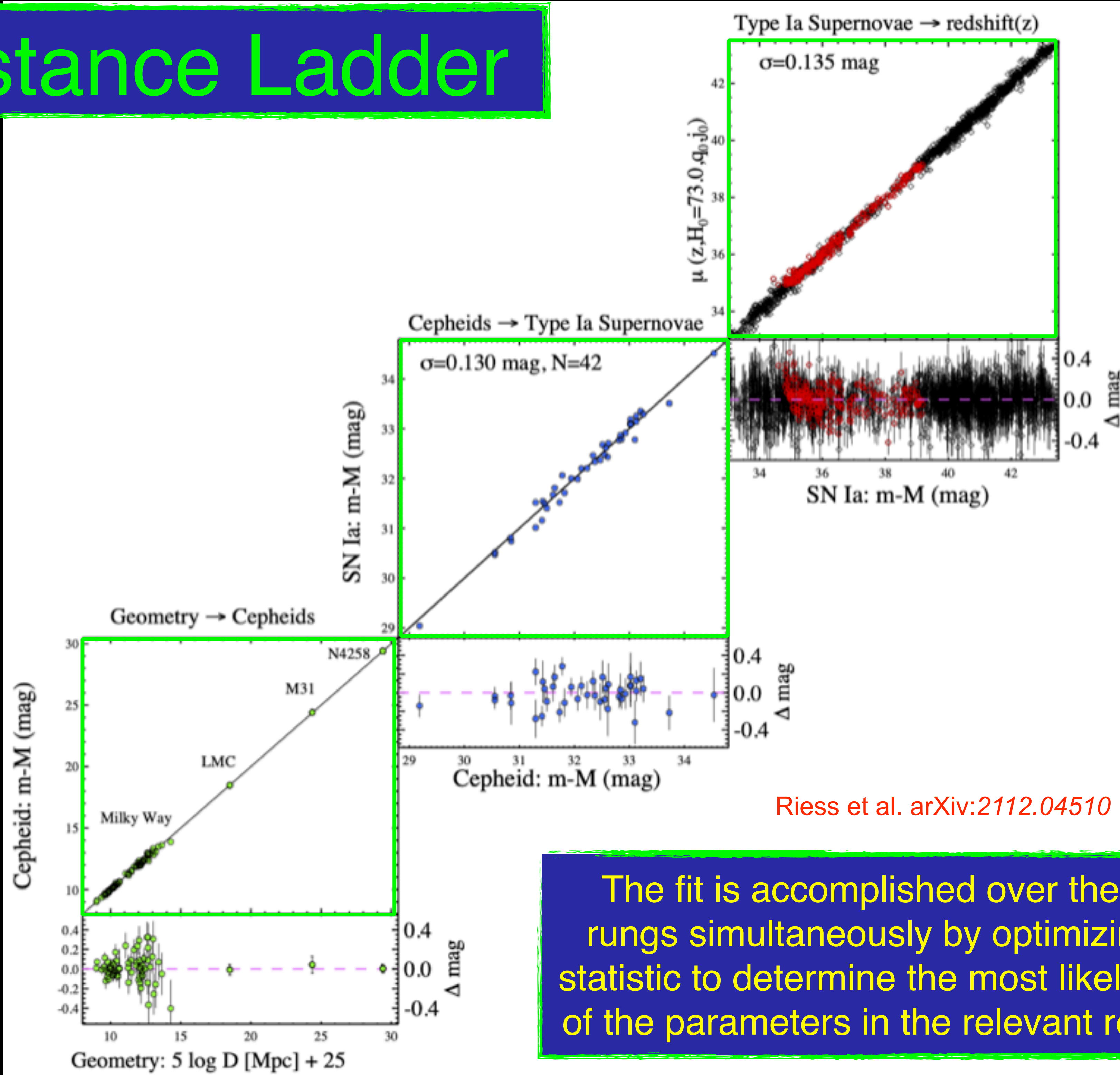
H0 is measured via a three-step (or three-rung) distance ladder employing a single, simultaneous fit between:



Riess et al. arXiv:*2112.04510*

(3) SNe Ia in the Hubble flow (top right).

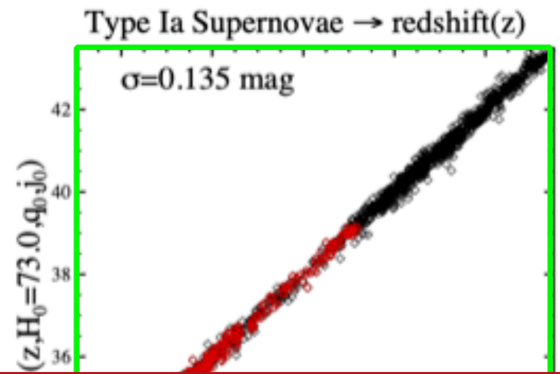
Distance Ladder



Riess et al. arXiv:*2112.04510*

The fit is accomplished over the three rungs simultaneously by optimizing a χ^2 statistic to determine the most likely values of the parameters in the relevant relations.

Distance Ladder



arXiv > astro-ph > arXiv:2404.08038

Search...

Help | Adv

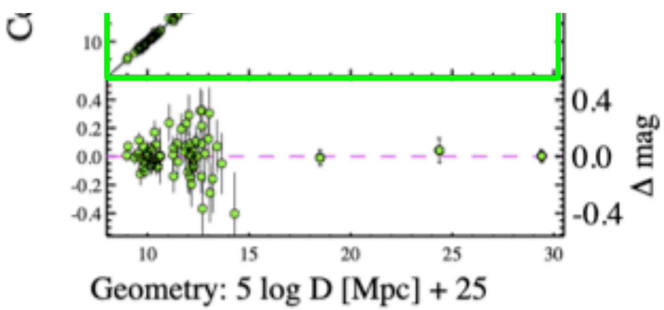
Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 11 Apr 2024]

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

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

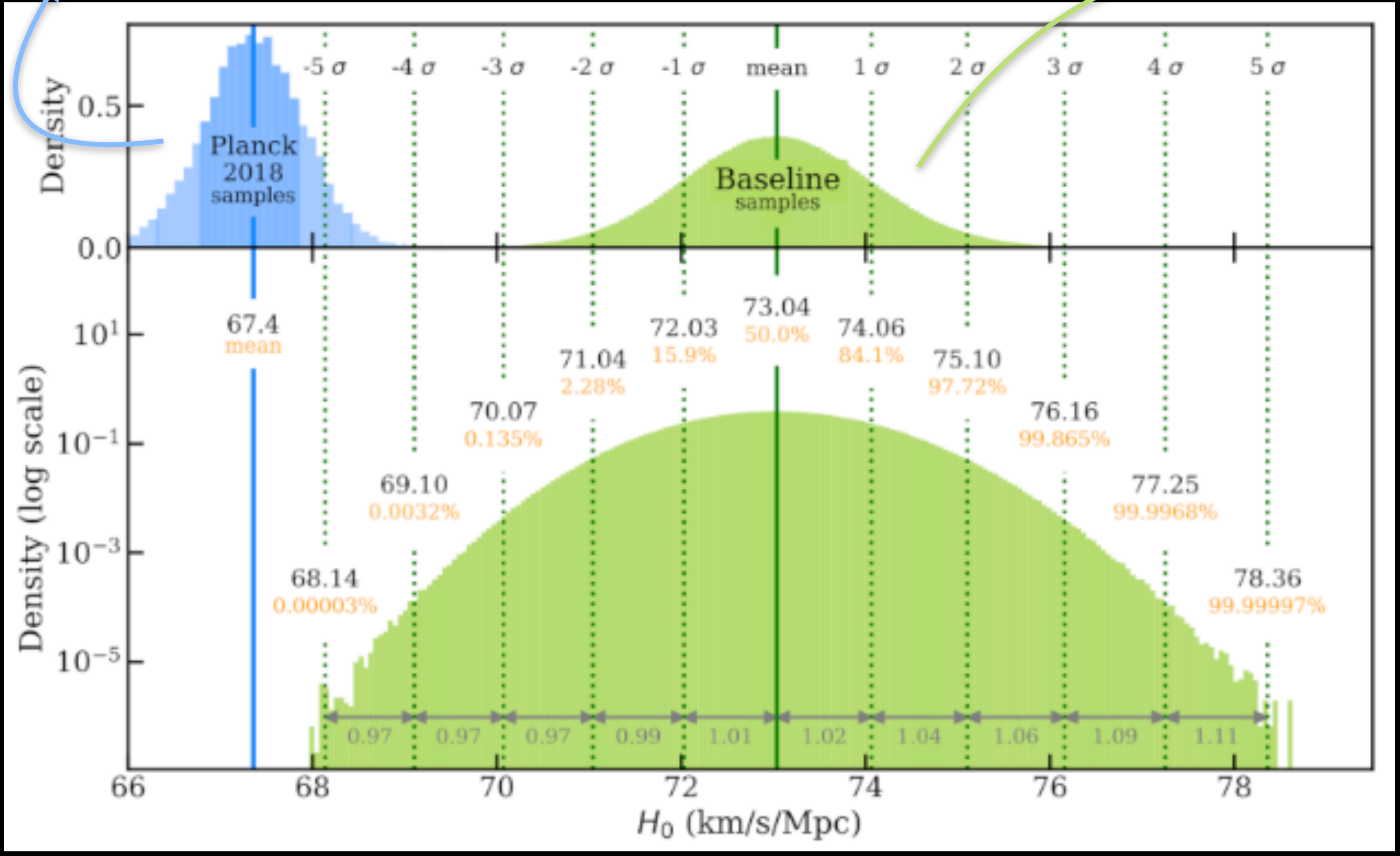
We present photometric measurements of 88 Cepheid variables in the core of the Small Magellanic Cloud (SMC), the first sample obtained with the Hubble Space Telescope (HST) and Wide Field Camera 3, in the same homogeneous photometric system as past measurements of all Cepheids on the SH0ES distance ladder.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



CMB constraints

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*

CMB constraints

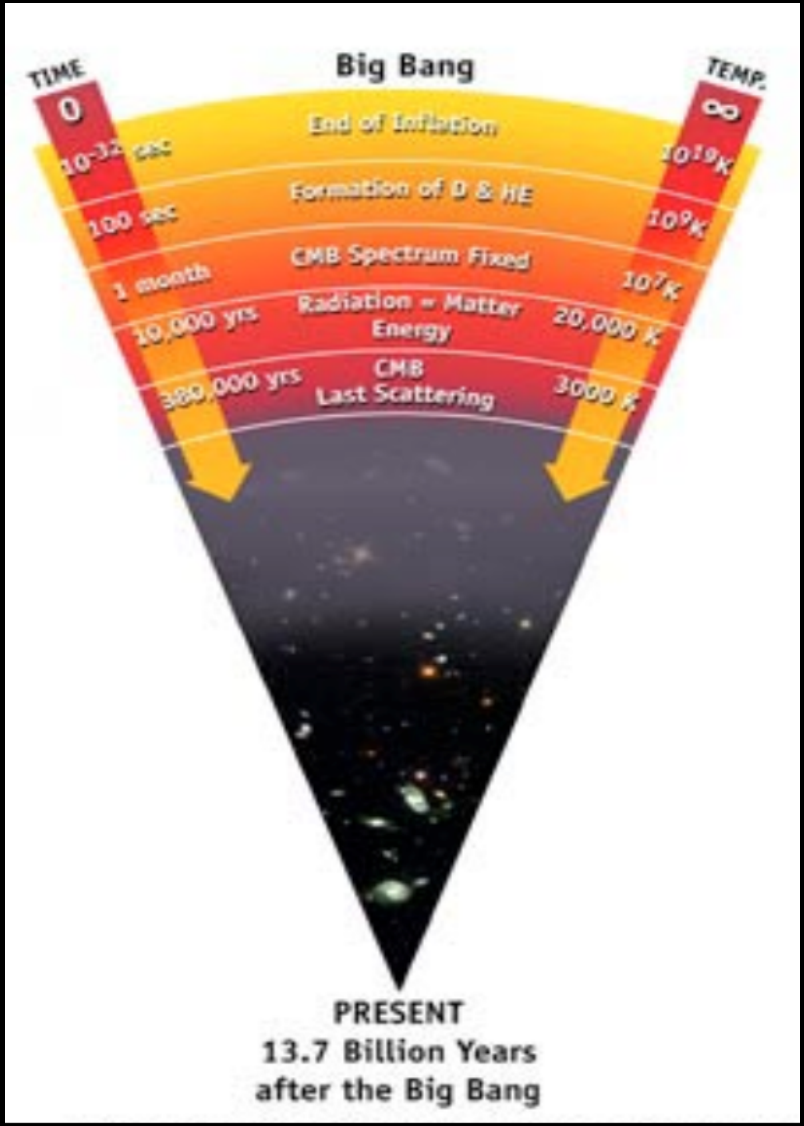


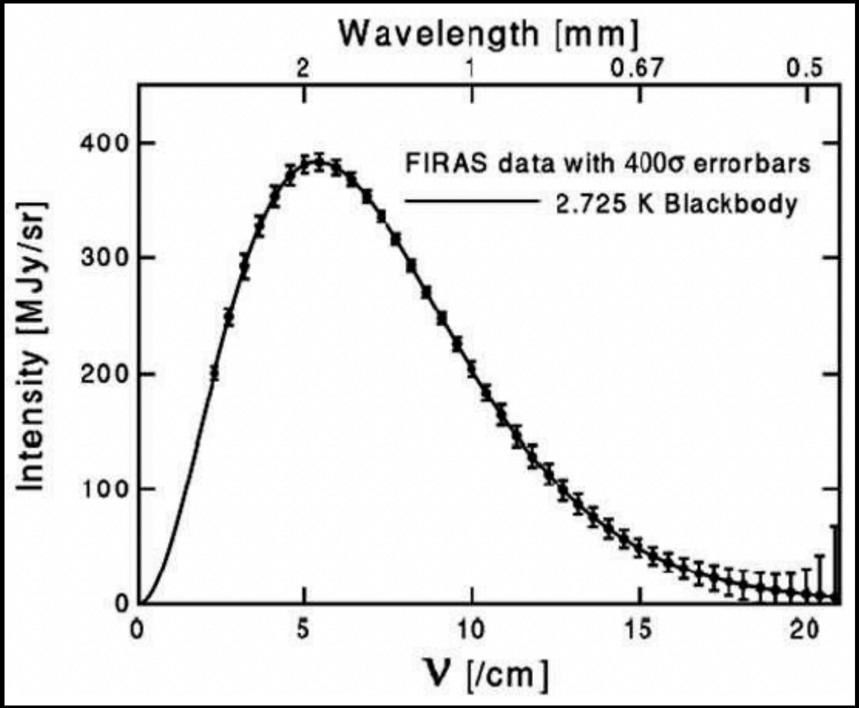
Figura: http://wmap.gsfc.nasa.gov

The Universe originates from a hot Big Bang.

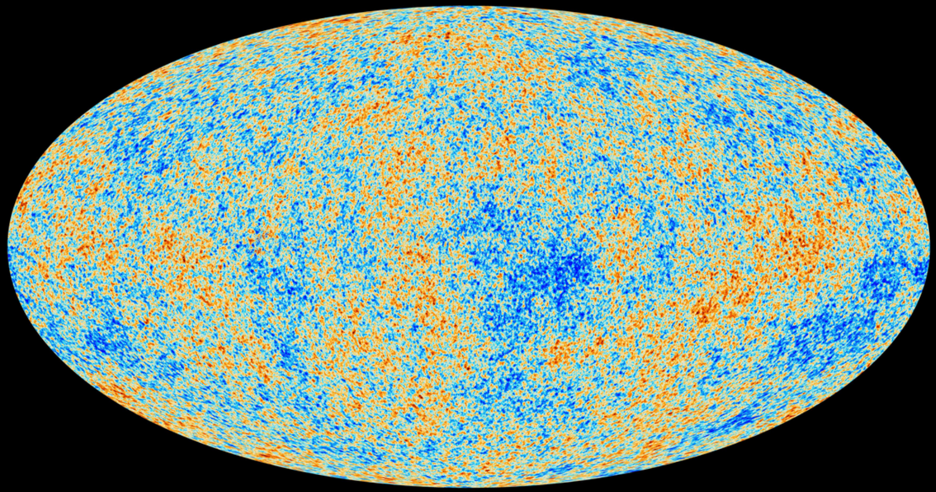
The primordial plasma in thermodynamic equilibrium cools with the expansion of the Universe. It goes through the phase of recombination, where electrons and protons combine into hydrogen atoms, and decoupling, where the Universe becomes transparent to the motion of photons.

The Cosmic Microwave Background (CMB) is the radiation coming from recombination, emitted about 13 billion years ago, just 380,000 years after the Big Bang.

The CMB shows us the state of the early Universe, when photons were in thermal equilibrium.
It has a nearly perfect black-body spectrum that has cooled over time due to the Universe's expansion, reaching a temperature of 2.725 K today.
This radiation, coming from all directions, is almost uniform but contains tiny variations in temperature of about 1/100000.
These anisotropies reflect the small density differences at the time of recombination and carry the imprint of everything that happened to the photons on their journey to us.

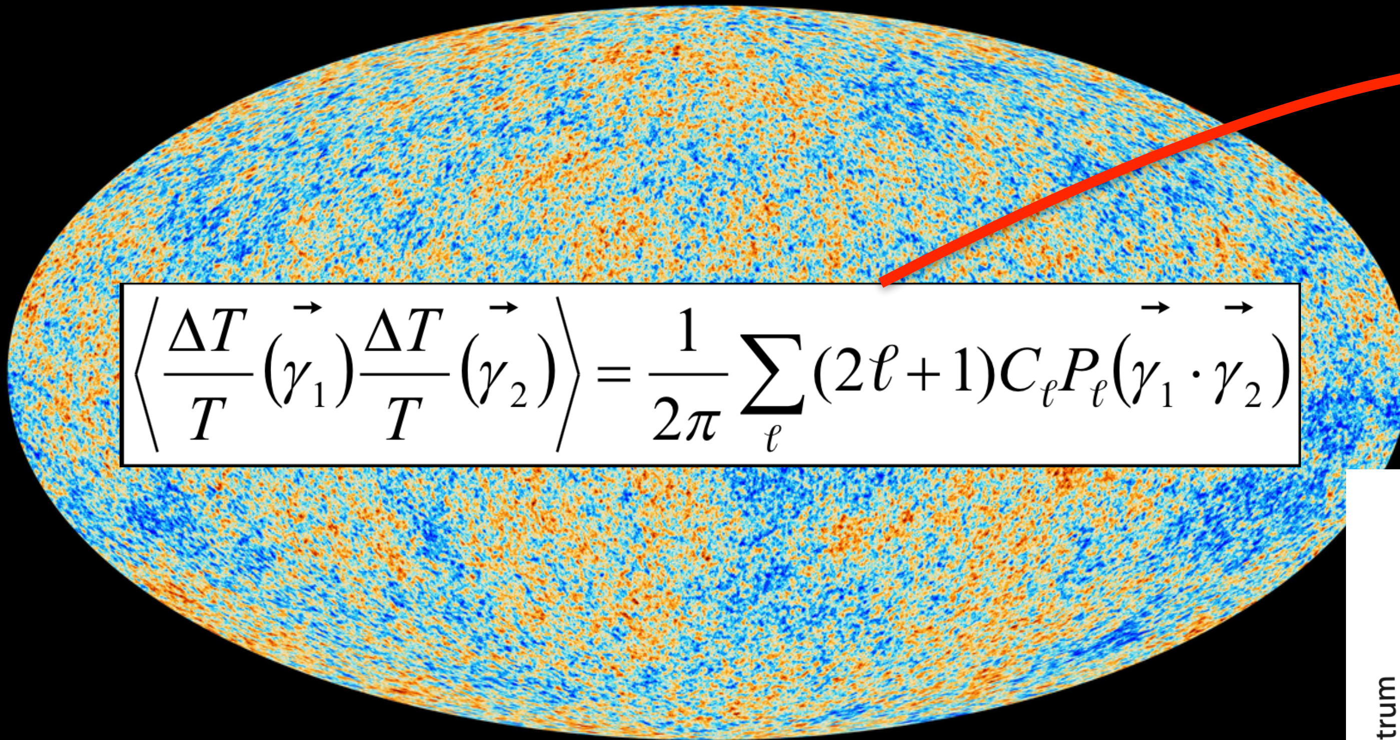


Wuensche & Villa, arXiv:1002.4902

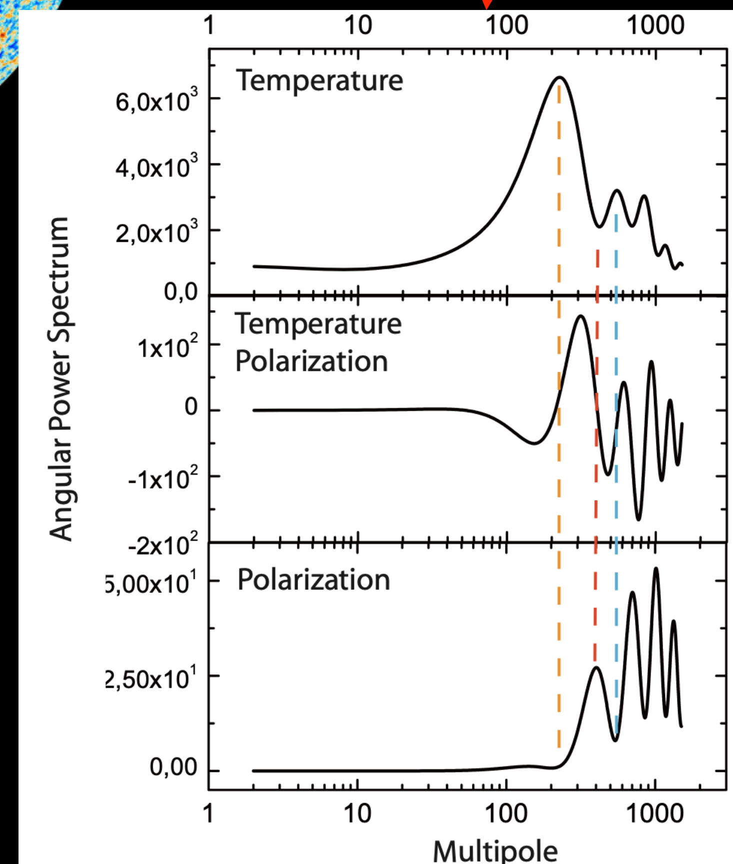


Planck collaboration, 2018

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



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



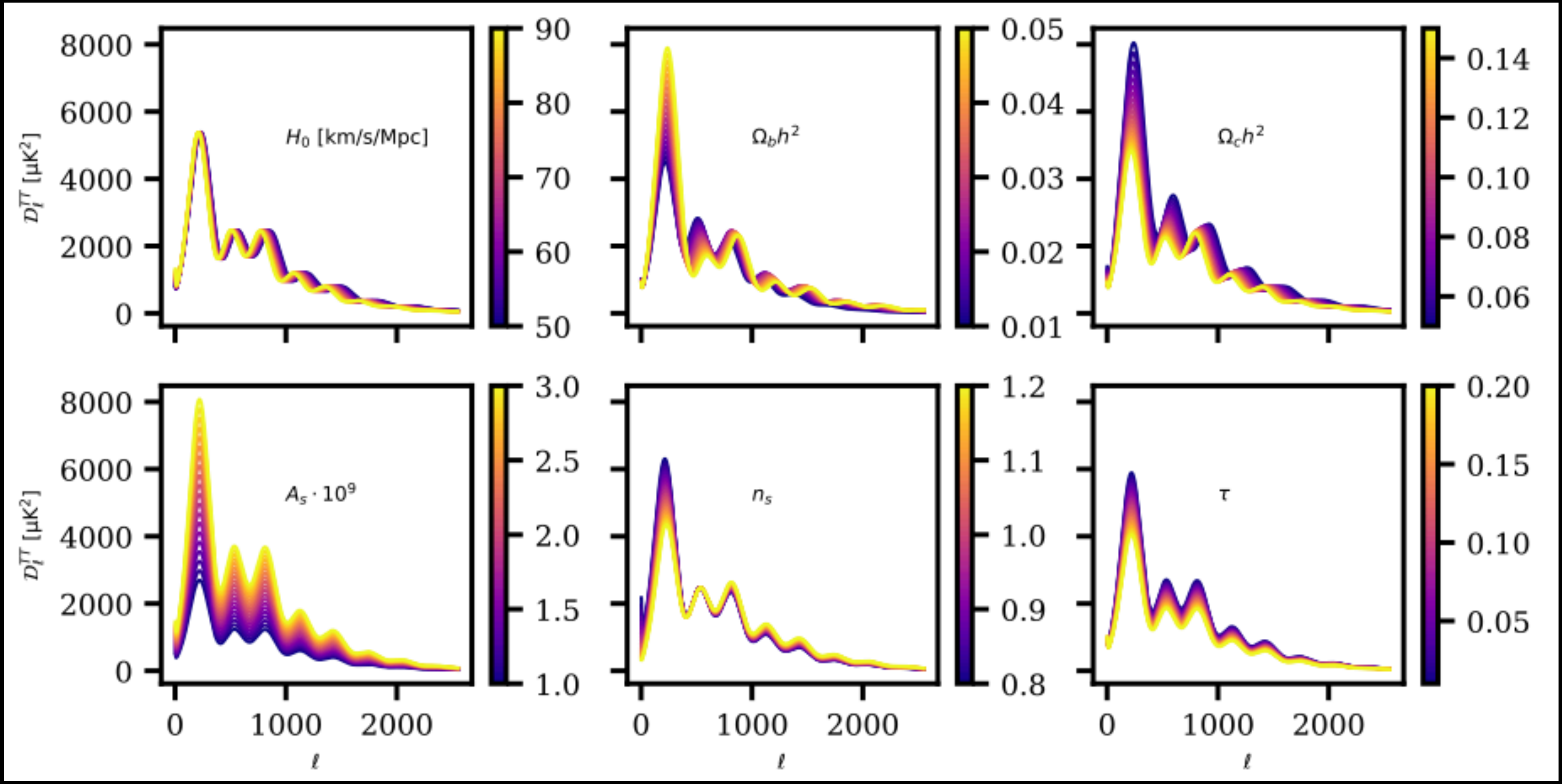
Borstnik et al., hep-ph/0401043

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)

Cosmological parameters: ($\Omega_b h^2$, $\Omega_m h^2$, H0, n_s, τ, As) → Theoretical model

We choose a set of cosmological parameters that describes our theoretical model and compute the angular power spectra. Because of the correlations present between the parameters, variation of different quantities can produce similar effects on the CMB.

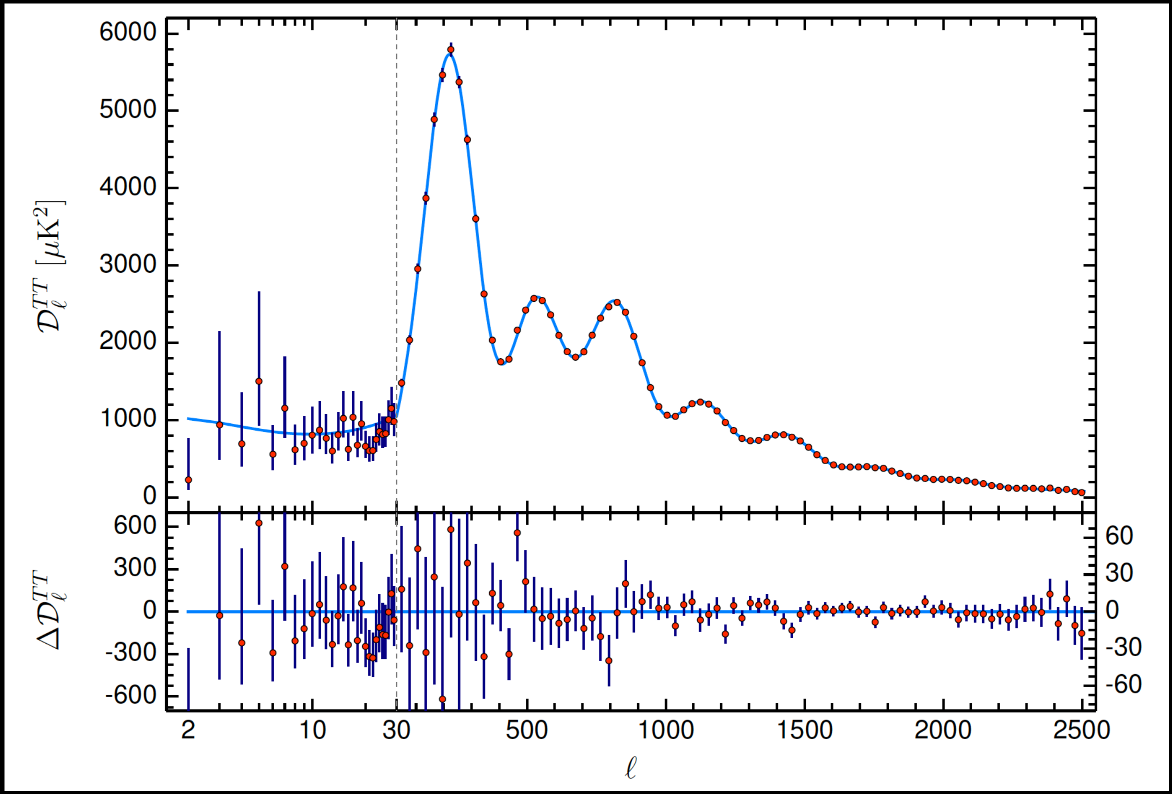


Lemos & Shah, arXiv:2307.13083

Cosmological parameters:
($\Omega_b h^2$, $\Omega_m h^2$, H0 , n_s , τ, As)

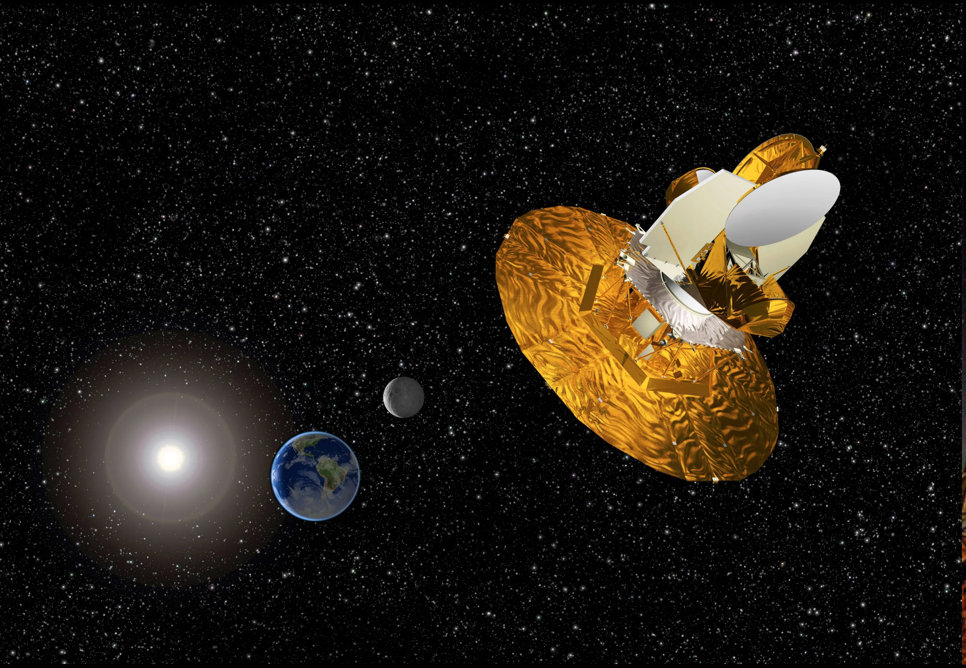
Theoretical model

We compare the angular power spectra we computed with the data and, using a bayesian analysis, we get a combination of cosmological parameter values in agreement with these.



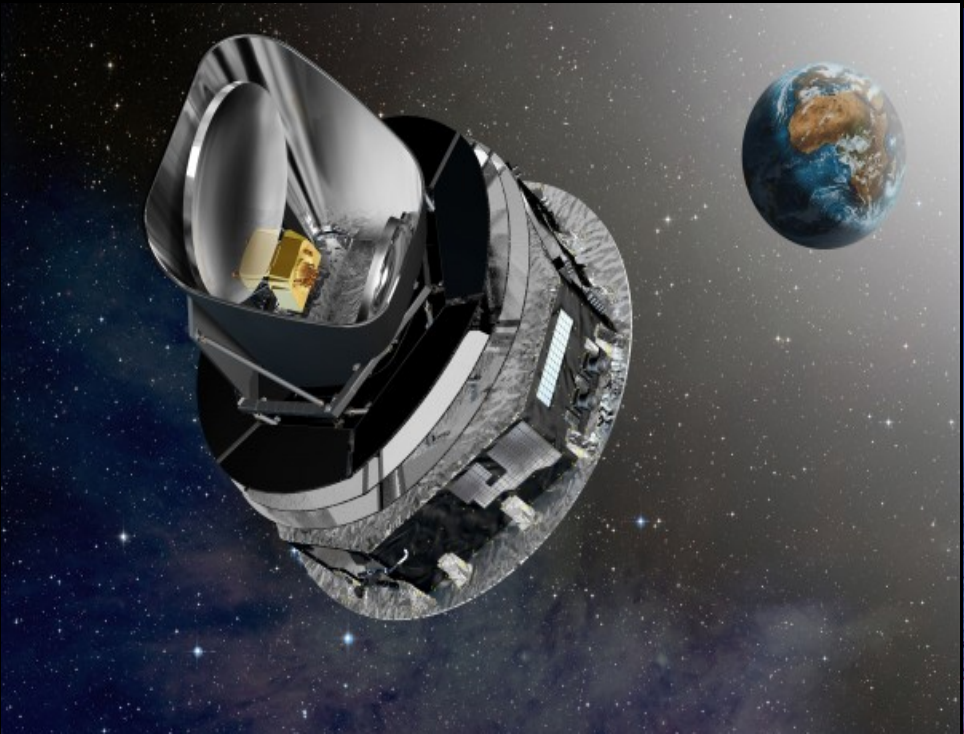
Planck 2018, Astron.Astrophys. 641 (2020) A6

Parameter constraints



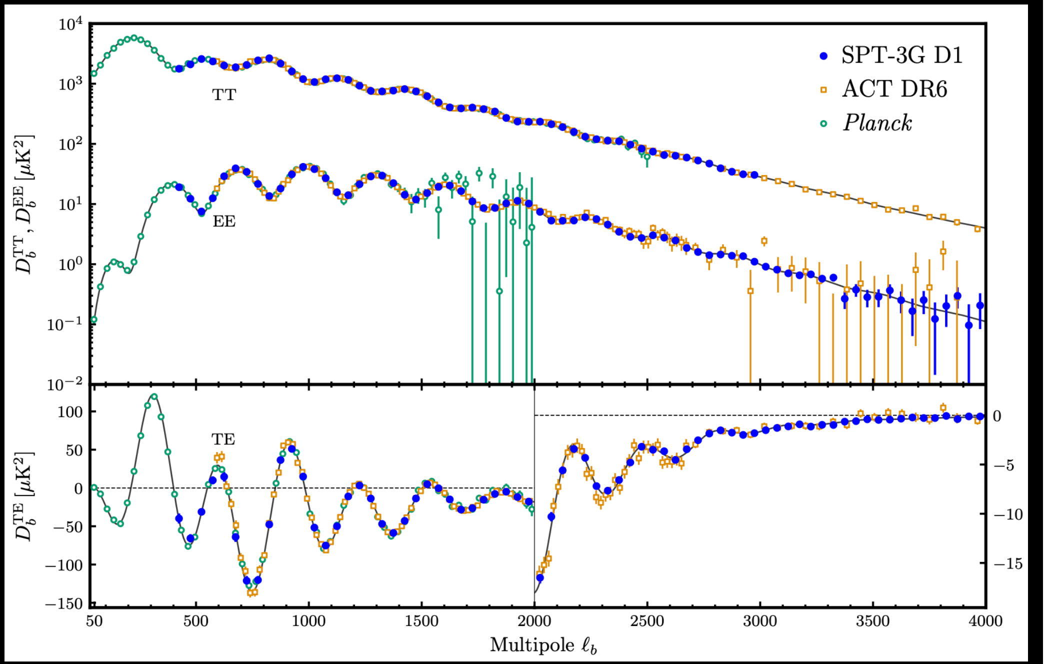
Satellite CMB telescopes

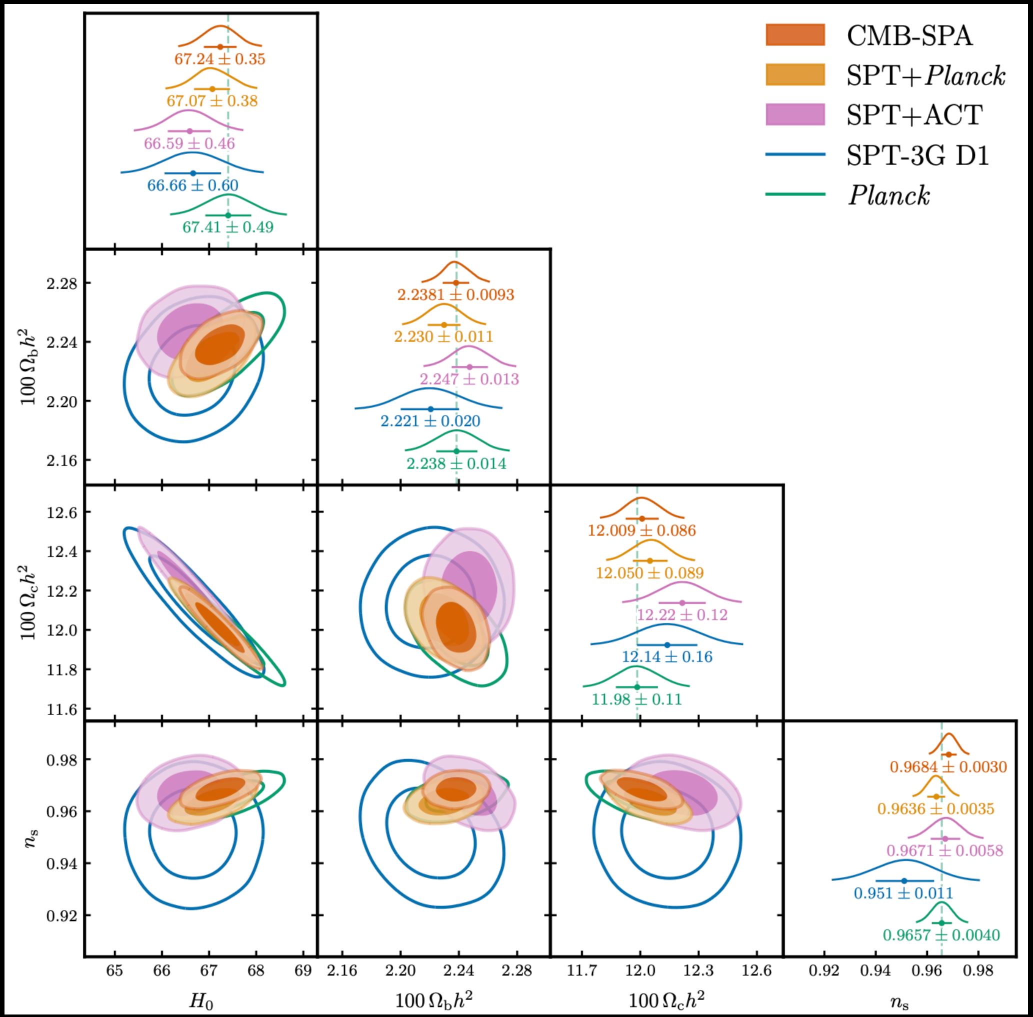
Ground based CMB telescopes



CMB constraints

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





- The cosmological constraints are obtained assuming a cosmological model.
- The results are affected by the degeneracy between the parameters that induce similar effects on the observables.

CMB constraints

arXiv > astro-ph > arXiv:2506.20707

Search...

Help | Adva

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

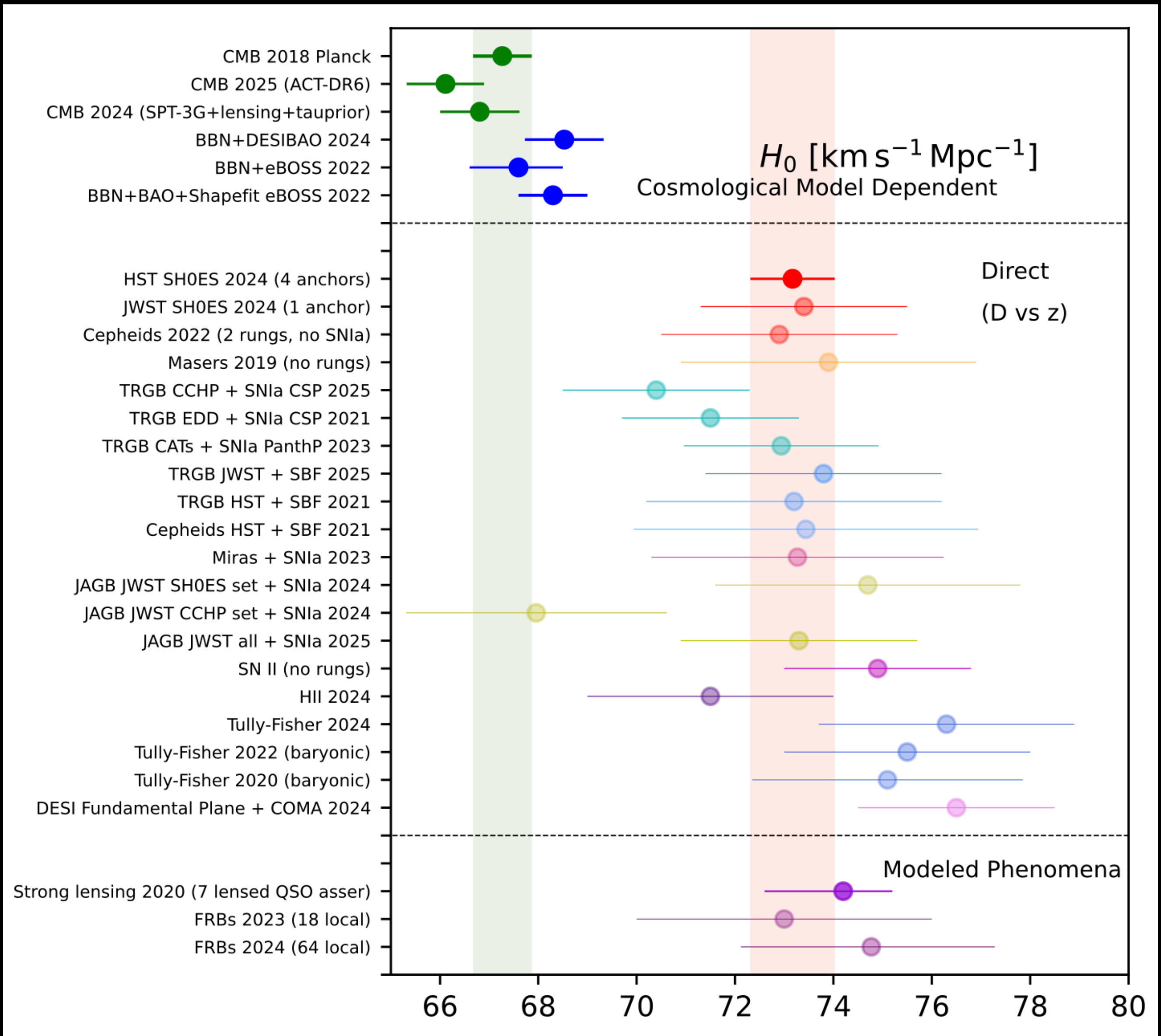
We present measurements of the temperature and E-mode polarization angular power spectra of the cosmic microwave background (CMB) from observations of 4% of the sky with SPT-3G, the current camera on the South Pole Telescope (SPT). The maps used in this analysis are the deepest used in a CMB TT/TE/EE 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... MB constraints to date, with $H_0 = 67.24 \pm$ ... CDM; however, we observe a 2.8 sigma d... els. 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 ± 0.02	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	230 ± 0.011	2.2381 ± 0.0093
$100\,\Omega_c h^2$	11.98 ± 0.11	12.14 ± 0.16	12.26 ± 0.17		050 ± 0.089	12.009 ± 0.086
n_s	0.9657 ± 0.0040	0.951 ± 0.011	0.9682 ± 0.00		$.9636 \pm 0.0035$	0.9684 ± 0.0030
$\log(10^{10}\,A_s)$	3.042 ± 0.011	3.054 ± 0.015	3.038 ± 0.012	± 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



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

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

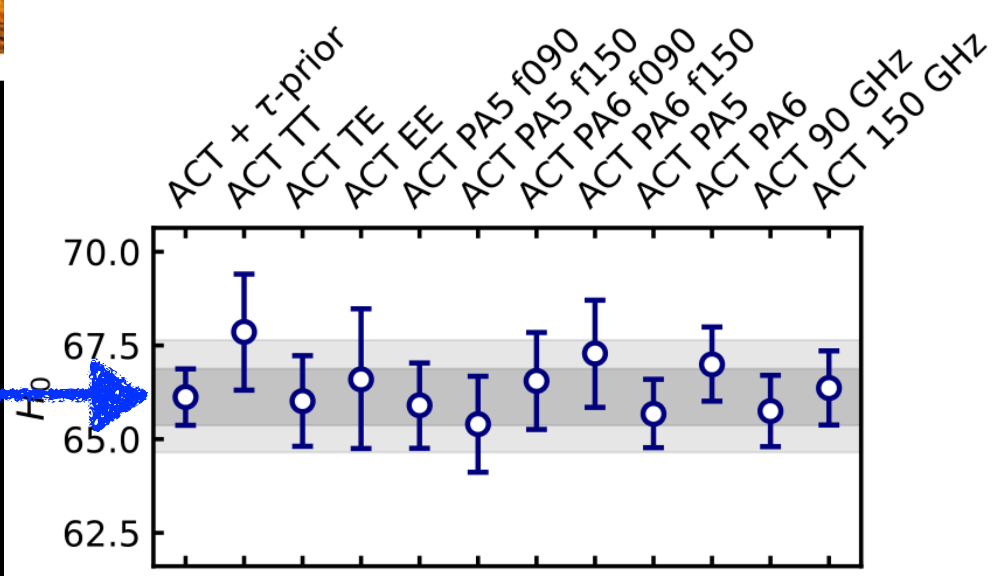
CosmoVerse, Di Valentino et al., arXiv:2504.01669

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

Ground based CMB telescope

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

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

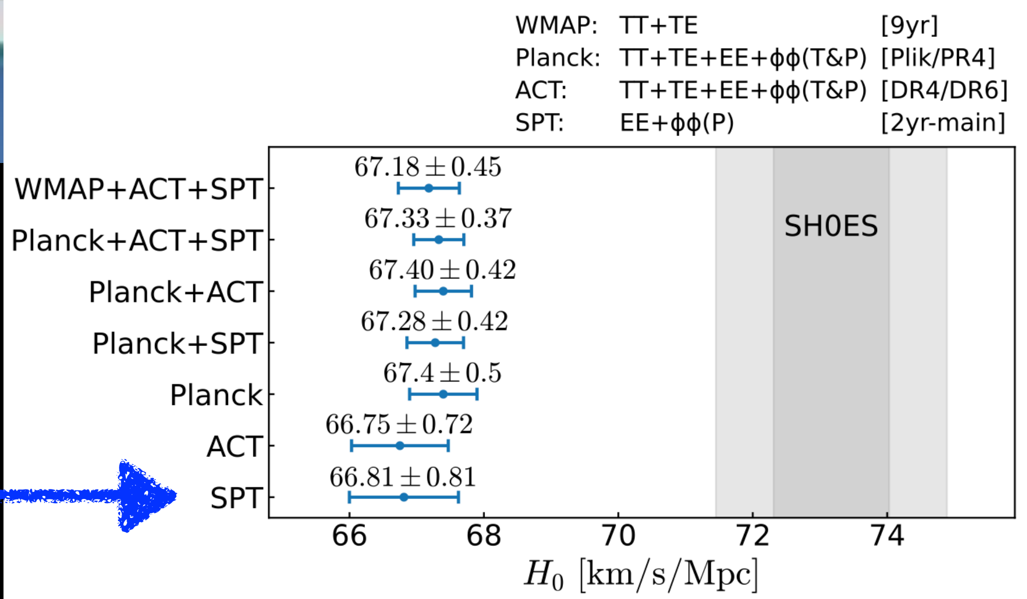


ACT-DR6 2025

ΛCDM - dependent

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

Ground based CMB telescope



SPT-3G:
$H0 = 66.81 \pm 0.81$ km/s/Mpc in ΛCDM

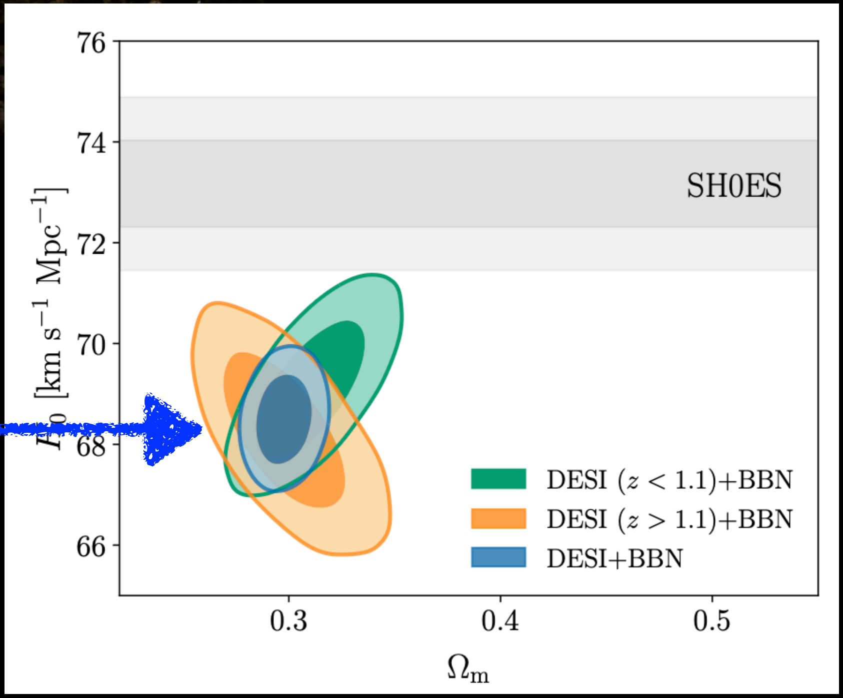
SPT-3G collaboration, arXiv:2411.06000

ΛCDM - dependent

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

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

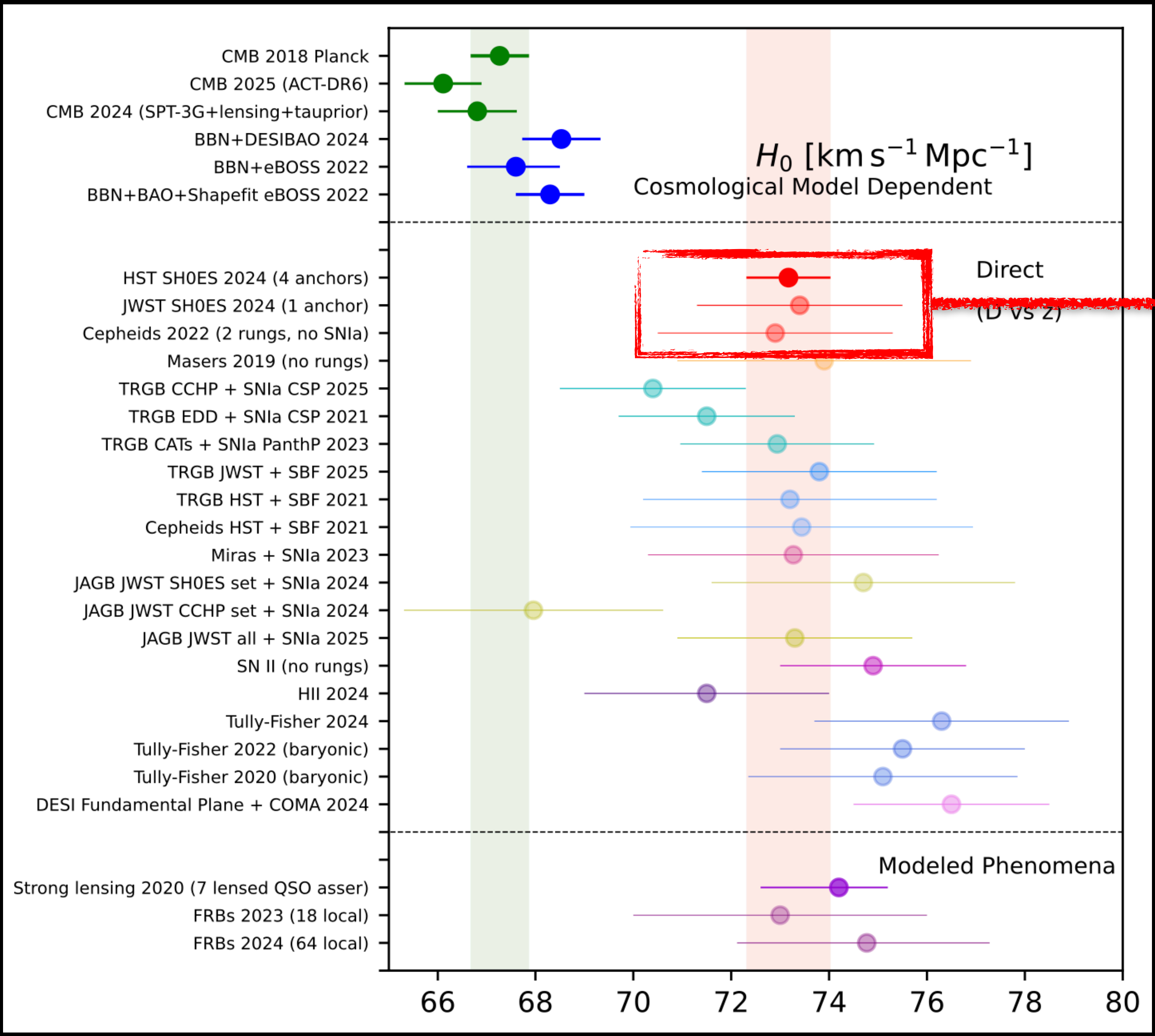
DESI+BBN:
H0 = 68.51 ± 0.58 km/s/Mpc in ΛCDM



ΛCDM - dependent

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

Latest H0 measurements



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

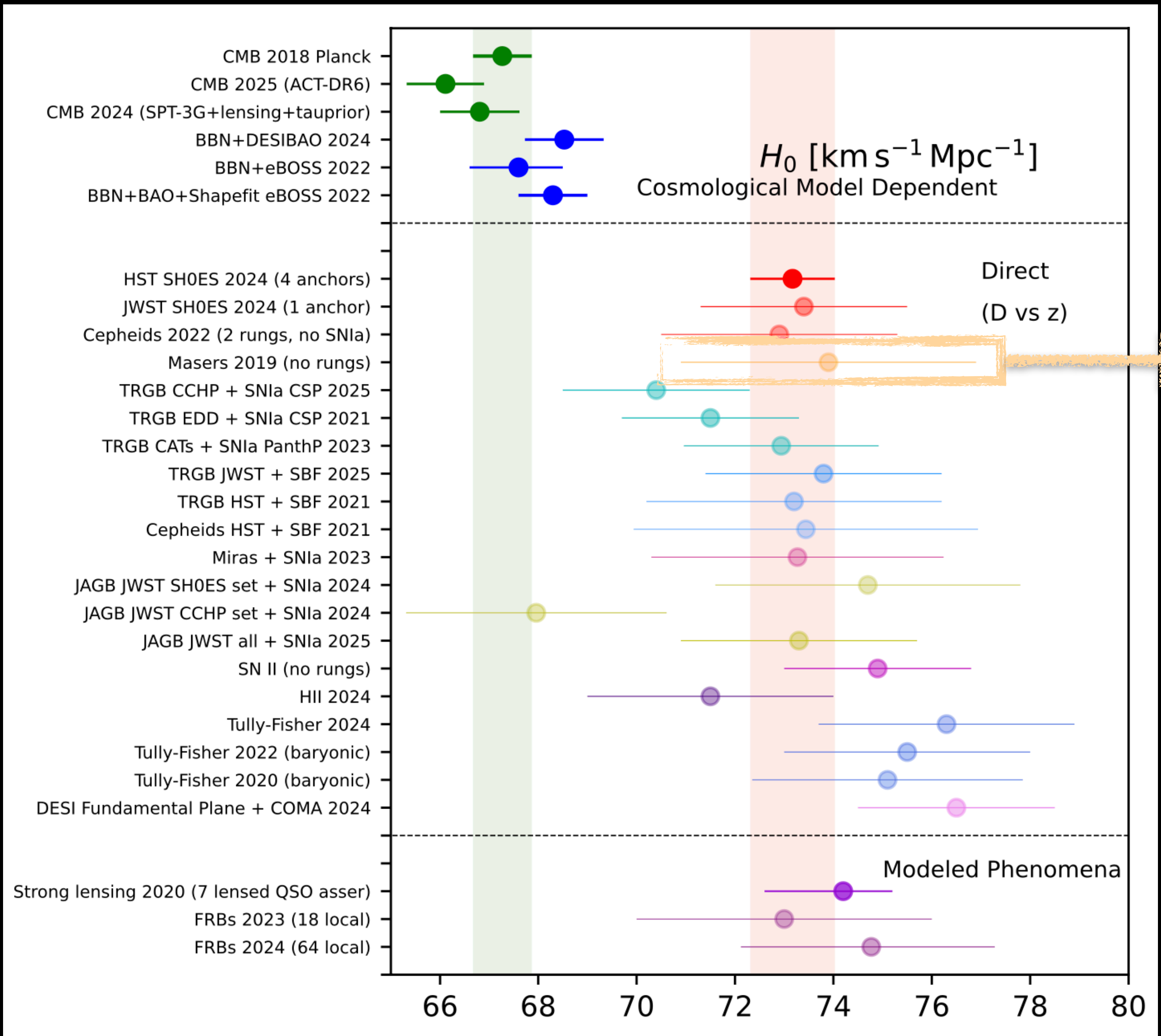
Breuval et al., arXiv:*2404.08038*

H0 = 72.9 ± 2.4 km/s/Mpc

Kenworthy et al., arXiv:2204.10866

CosmoVerse, Di Valentino et al., arXiv:2504.01669

Latest H0 measurements



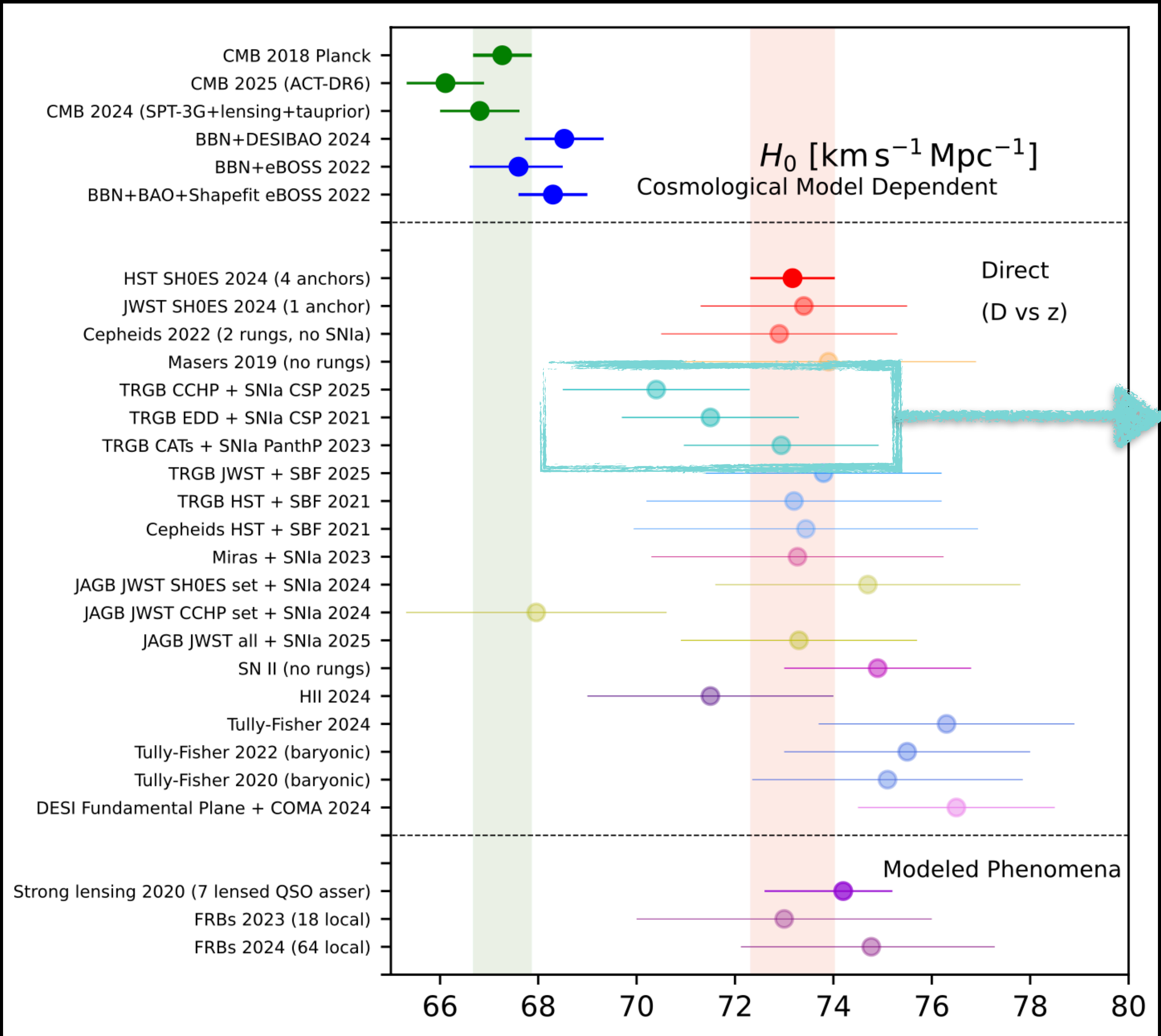
The Megamaser Cosmology Project measures H0 using geometric distance measurements to six Megamaser - hosting galaxies. This approach avoids any distance ladder by providing geometric distance directly into the Hubble flow.

H0 = 73.9 ± 3.0 km/s/Mpc

Pesce et al. arXiv:2001.09213

CosmoVerse, Di Valentino et al., arXiv:2504.01669

Latest H0 measurements



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

H0 = 70.39 ± 1.94 km/s/Mpc

Freedman et al., arXiv:*2408.06153*

H0 = 71.5 ± 1.8 km/s/Mpc

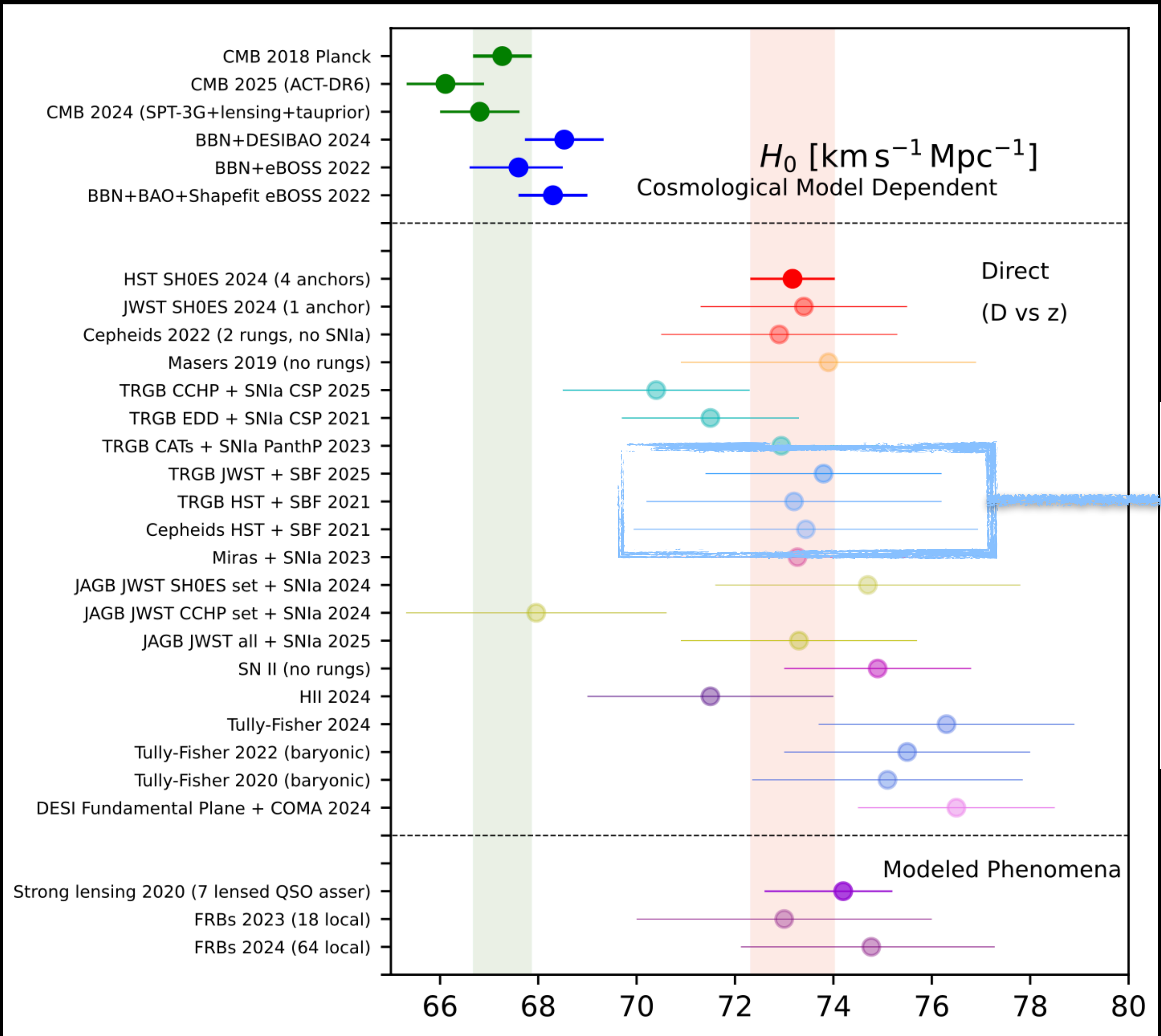
Anand et al., arXiv: *2108.00007*

H0 = 73.22 ± 2.06 km/s/Mpc

Scolnic et al., arXiv:2304.06693

CosmoVerse, Di Valentino et al., arXiv:2504.01669

Latest H0 measurements



CosmoVerse, Di Valentino et al., arXiv:2504.01669

H0 = 73.8 ± 2.4 km/s/Mpc

Jensen et al., arXiv:2502.15935

H0 = 73.2 ± 3.5 km/s/Mpc

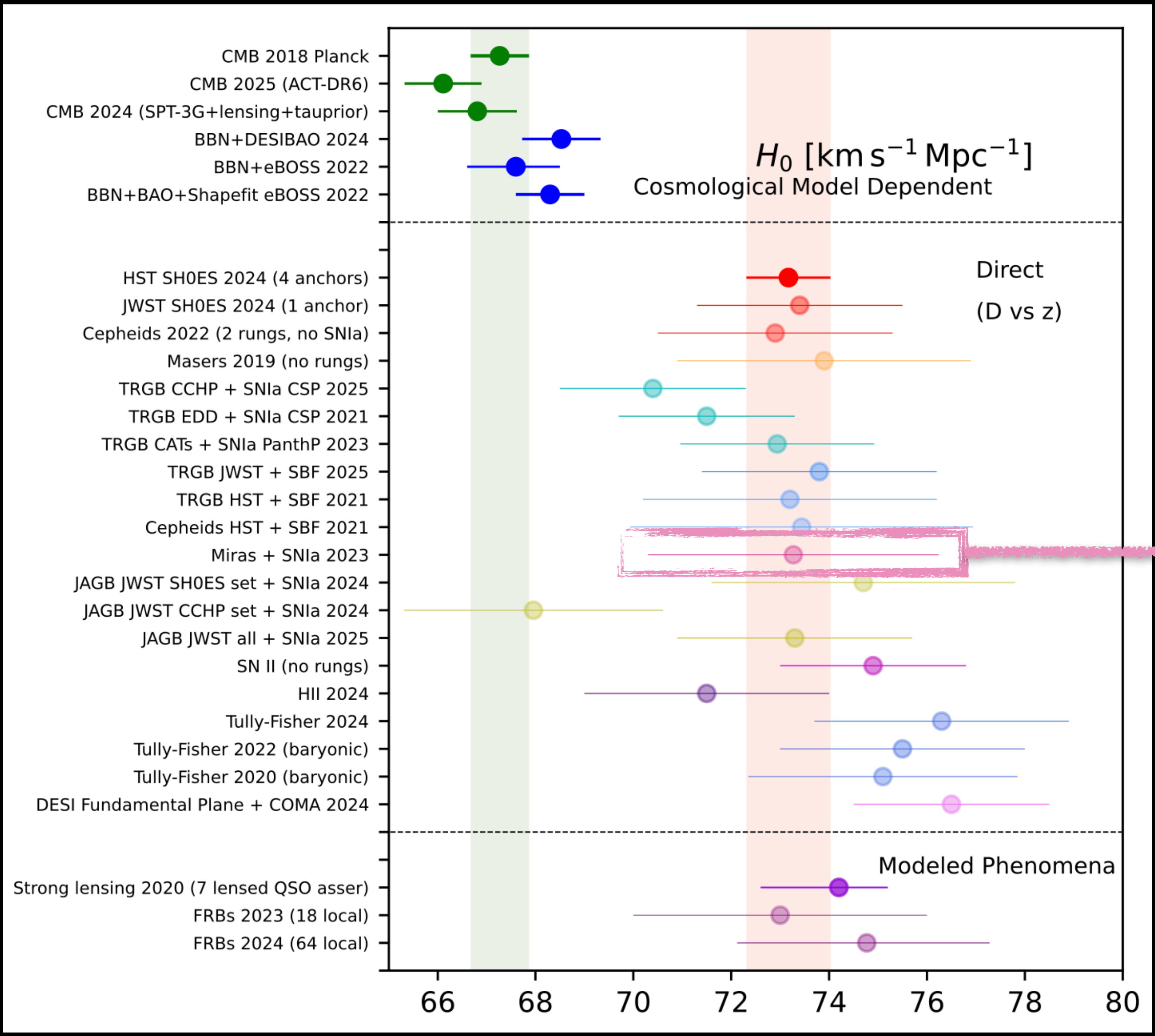
Blakeslee et al., arXiv:2101.02221

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)

Latest H0 measurements



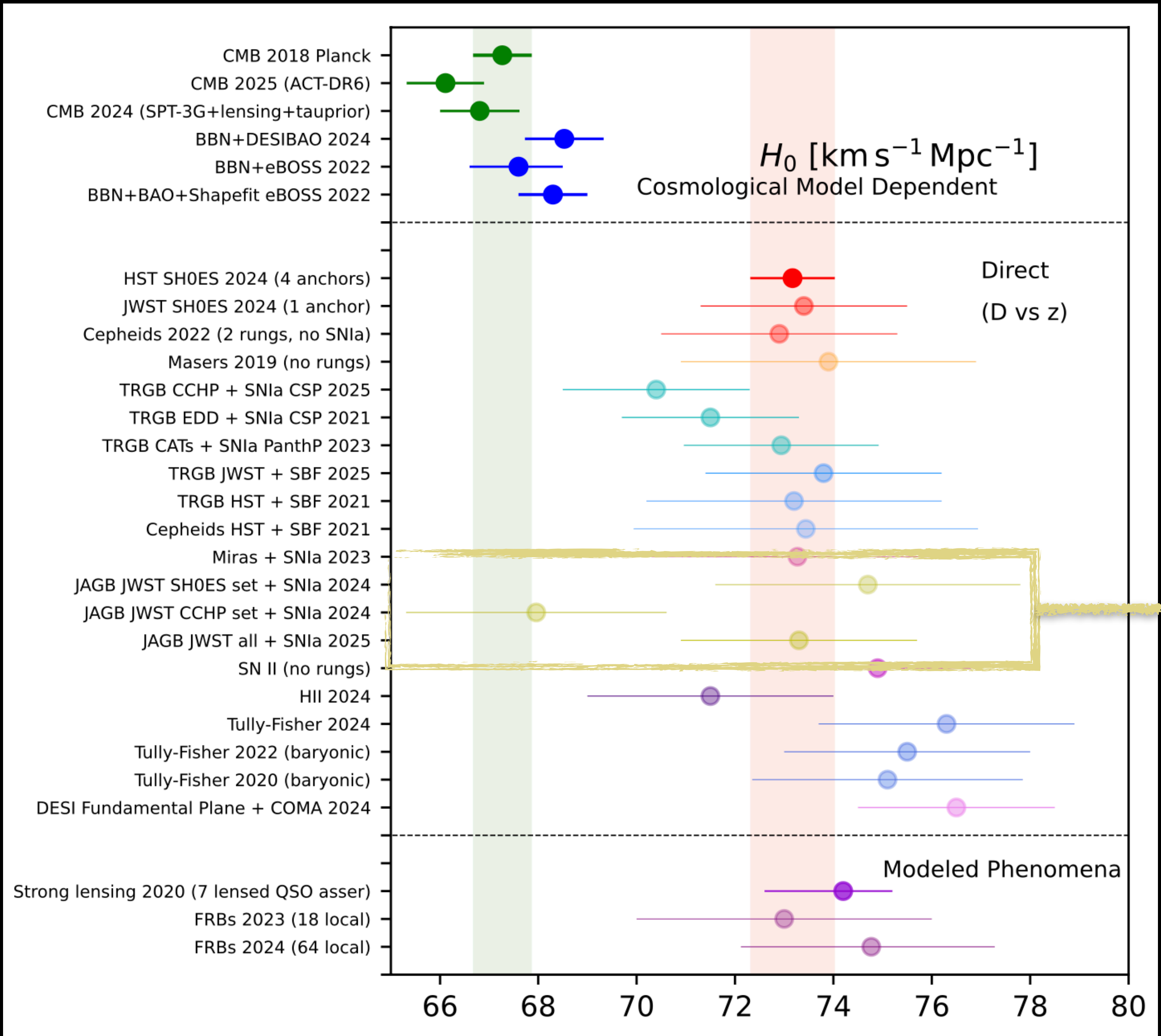
MIRAS
variable red giant stars from older stellar populations

H0 = 72.37 ± 2.97 km/s/Mpc

Huang et al., arXiv:2312.08423]

CosmoVerse, Di Valentino et al., arXiv:2504.01669

Latest H0 measurements



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

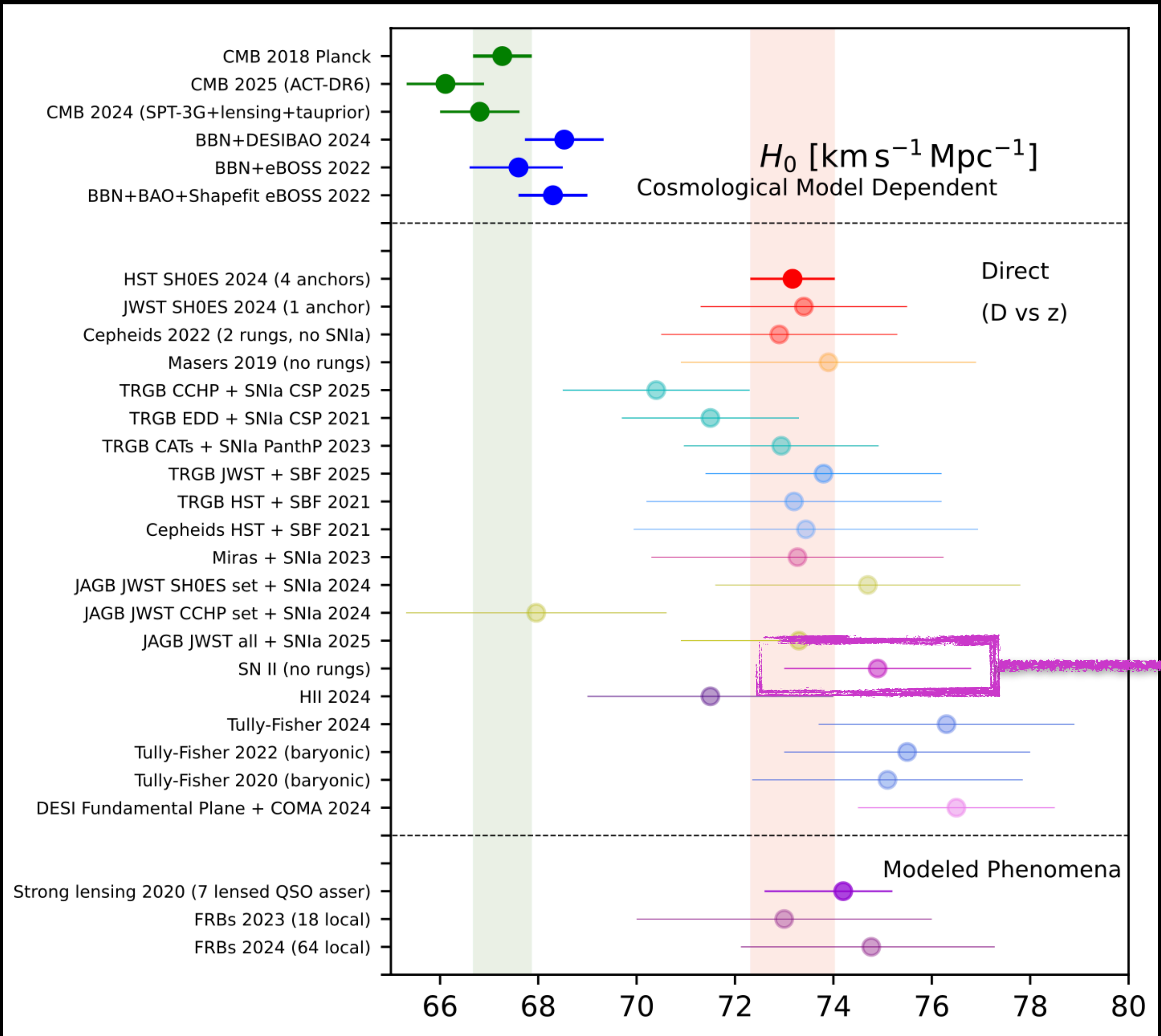
Li et al., arXiv: *2502.05259*

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, Di Valentino et al., arXiv:2504.01669

Latest H0 measurements



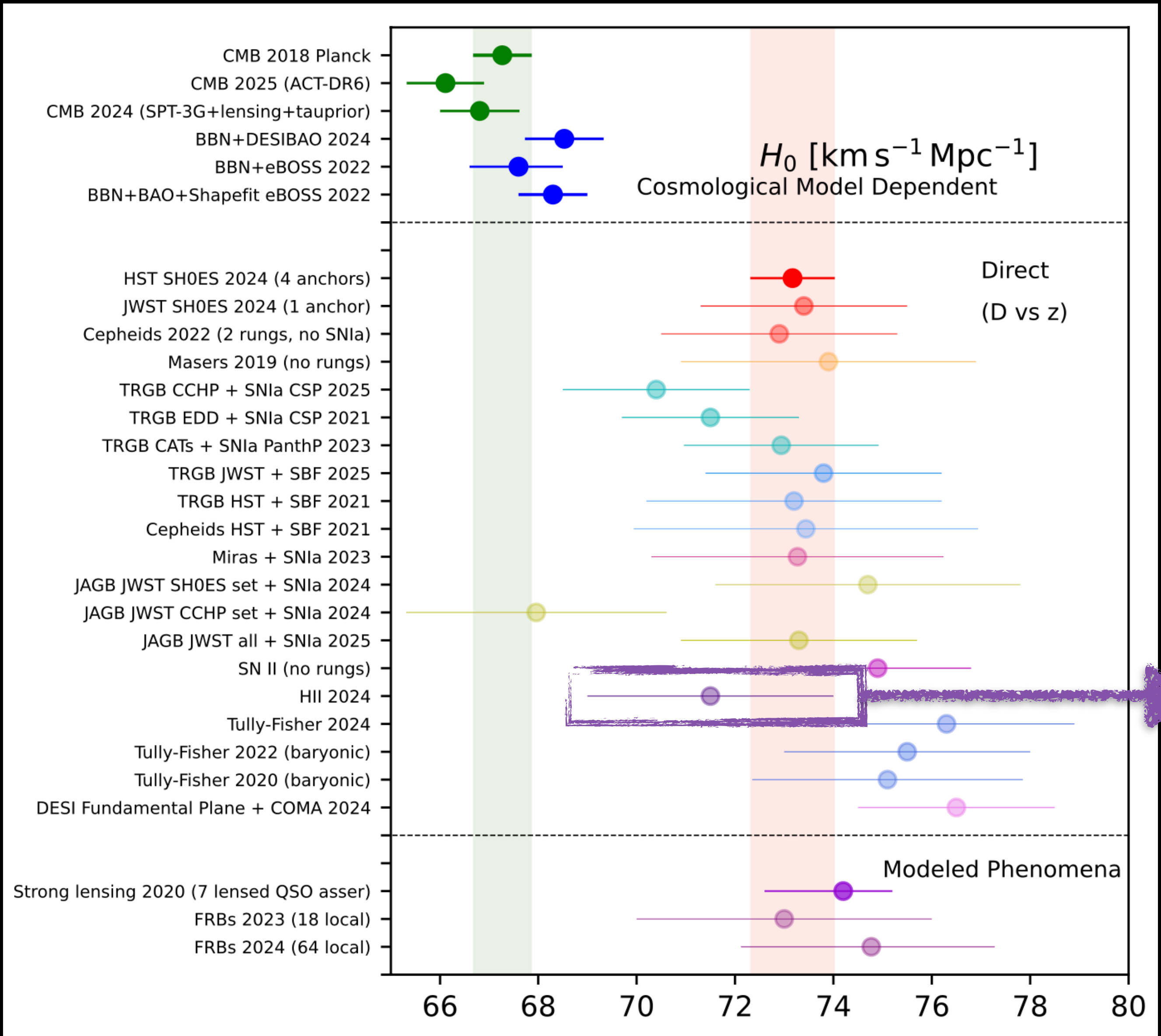
CosmoVerse, Di Valentino et al., arXiv:2504.01669

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.

Latest H0 measurements



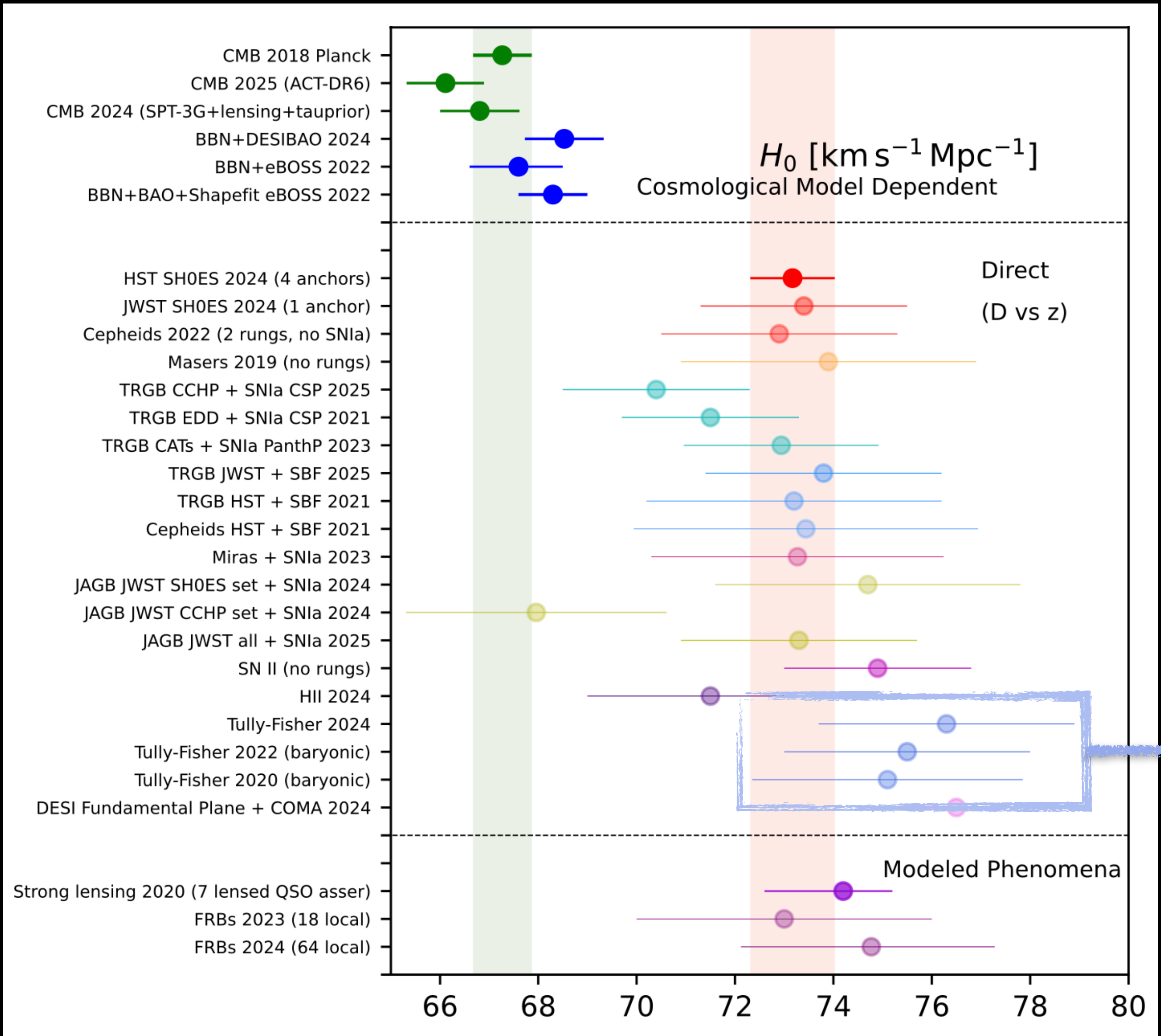
CosmoVerse, Di Valentino et al., arXiv:2504.01669

H0 = 71.5 ± 2.5 km/s/Mpc

Chávez et al., arXiv:2404.16261

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

Latest H0 measurements



CosmoVerse, Di Valentino et al., arXiv:2504.01669

H0 = 76.3 ± 2.6 km/s/Mpc

Scolnic et al. arXiv:2412.08449

H0 = 75.5 ± 2.5 km/s/Mpc

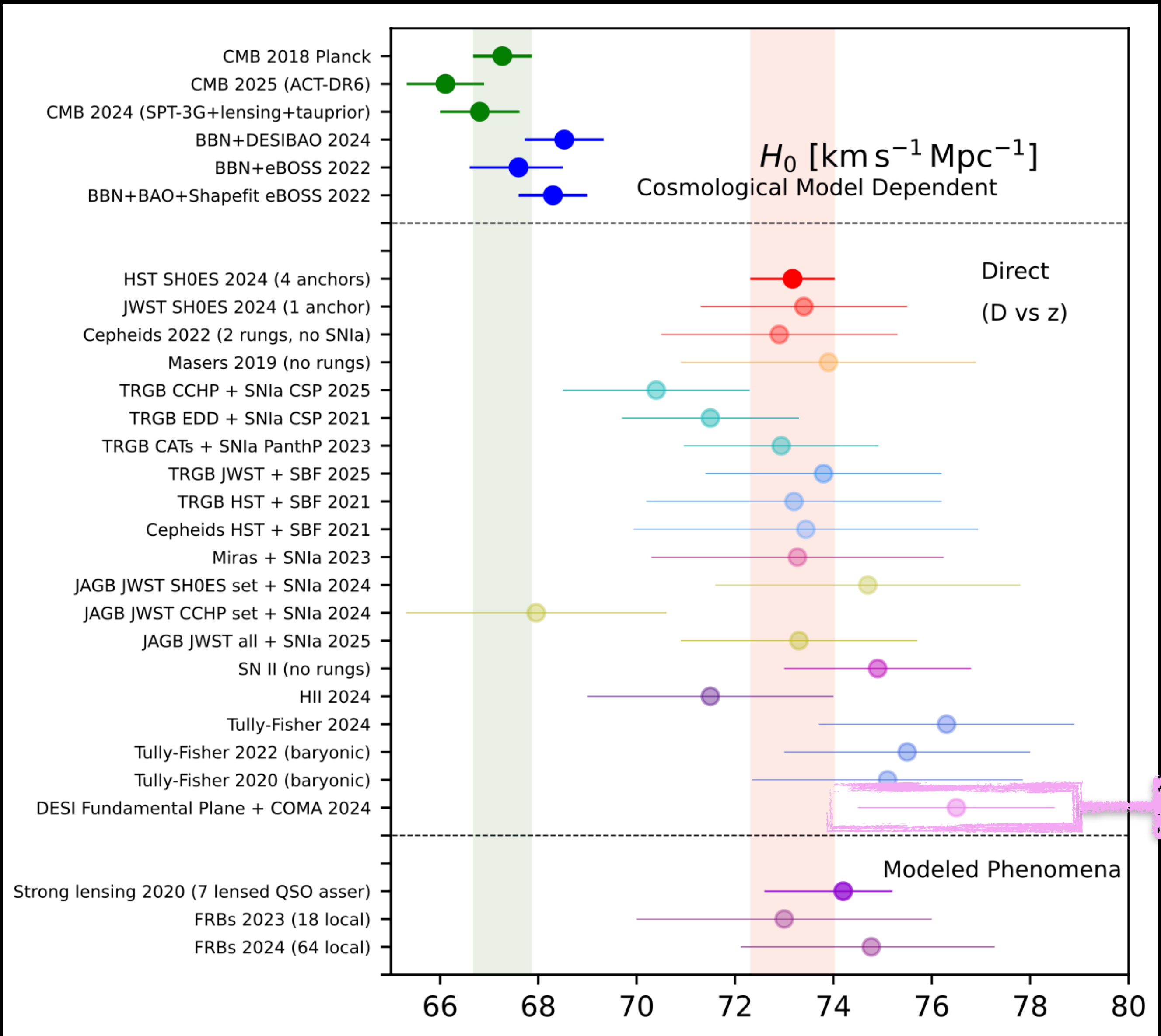
Kourkchi et al. arXiv:2201.13023

H0 = 75.10 ± 2.75 km/s/Mpc

Schombert et al. arXiv:2006.08615

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

Latest H0 measurements



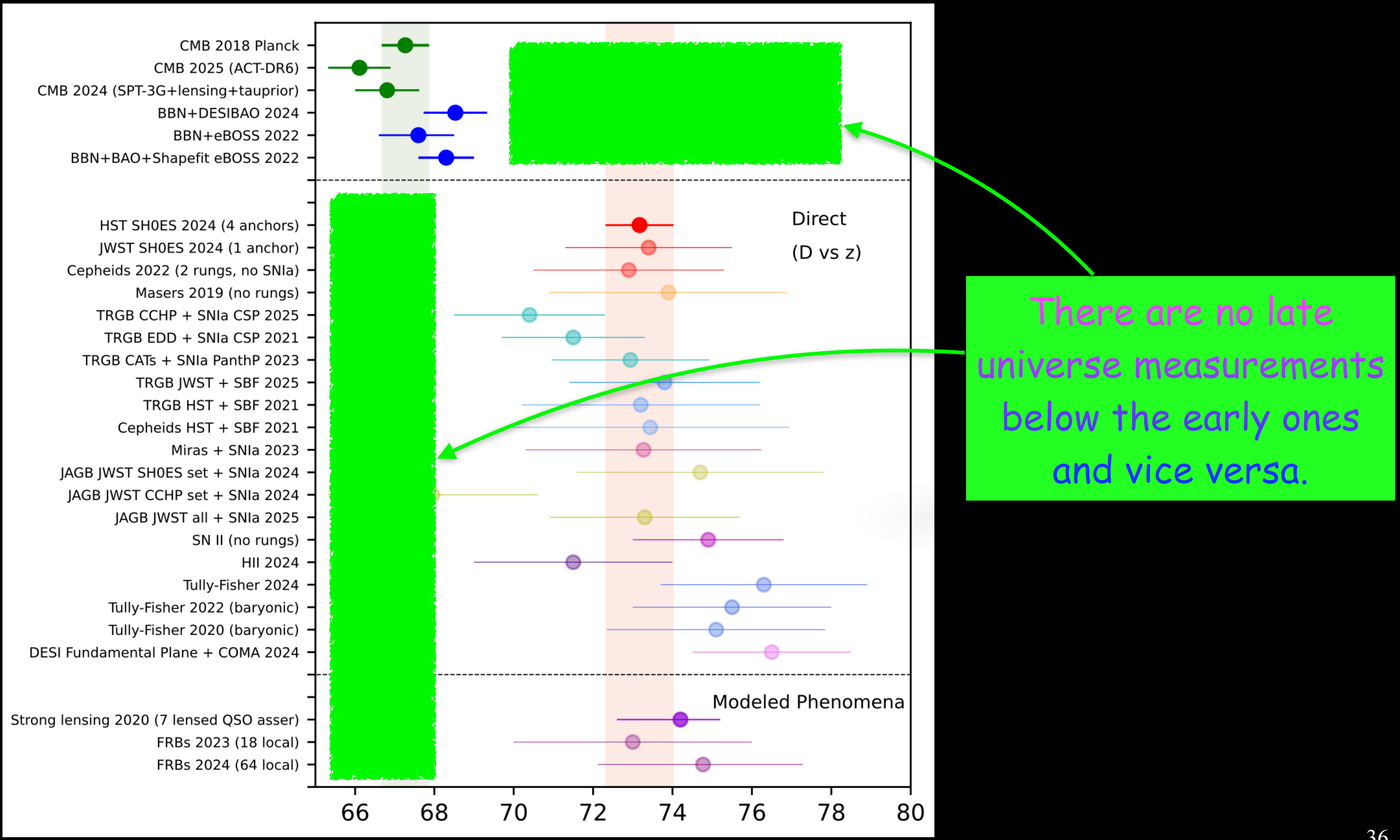
DESI measured relation between H0 and the distance to the Coma cluster using the fundamental plane relation of early-type galaxies.

H0 = 76.5 ± 2.2 km/s/Mpc

Scolnic et al., arXiv: *2409.14546*

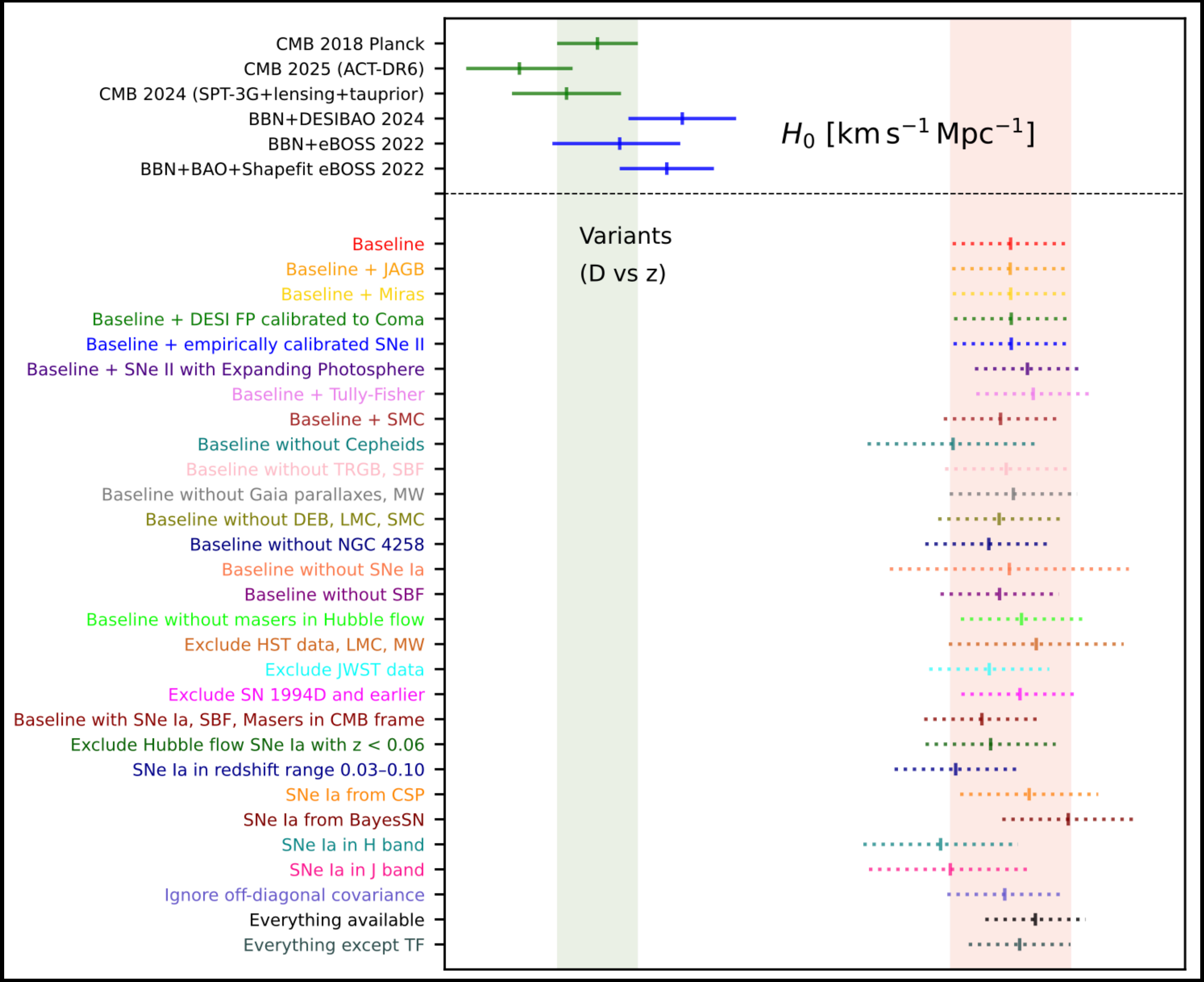
CosmoVerse, Di Valentino et al., arXiv:2504.01669

Latest H0 measurements



CosmoVerse, Di Valentino et al., arXiv:2504.01669

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.

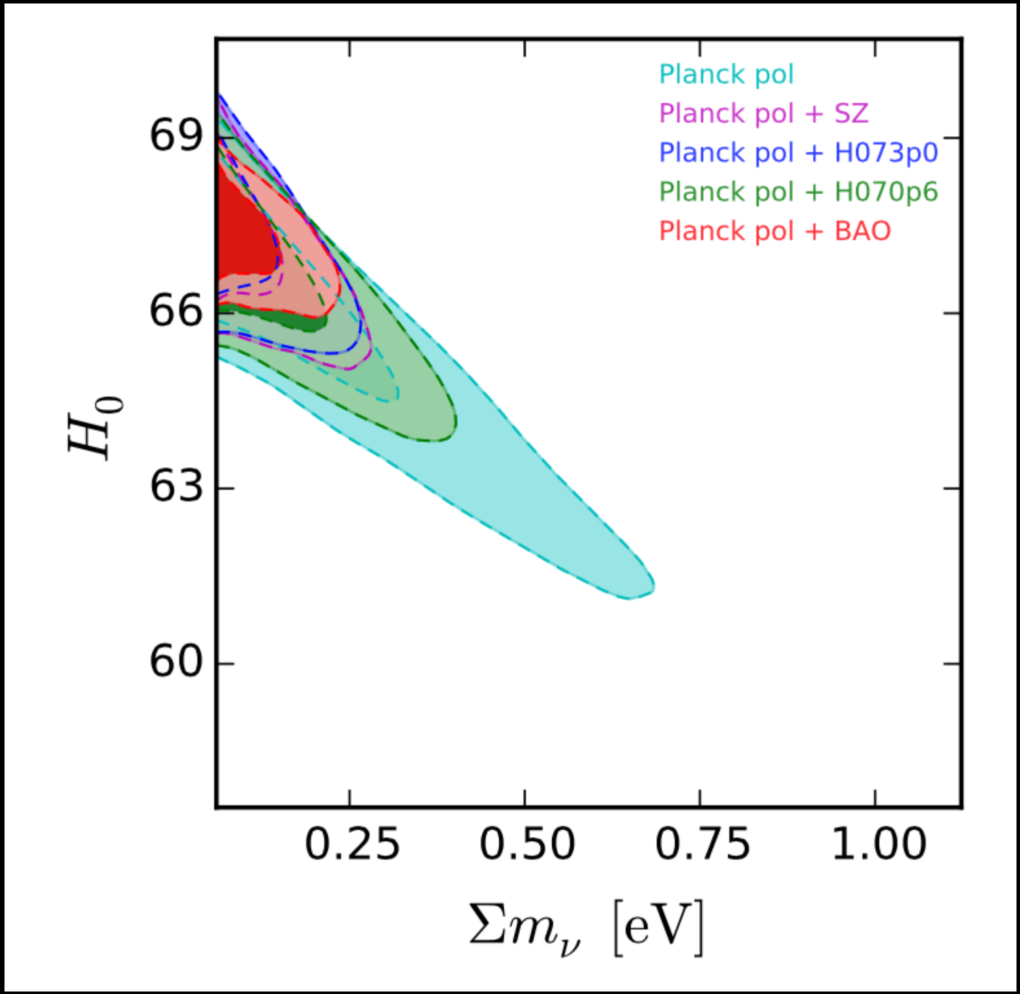
Casertano et al., in preparation

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

Why Do We Care?

H0 correlates with neutrinos

The H0 value is very important for the determination of the
total neutrino mass.
In fact, there exist a strong negative correlation between the Hubble constant and the sum of the neutrino masses.

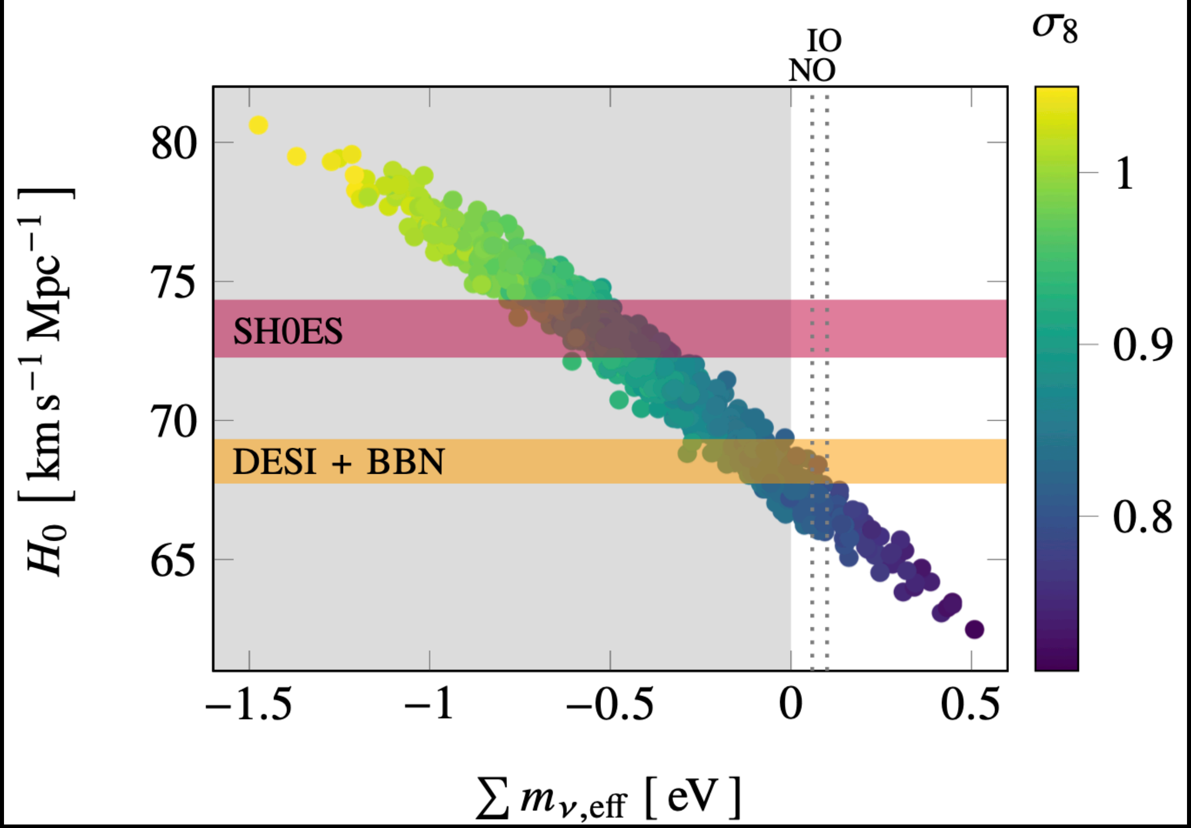


Di Valentino et al. Phys.Rev. D93 (2016) no.8, 083527

H0 correlates with neutrinos

We can see a clear geometrical degeneracy between these two parameters. To reconcile the SH0ES measurement of H0 with Planck we need a negative effective neutrino mass of

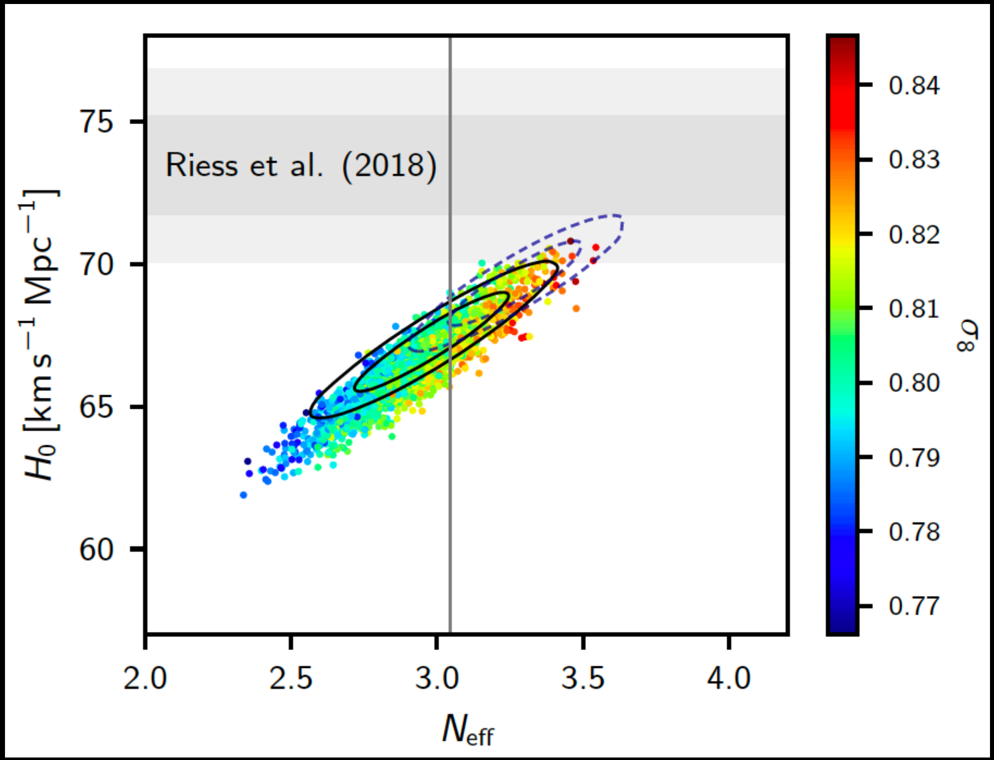
$$\sum m_{\nu,\mathrm{eff}} = -0.5 \pm 0.1\ \mathrm{eV}$$



Elbers al., arXiv:2407.10965

H0 correlates with neutrinos

Moreover, there is a very strong positive correlation between H0 and the neutrino effective number. Therefore, imposing an H0 prior as obtained by SH0ES can give an indication for extra particles at recombination.



Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

Systematics or problems with ΛCDM?

It is difficult to attribute the Hubble constant tension
to a single systematic error because such an error would need to consistently explain discrepancies across a wide range of phenomena.

This tension persists at a statistically significant level $>6\sigma$ even when different types of measurements, teams, and calibrations are considered.

While multiple independent systematic errors could theoretically resolve the tension, they are unlikely to bias the measurements all in the same direction.

Since indirect constraints rely on model assumptions, it is worth exploring modifications to the Standard cosmological model ΛCDM. Investigating these extensions could help resolve discrepancies between different cosmological observations.

All the models are wrong, but some are useful

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

Unknown quantities:

- 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).

The ΛCDM model

Unknown quantities:

- 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.

The ΛCDM model - sanity check

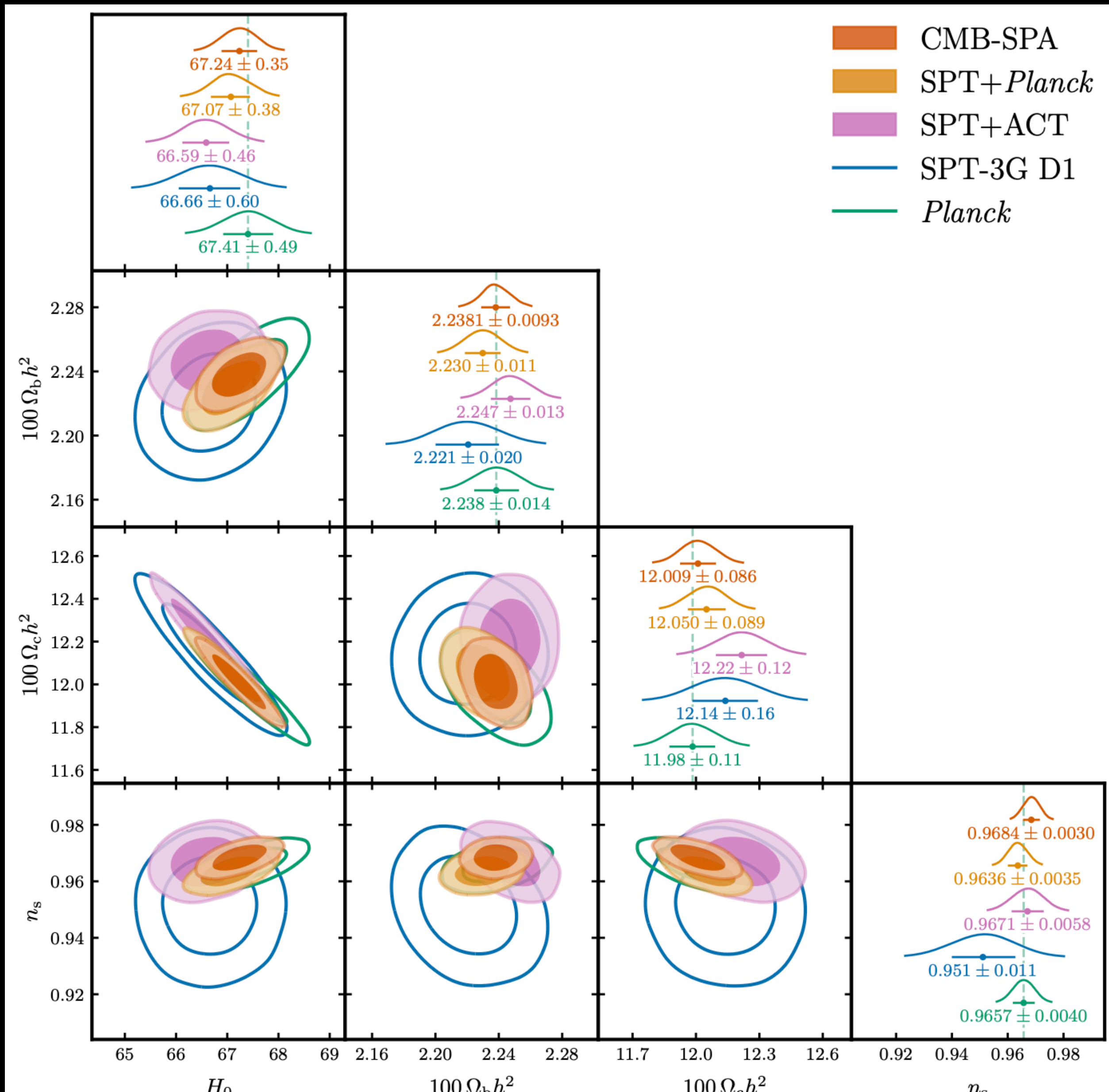
Despite its theoretical shortcomings, ΛCDM remains the preferred model due to its ability to accurately describe observed phenomena. However, the ΛCDM model with its six parameters is not based on deep-rooted physical principles and should be considered, at best, an approximation of an underlying physical theory that remains undiscovered.

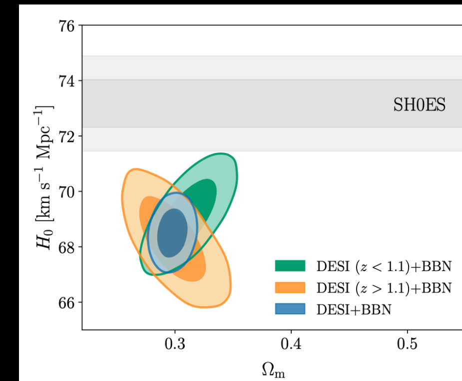
Hence, as observations become more numerous and accurate, deviations from the ΛCDM model are expected to be detected. And in fact, discrepancies in important cosmological parameters, not only H0, have already arisen in other observations with different statistical significance.

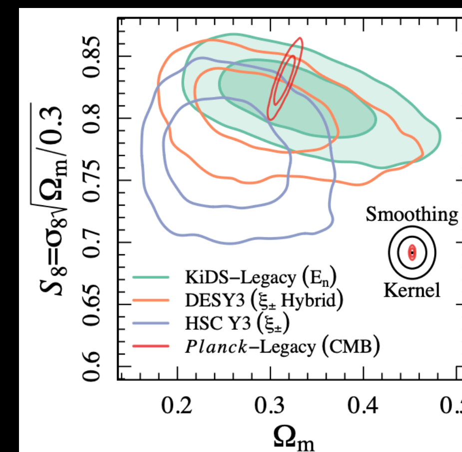
While some of these tensions may have a systematic origin, their recurrence across multiple probes suggests that there may be flaws in the standard cosmological scenario, and that new physics may be necessary to explain these observational shortcomings.

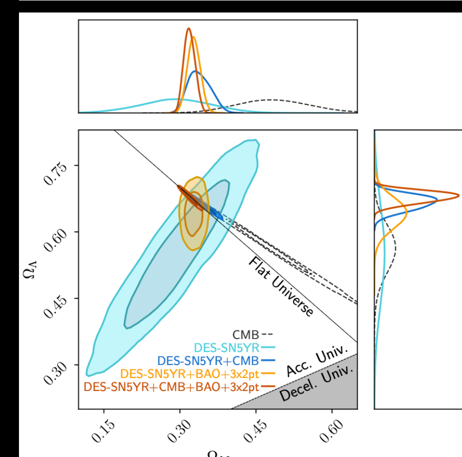
Therefore, the persistence of these tensions could indicate the failure of the canonical ΛCDM model.

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









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

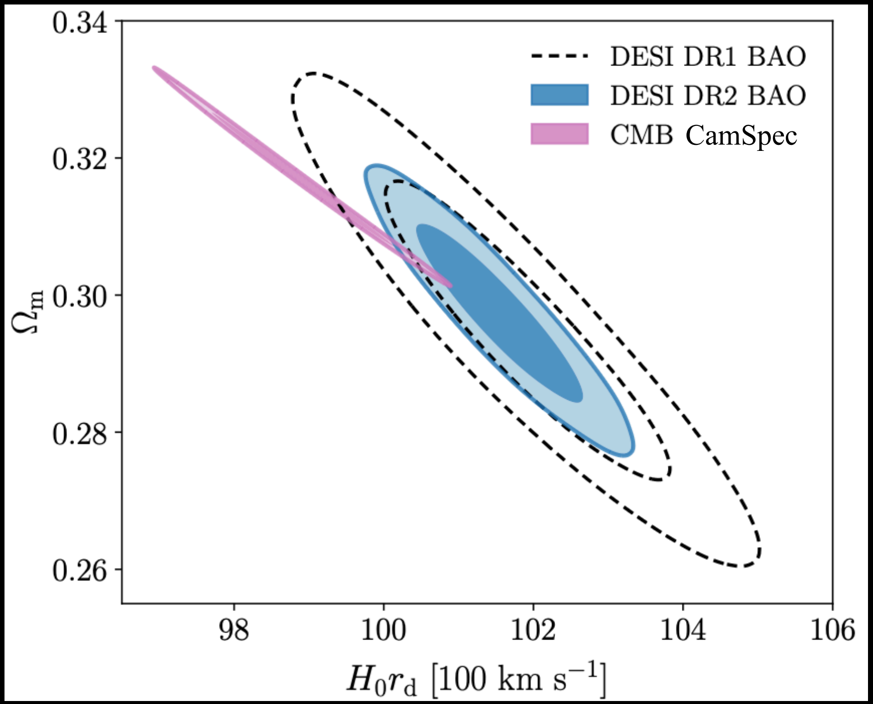
In a Bayesian framework, all models can, in principle, agree with the data.
What matters is whether they are disfavoured due to a poor fit
or because another model is preferred.
Therefore, to me, this means that ΛCDM provides a good fit to the data
and shows no clear signs of deviation, even when extended.

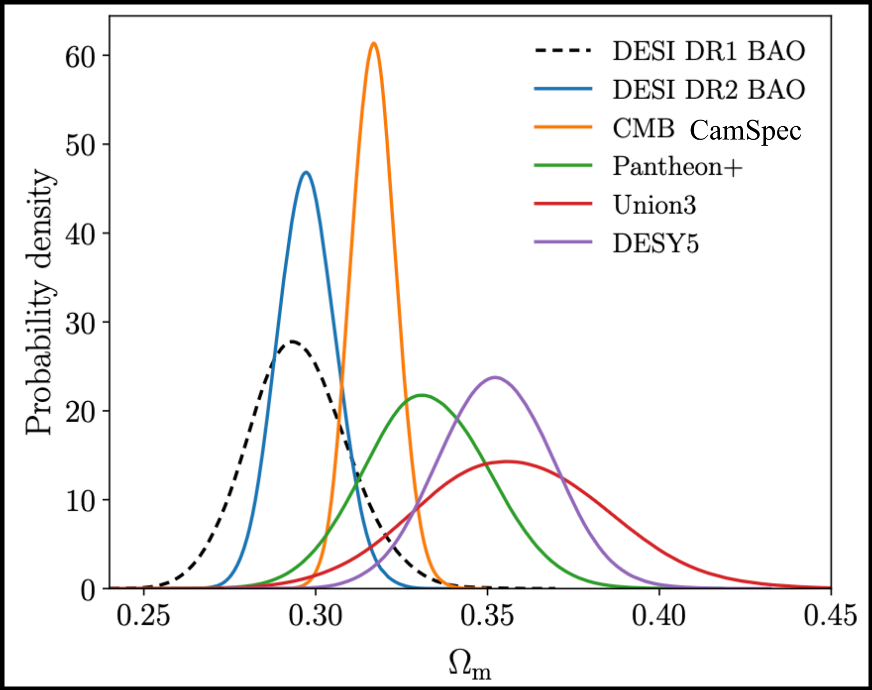
However, currently the cosmological parameters inferred
from different probes are not the same.

So ΛCDM appears different for the different data!

Tensions and Disagreements in ΛCDM

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





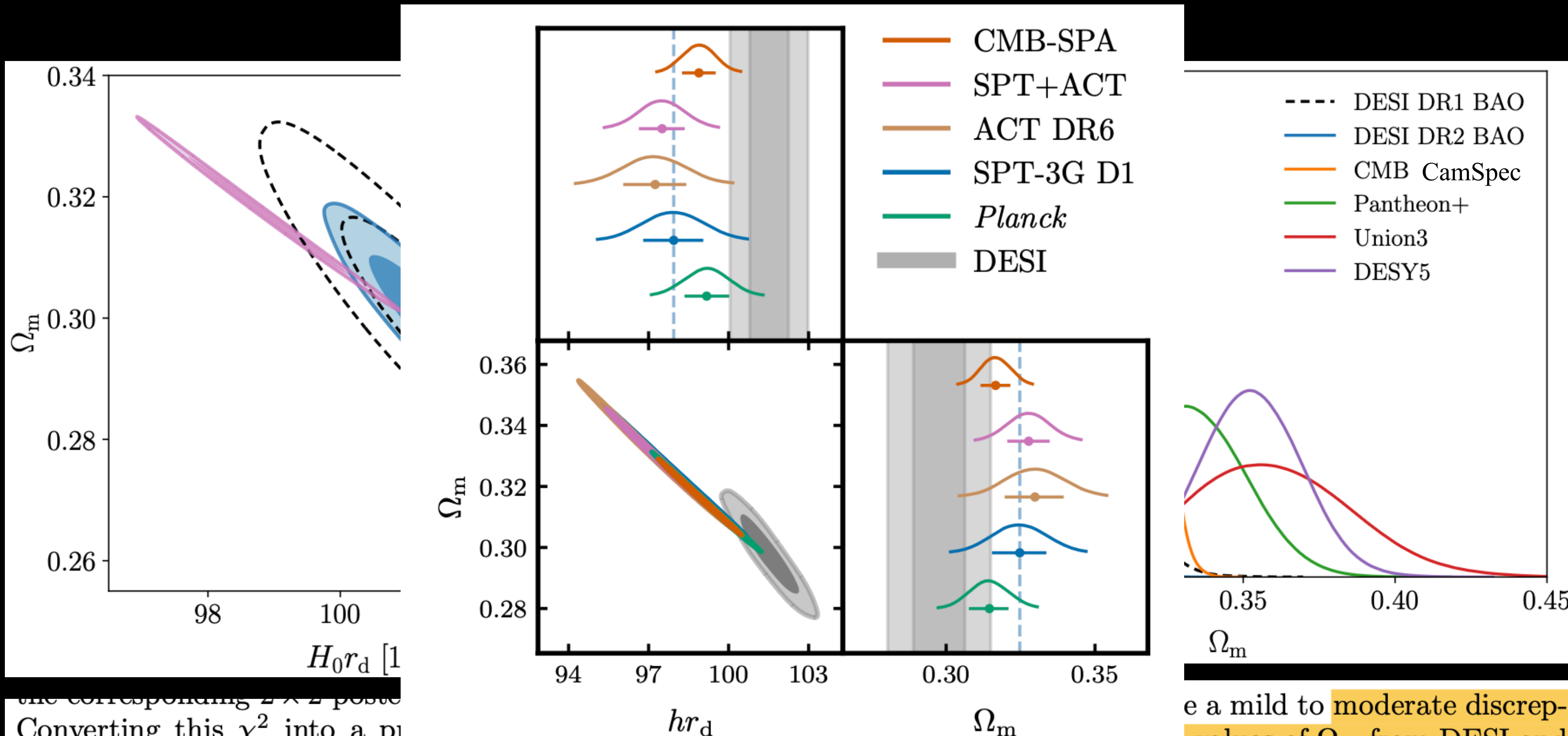
the corresponding 2 × 2 posterior parameter covariances. Converting this χ^2 into a probability-to-exceed (PTE) value, we find it is equivalent to a 2.3σ discrepancy between BAO and CMB in ΛCDM, increased from 1.9σ in DR1. However, we note that this reduces to 2.0σ if CMB lensing is excluded. This discrepancy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

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

The same ΛCDM cannot fit 2 datasets together!

Tensions and Disagreements in ΛCDM

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



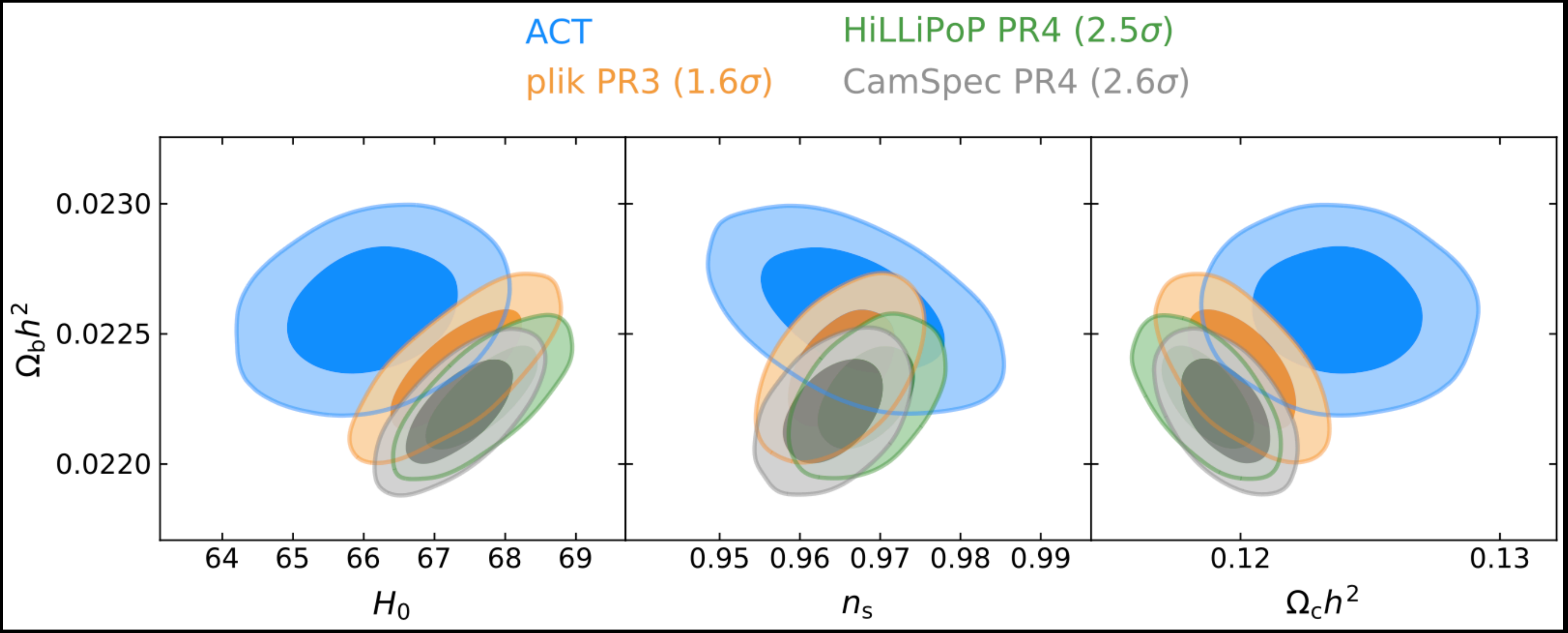
Converting this χ^2 into a pr
value, we find it is equivalent
tween BAO and CMB in ΛC
in DR1. However, we note t
CMB lensing is excluded. Thi
reason why more models with
expansion history than ΛCDM

	$100\,\Omega_m$	hr_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	

e a mild to moderate discrep-
values of Ω_m from DESI and
ΛCDM model. This is shown
ors in Figure 10: the discrep-
+, 2.1σ for Union3, and 2.9σ
mples preferring higher values
uncertainties. For ΛCDM we
ints on parameters from any
SNe data. However, as with

The same ΛCDM cannot fit 2 datasets together!

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

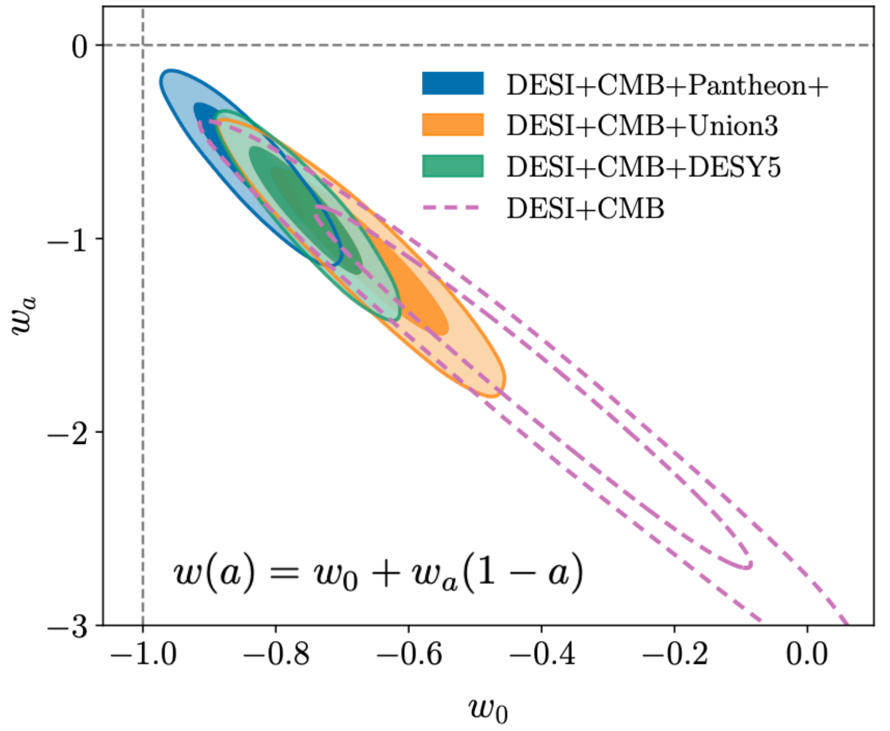
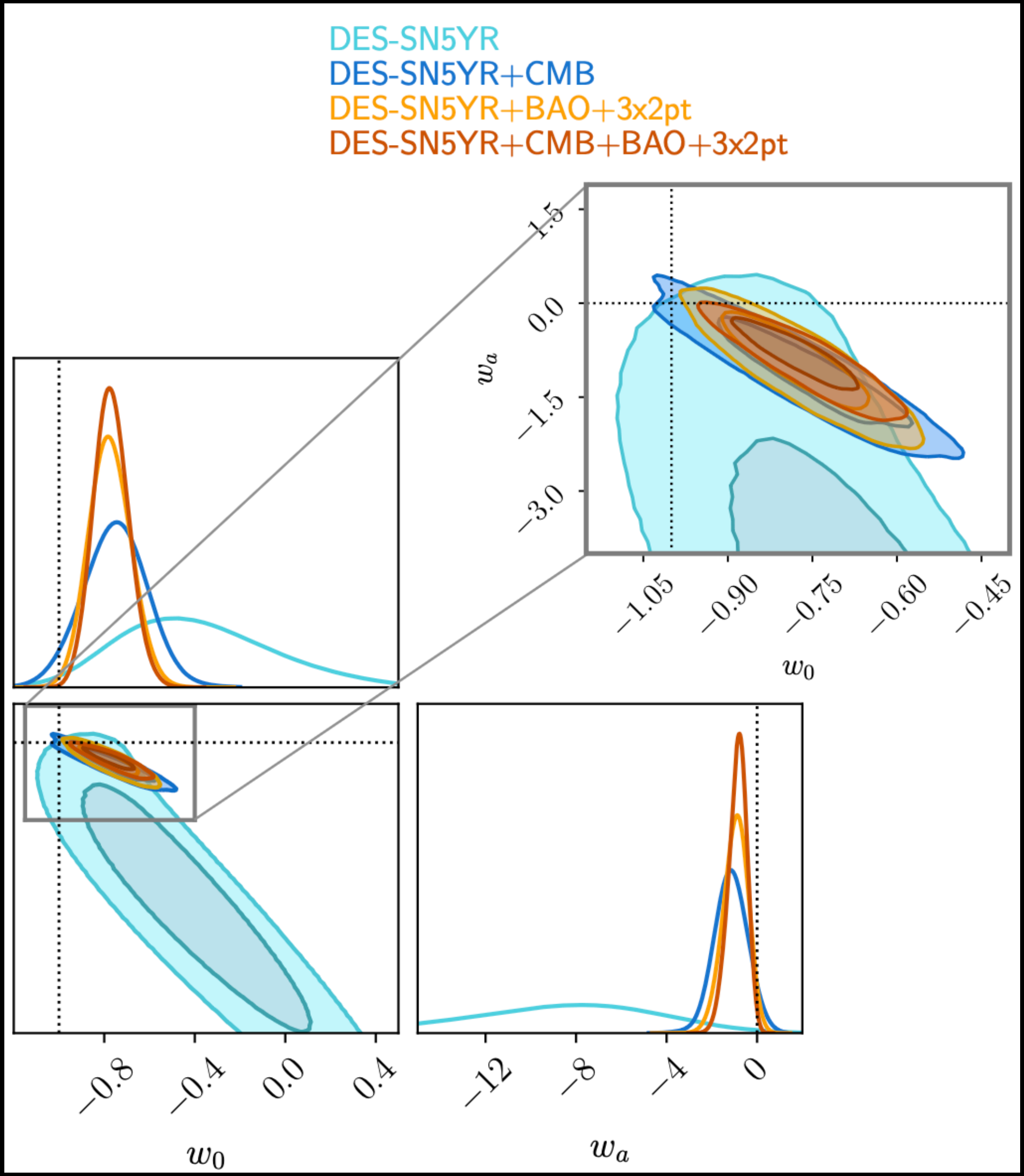


FIG. 11. Results for the posterior distributions of w_0 and w_a, from fits of the w_0w_aCDM model to DESI in combination with CMB and three SNe datasets as labelled. We also show the contour for DESI combined with CMB alone. The contours enclose 68% and 95% of the posterior probability. The gray dashed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

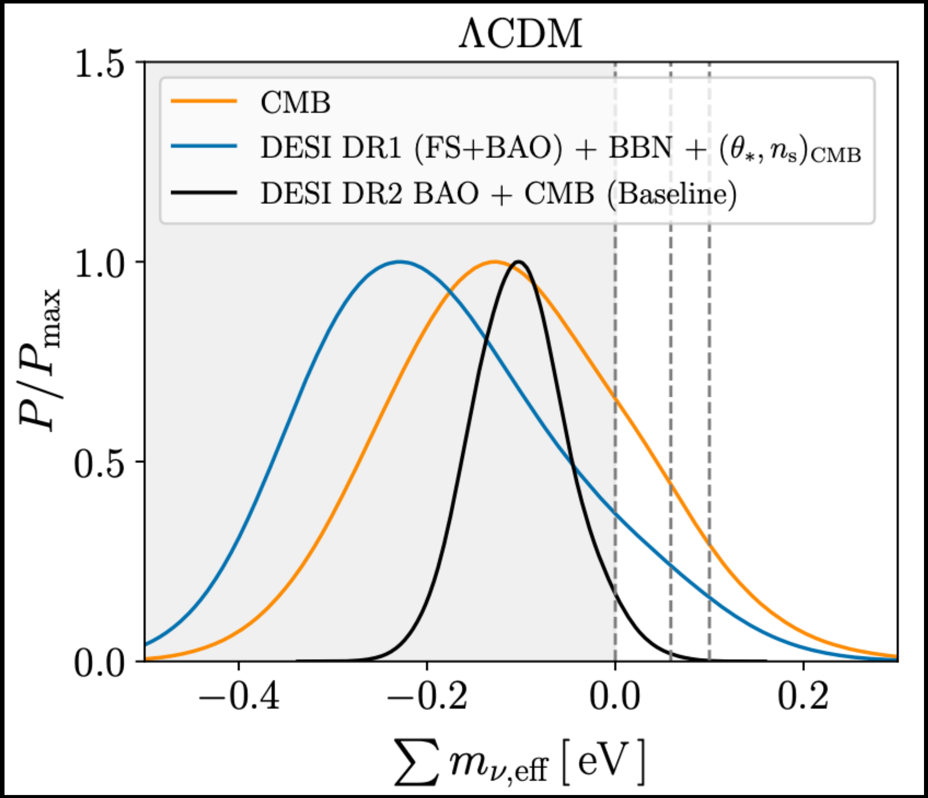
DESI collaboration, Abdul Karim et al., arXiv:2503.14738

Consequences? Indication for DDE



DESY5 collaboration: Abbott et al., arXiv:2401.02929

Consequences? Indication for negative neutrino mass



Model/Dataset	$\Omega_{\rm m}$	H_0 [km s^{-1} Mpc^{-1}]	$\sum m_{\nu,\rm eff}$ [eV]
ΛCDM+$\sum$m$_{\nu,\rm eff}$			
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

Could these additional tensions be due to systematics?

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

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.

Search...

Help | Adv

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 5 May 2025]

Baryon Acoustic Oscillations from a Different Angle

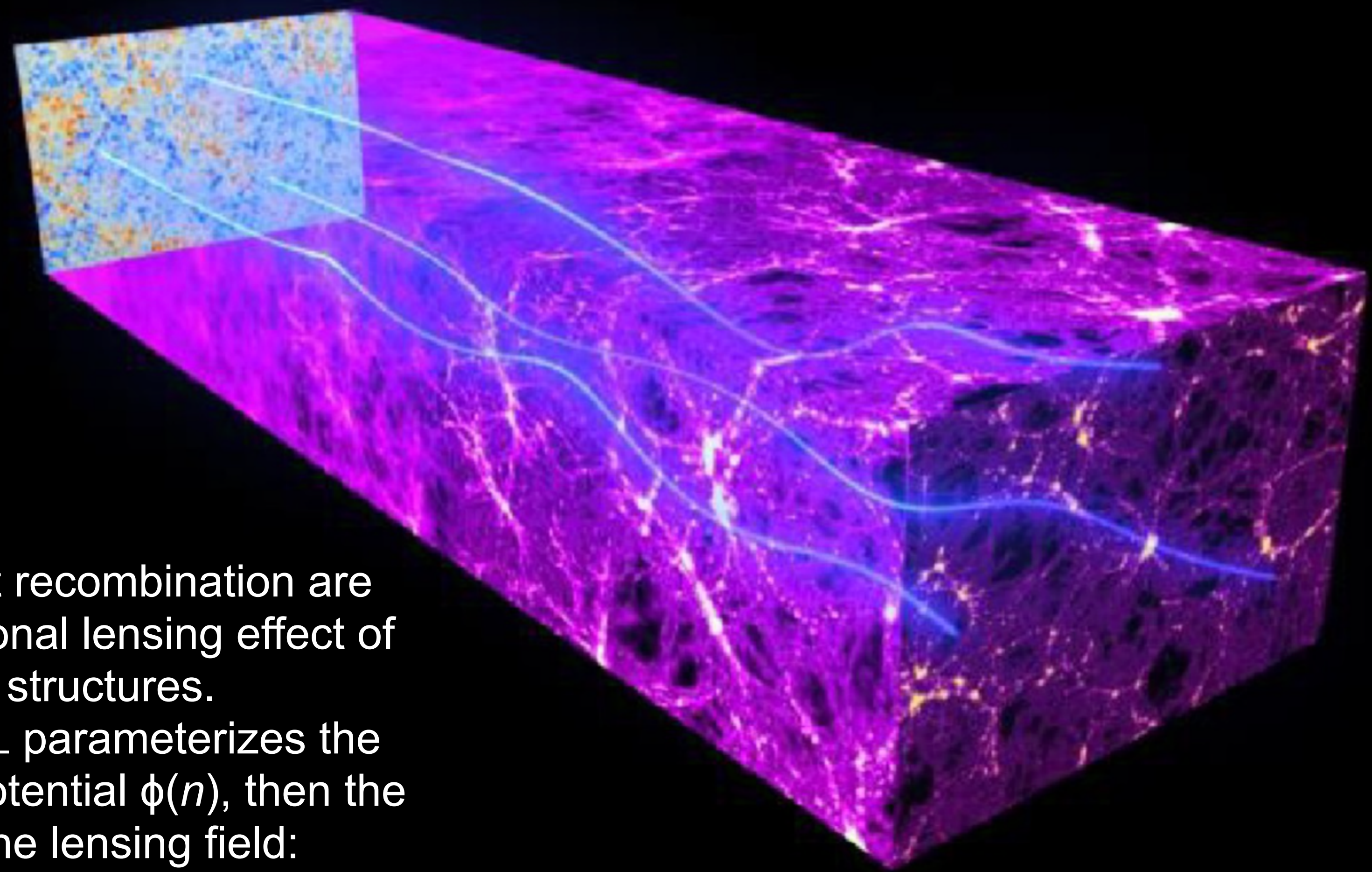
George Efstathiou

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

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

What about the CMB problems?

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:

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

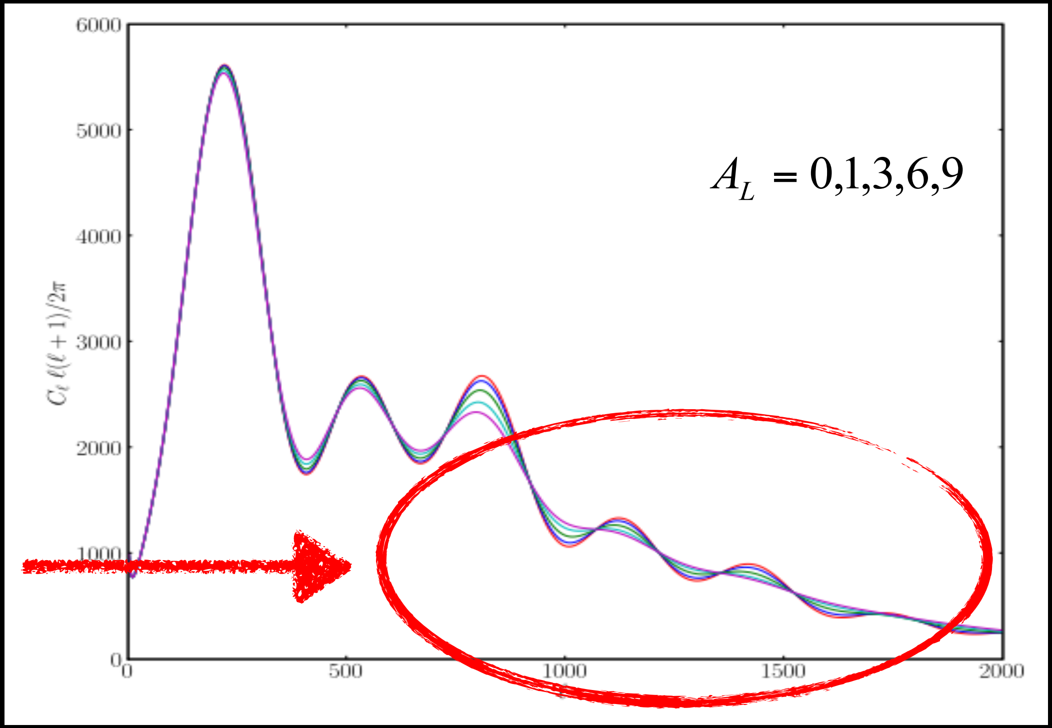
The gravitational lensing deflects the photon path by a quantity defined by the gradient of the lensing potential $\phi(n)$, integrated along the line of sight n, remapping the temperature field.

Plik PR3 A_L problem

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

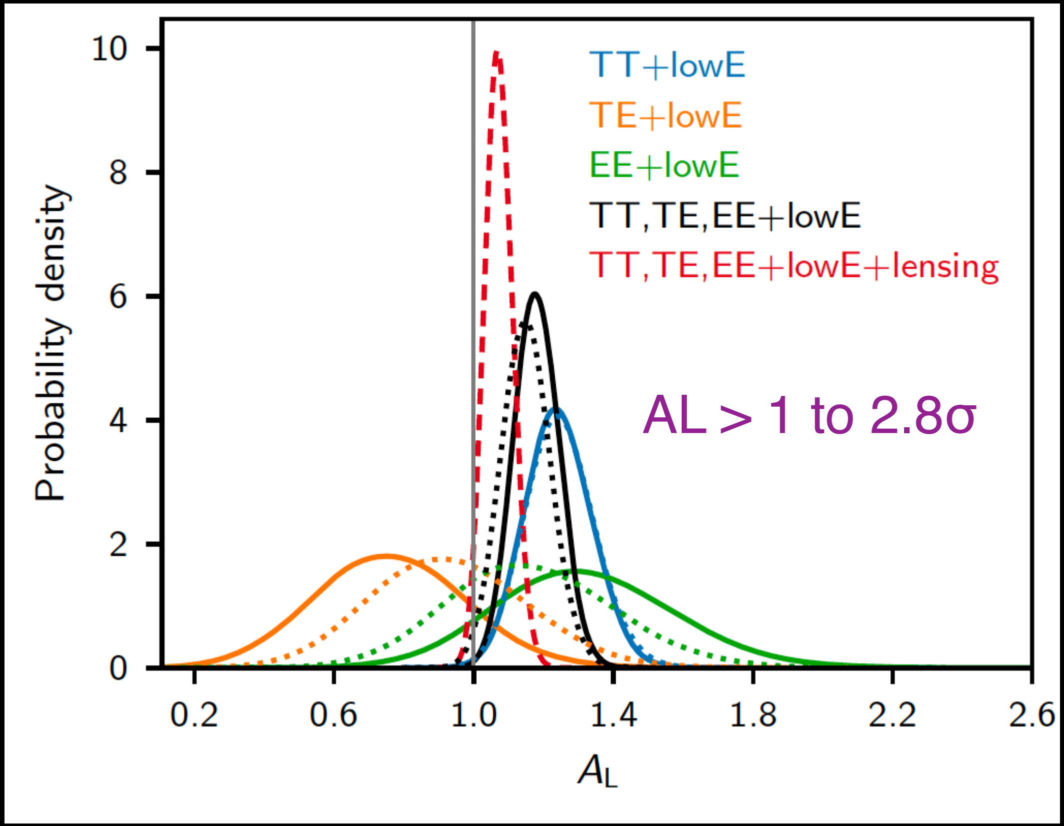
If AL =1 then the theory is correct, otherwise we have a new physics or systematics.



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

Plik PR3 A_L problem

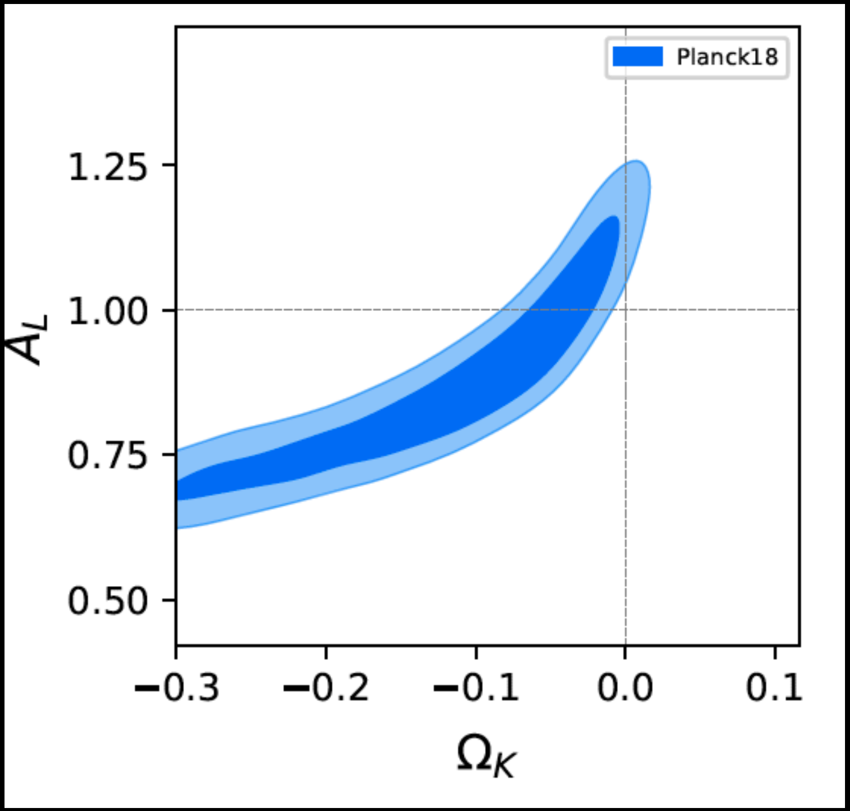
Planck 2018, Astron.Astrophys. 641 (2020) A6

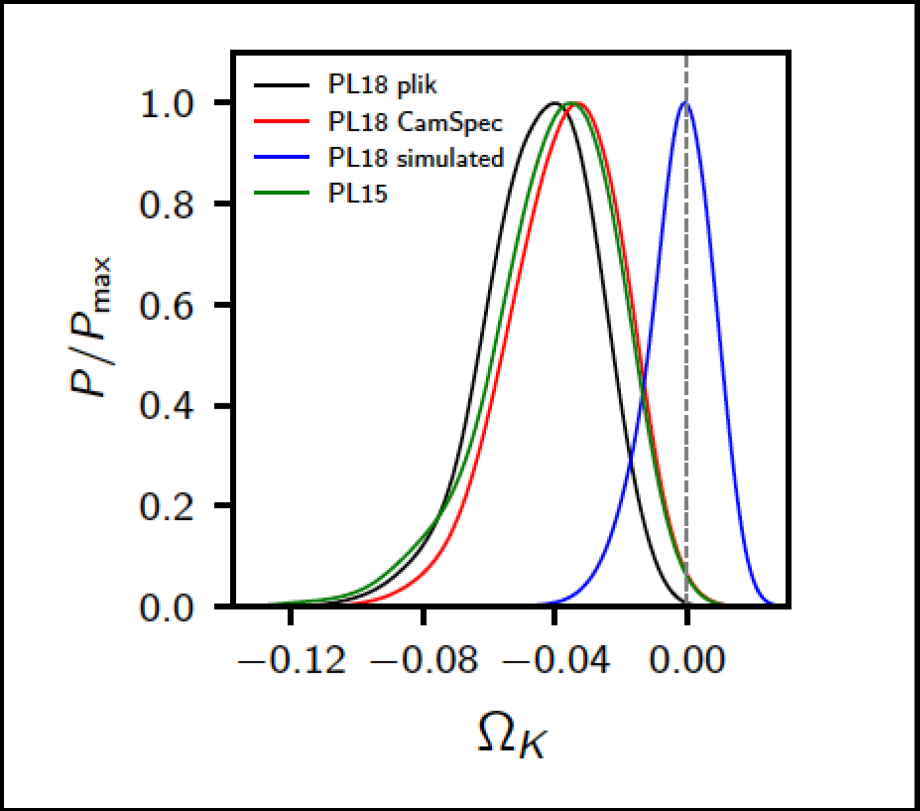


$$A_L = 1.243 \pm 0.096 \quad (68\,\%,\ \textit{Planck}\ \text{TT+lowE}),$$
$$A_L = 1.180 \pm 0.065 \quad (68\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE}),$$

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

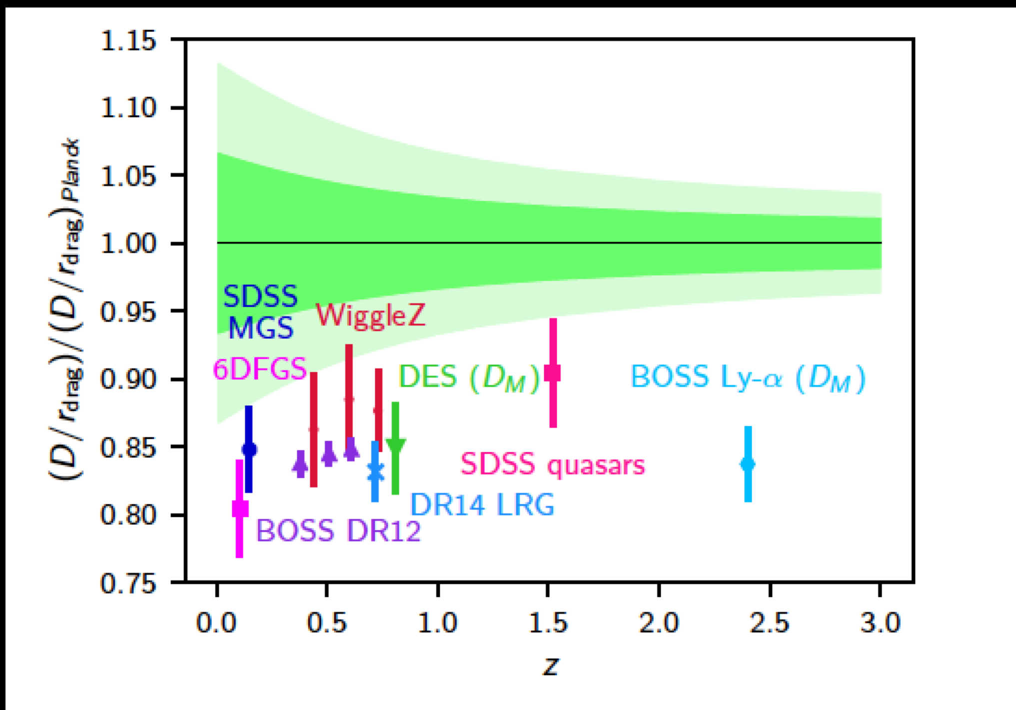
This excess of lensing affects the constraints on the curvature of the universe:

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

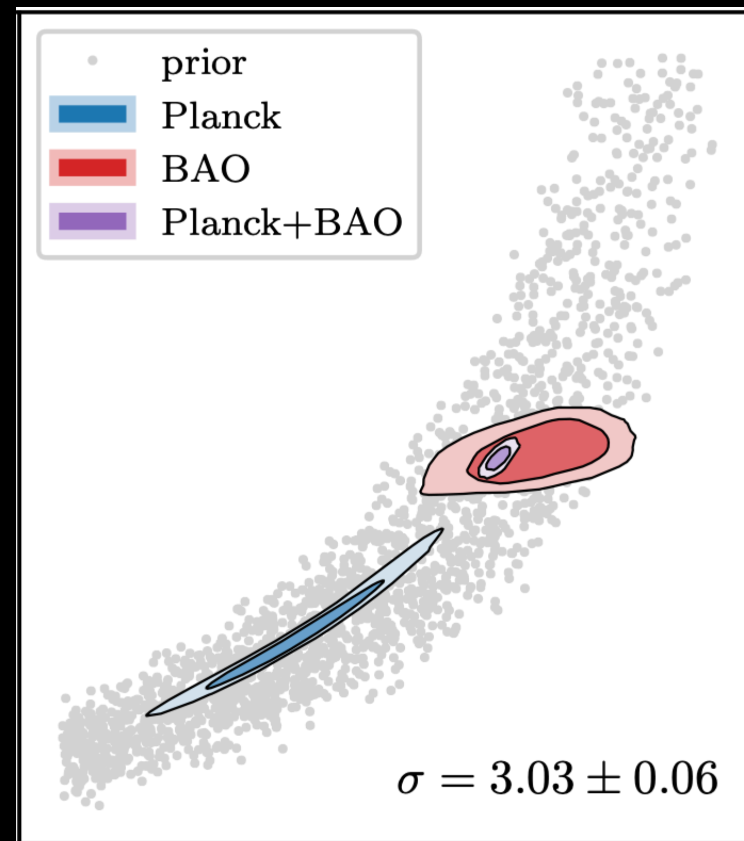
Planck 2018, Astron.Astrophys. 641 (2020) A6

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

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.

What about Planck PR4 (NPIPE) with CamSpec?

arXiv > astro-ph > arXiv:2205.10869

Search...

Help | Advar

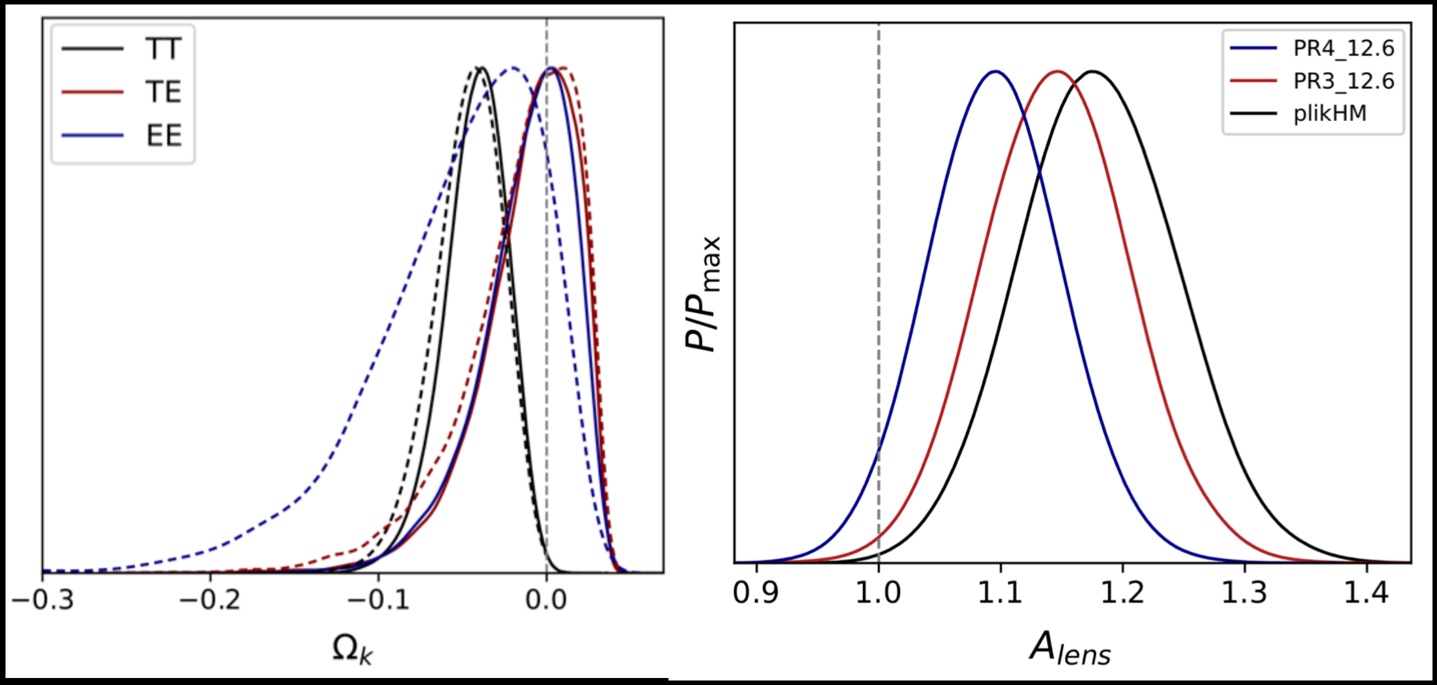
Astrophysics > Cosmology and Nongalactic Astrophysics

[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

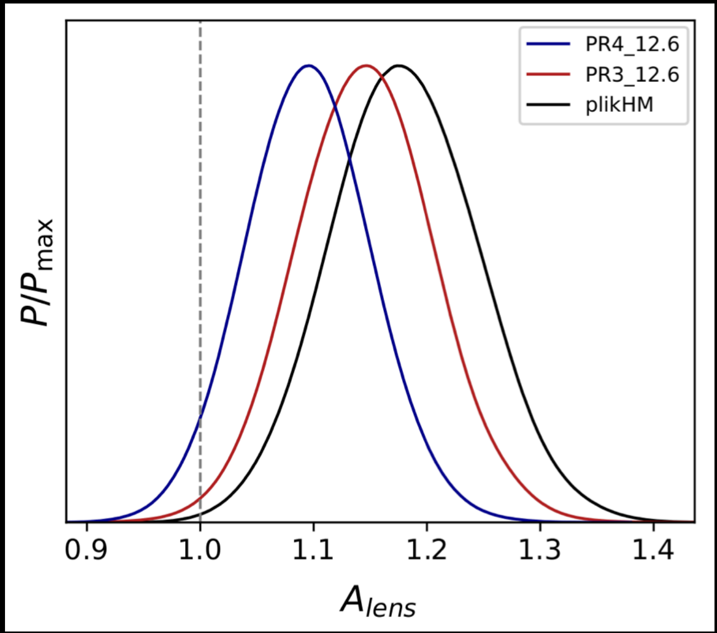
Erik Rosenberg, Steven Gratton, George Efstathiou

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.

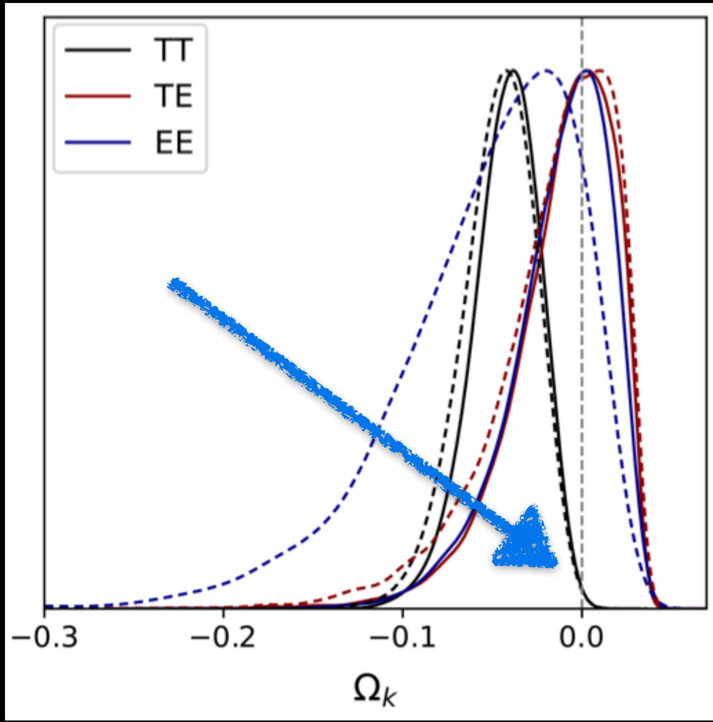


CamSpec PR4

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	$-0.053^{+0.063}_{-0.029}$	$2.46^{+0.94}_{-1.7}$	-



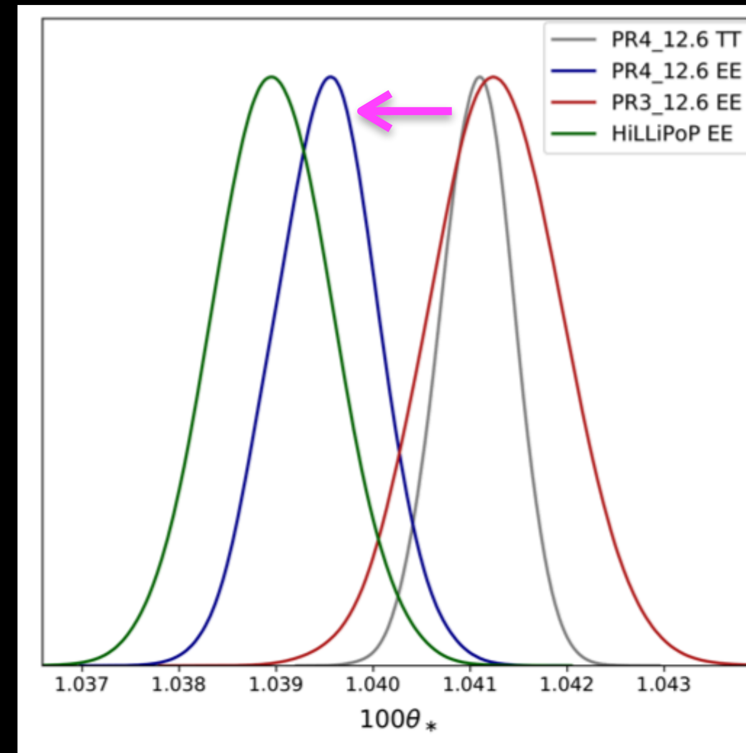
Rosenberg et al., arXiv:2205.10869



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

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



Rosenberg et al., arXiv:2205.10869

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

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

CamSpec PR4

Efstathiou & Gratton, arXiv:1910.00483

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

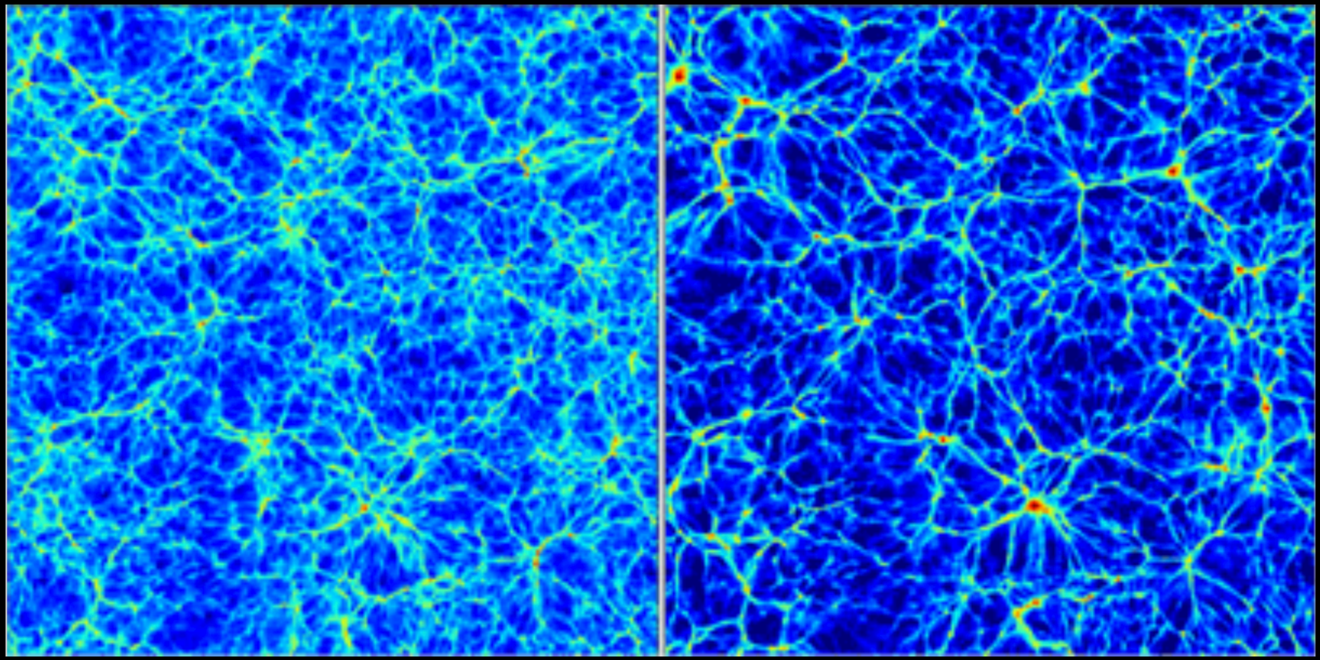
	ℓ range	N_D	$\hat{\chi}^2$	$(\hat{\chi}^2 - 1)/\sqrt{2/N_D}$
TT 143x143	30 – 2000	1971	1.021	0.67
TT 143x217	500 – 2500	2001	0.985	-0.47
TT 217x217	500 – 2500	2001	1.002	0.05
TT All	30 – 2500	5973	1.074	4.07
TE	30 – 2000	1971	1.055	1.73
EE	30 – 2000	1971	1.026	0.82
TEEE	20 – 2000	3942	1.046	2.02
TTTEEE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

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

Rosenberg et al., arXiv:2205.10869

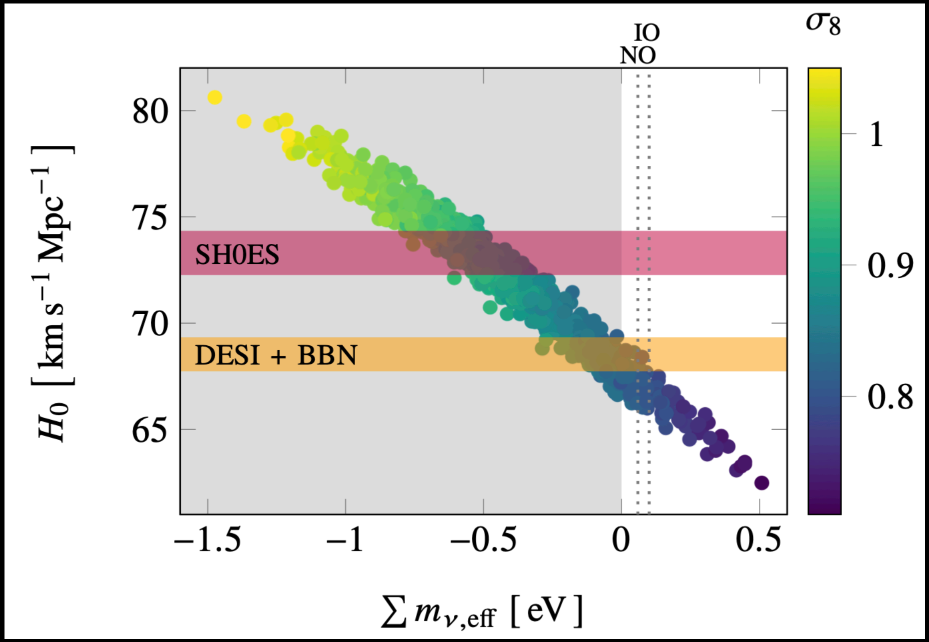
Moreover, the reduced χ2 values reveal a >4σ tension between the data and the ΛCDM best-fit from TTTEEE.

The total neutrino mass and CMB lensing

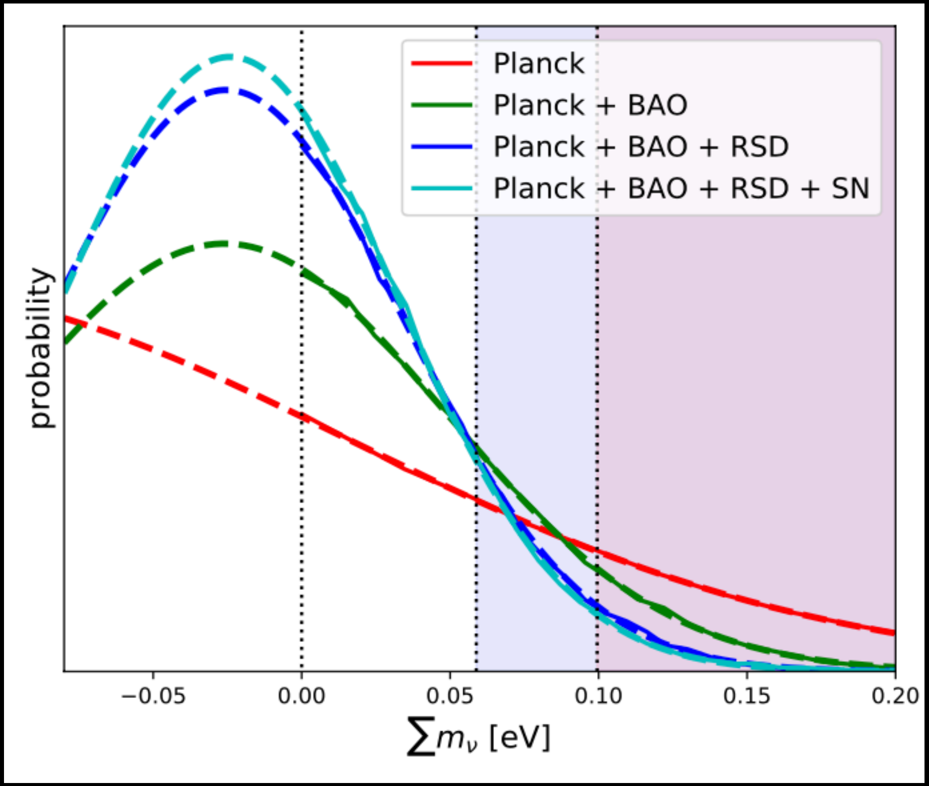


Given that massive neutrinos practically do not form structure,
more massive the neutrino is less structure we have, less the CMB lensing will be.
So a larger signal of lensing means a smaller neutrino mass.

Negative total neutrino mass



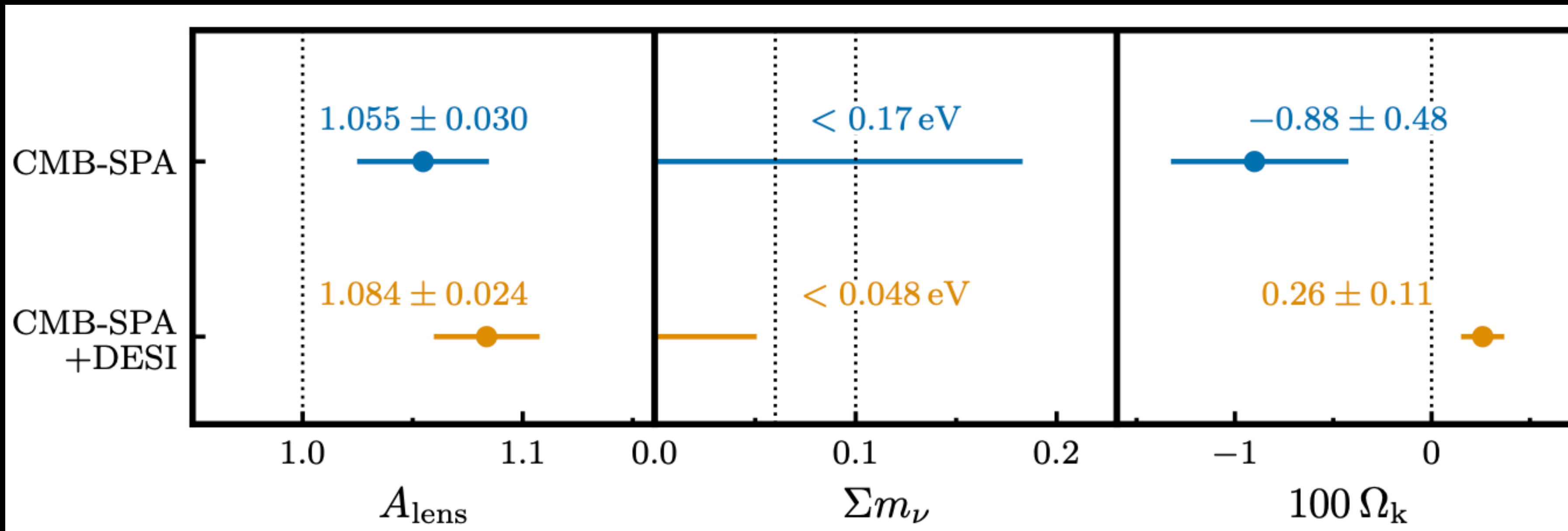
Elbers et al., arXiv: 2407.10965



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



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

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

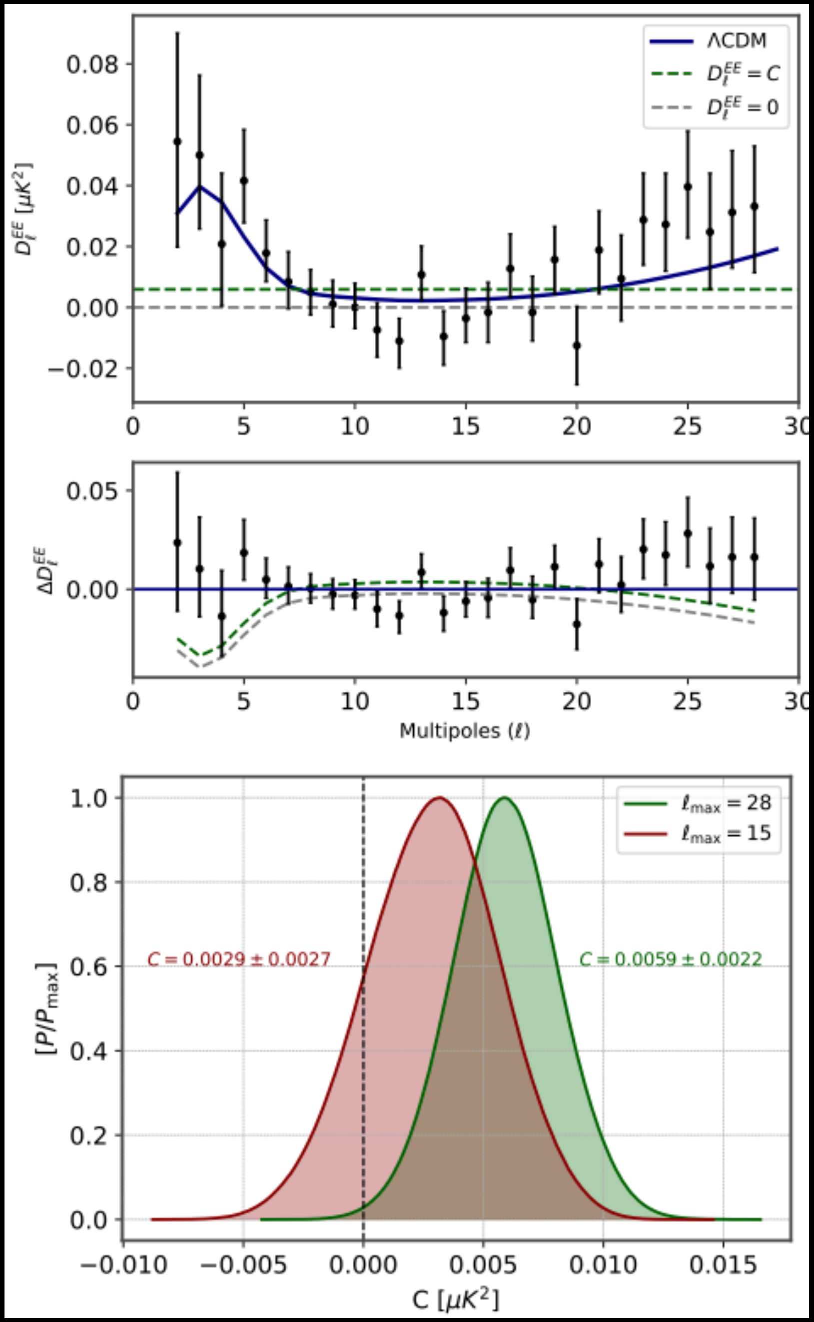
SPT-3G D1, arXiv:2506.20707 [astro-ph.CO]

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

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

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.

The role of the optical depth



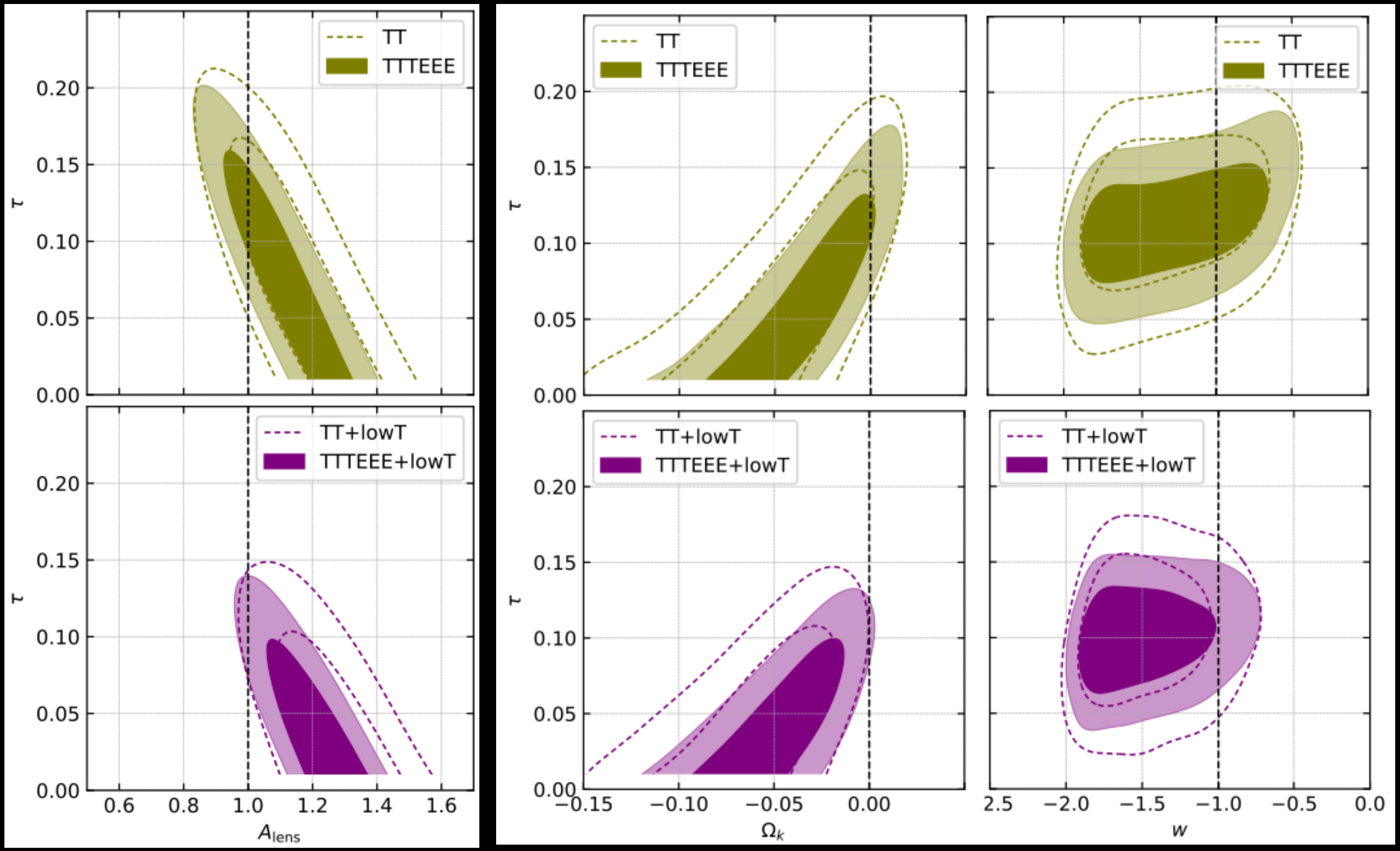
$$C_\ell^{EE} \propto \tau^2/\ell^4$$

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

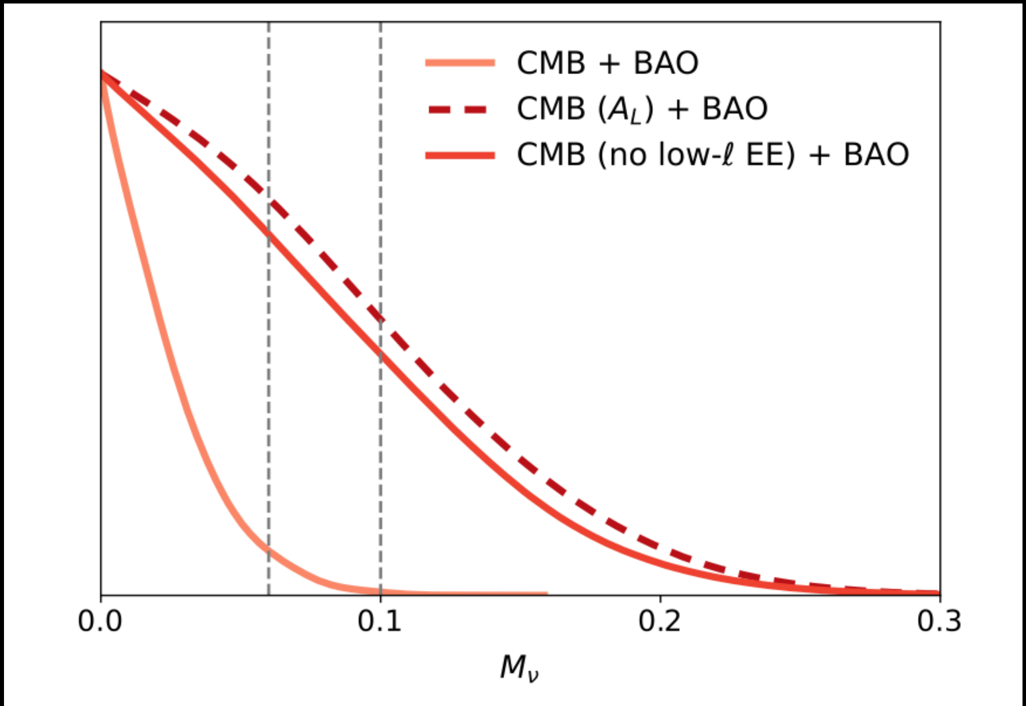
The role of the optical depth



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.

We have become too precise and not accurate enough

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.

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.

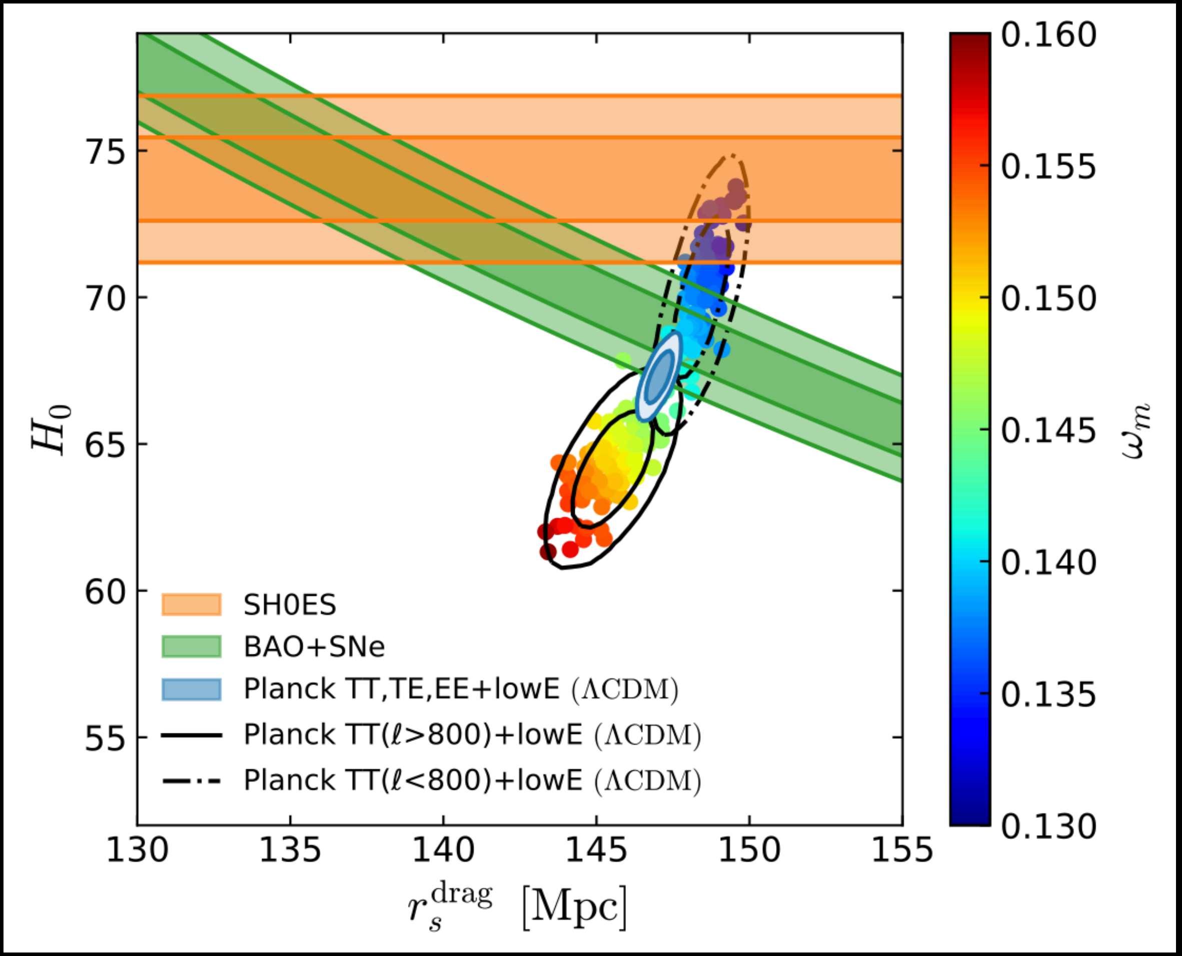
Instead of pointing fingers it is time to re-evaluate our standard model in cosmology and try to solve the cosmological tensions in this way.

Let's try to find a solution to the Hubble tension…

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.

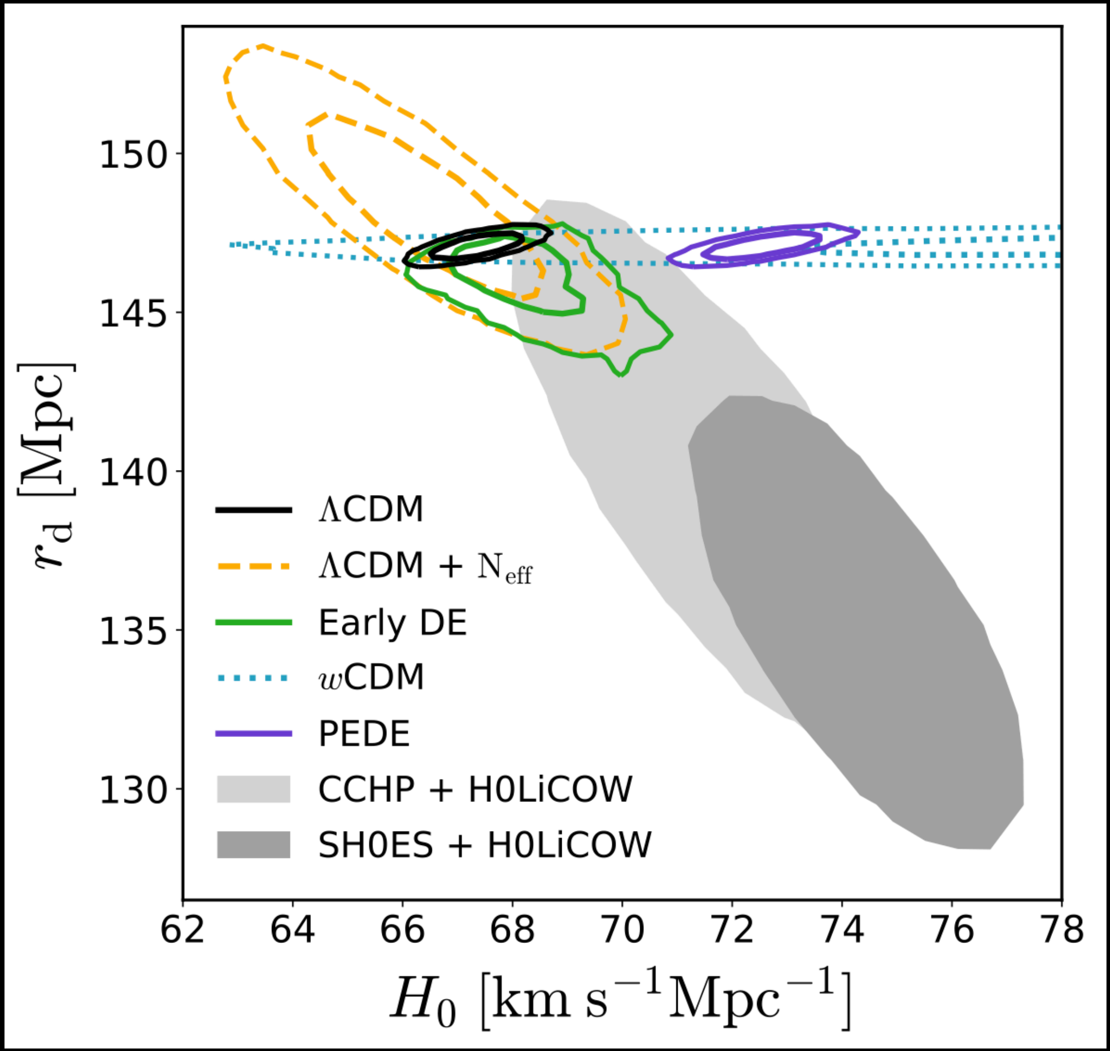


Knox and Millea, *Phys.Rev.D* 101 (2020) 4, 043533

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:

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

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

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

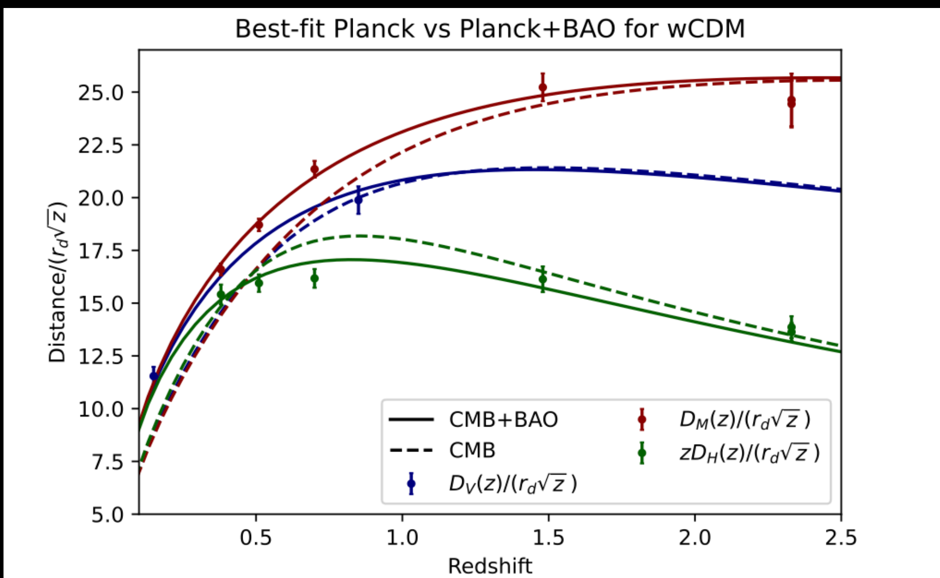


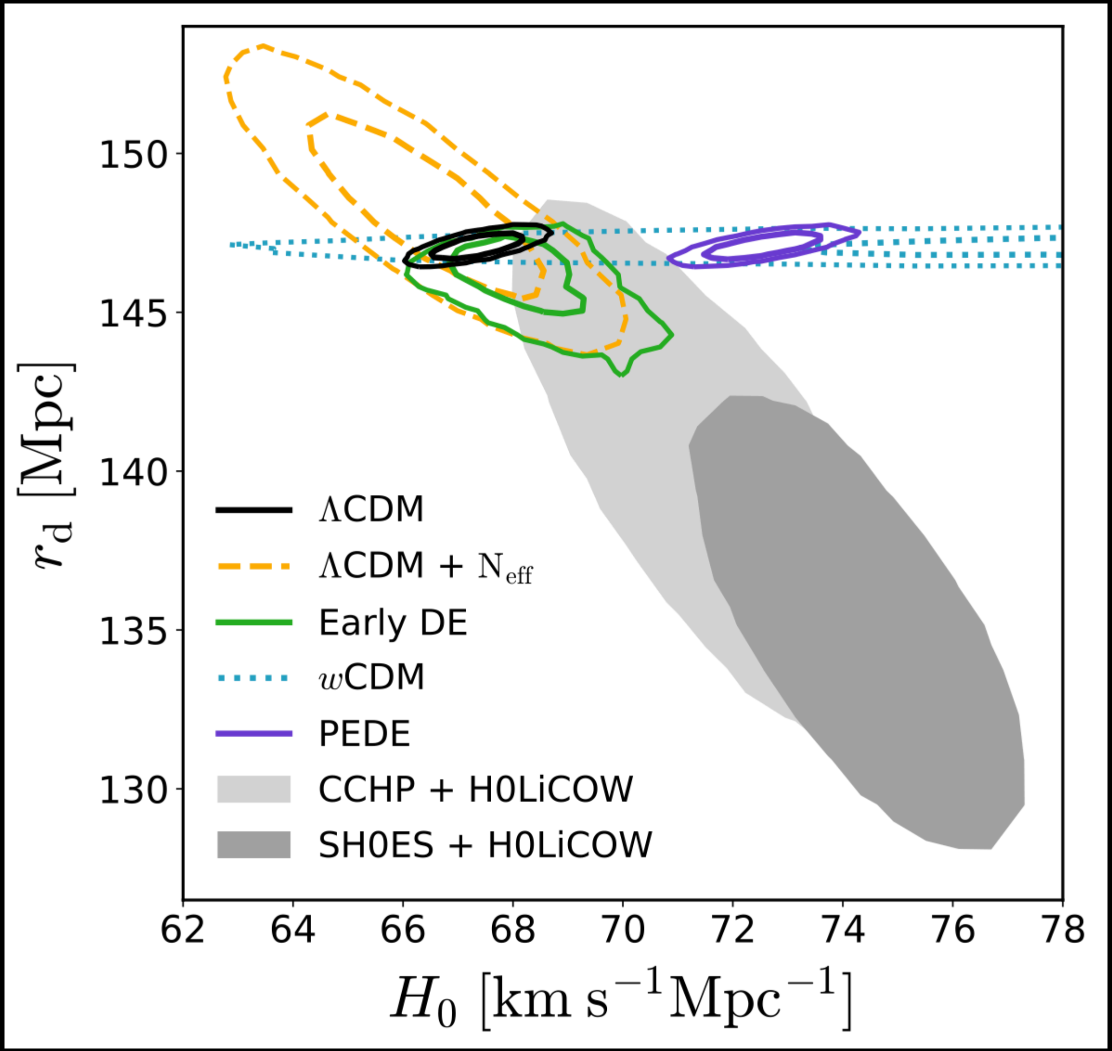
FIG. 5. Best-fit predictions for (rescaled) distance-redshift relations from a wCDM fit to *Planck* CMB data alone (dashed curves) and the CMB+BAO dataset (solid curves). These predictions are presented for the three different types of distances probed by BAO measurements (rescaled as per the y label), 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

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

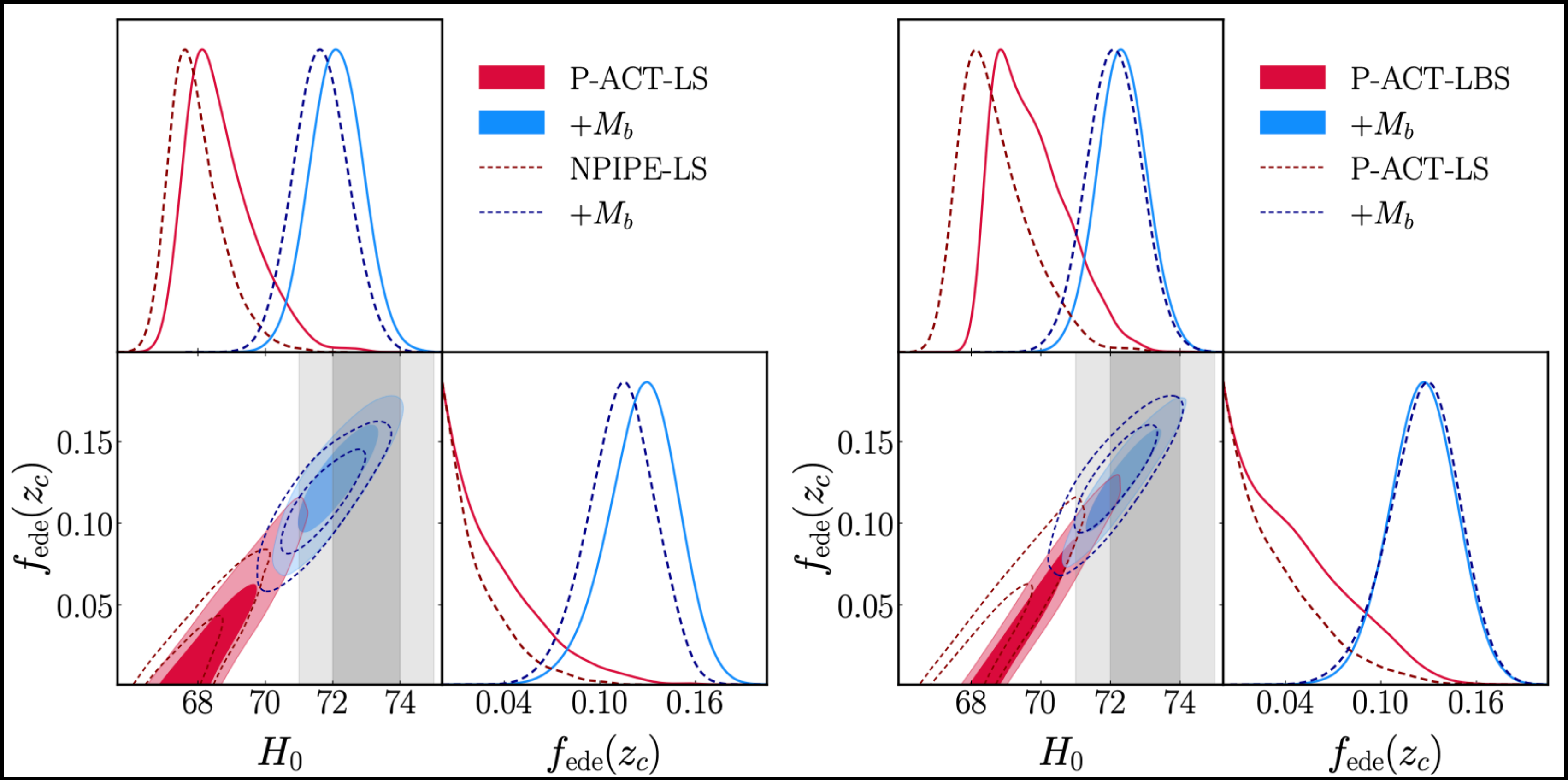
If we take n = 1 (the standard axion potential) then $w_\phi = 0$ near the potential minimum, and the EDE energy density redshifts as matter creating problems in the late-time cosmology, therefore it does not work phenomenologically.
For n = 2 instead it decays away like radiation ($\propto a^{-4}$),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

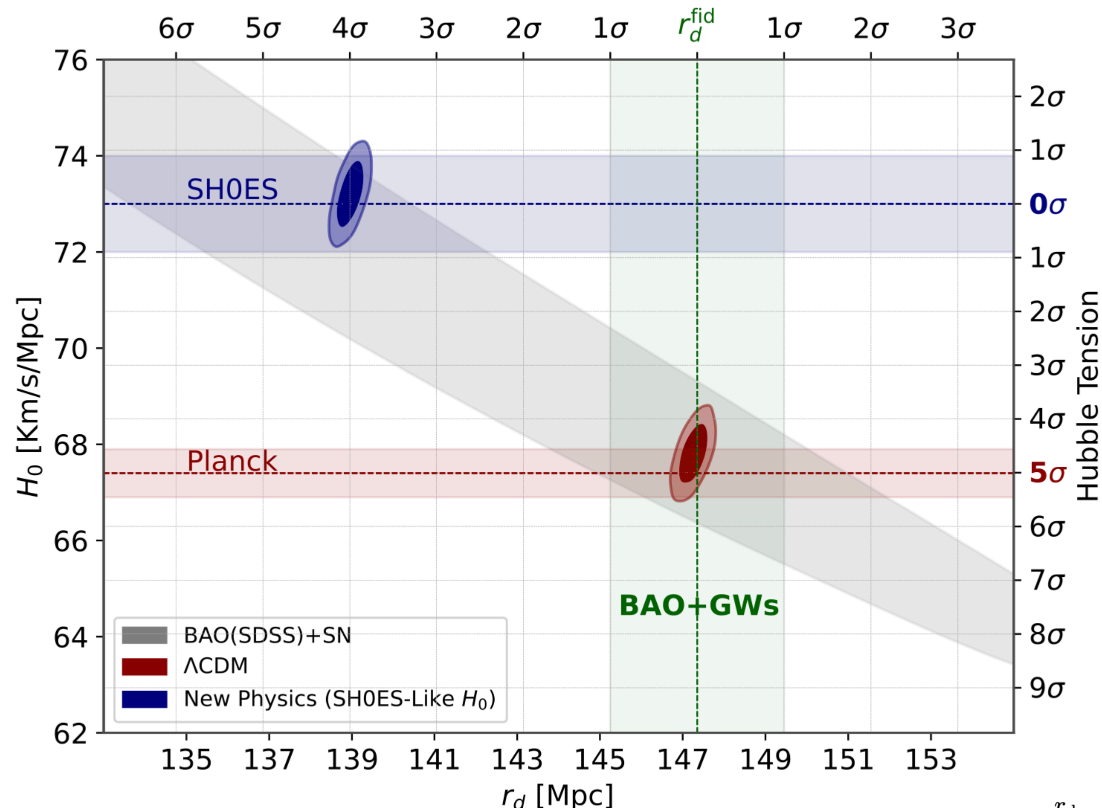
Constraints at 68% cl.

	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 $\sim 4\sigma$.

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}]	$72.8^{+3.0}_{-1.5}$	$74.0^{+1.2}_{-1.0}$

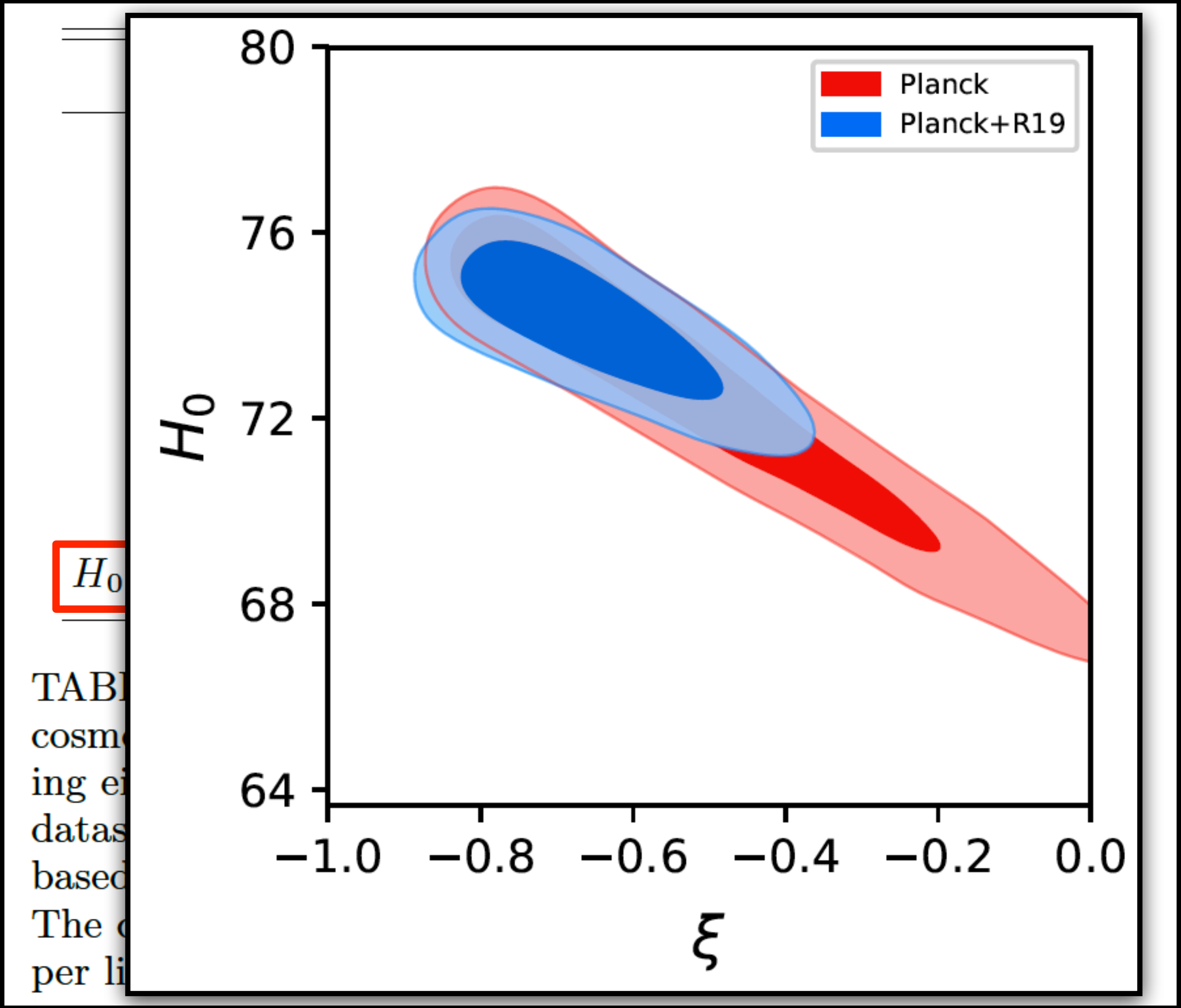
TABLE I. Mean values with their 68% C.L. errors on selected cosmological parameters within the $\xi\Lambda$CDM model, considering either the *Planck* 2018 legacy dataset alone, or the same dataset in combination with the *R19* Gaussian prior on H_0 based on the latest local distance measurement from *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

Therefore we can safely combine the two datasets together, and we obtain a non-zero dark matter-dark energy coupling ξ at more than FIVE standard deviations.

Computing the Bayes factor for the IDE model with respect to ΛCDM for the Planck dataset we find lnB = 1.2, i.e. a weak evidence for the IDE model. If we consider Planck + SH0ES we find the extremely high value lnB=10.0, indicating a strong evidence for the IDE model.



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

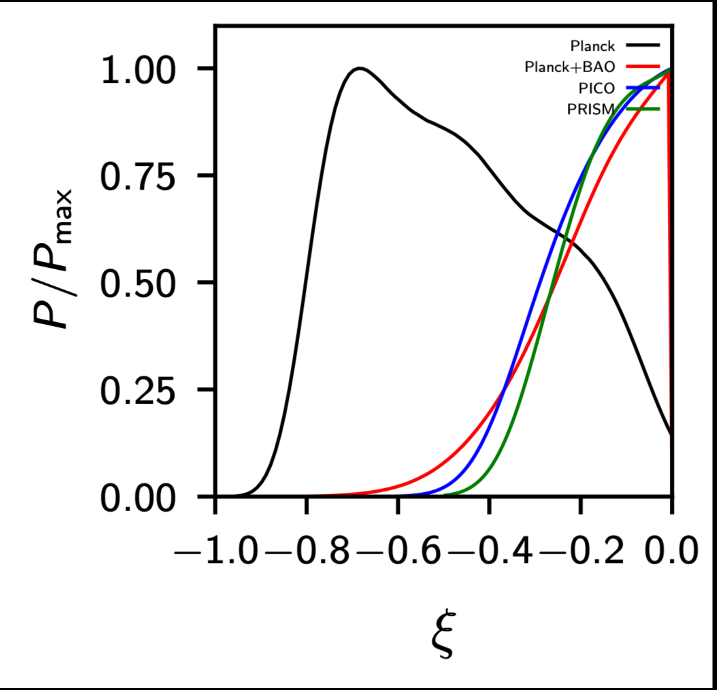
fake IDE detection

Parameters	Fiducial model	Planck	Planck+BAO	PICO	PRISM
$\Omega_b h^2$	0.02236	0.02238 ± 0.00015	0.02230 ± 0.00014	0.022364 ± 0.000029	0.022361 ± 0.000019
$\Omega_c h^2$	0.1202	$0.056^{+0.025}_{-0.047}$	$0.101^{+0.019}_{-0.006}$	$0.100^{+0.019}_{-0.008}$	$0.103^{+0.016}_{-0.007}$
$100\theta_{MC}$	1.04090	$1.0451^{+0.0021}_{-0.0032}$	$1.0419^{+0.0005}_{-0.0011}$	$1.04206^{+0.0005}_{-0.0011}$	$1.04191^{+0.00042}_{-0.00094}$
τ	0.0544	$0.0528^{+0.010}_{-0.009}$	0.0517 ± 0.0098	$0.0543^{+0.0016}_{-0.0019}$	$0.0542^{+0.0017}_{-0.0019}$
n_s	0.9649	0.9652 ± 0.0041	0.9624 ± 0.0036	0.9571 ± 0.0014	0.9657 ± 0.0012
$\ln(10^{10}A_s)$	3.045	$3.041^{+0.020}_{-0.018}$	3.042 ± 0.019	$3.0436^{+0.0030}_{-0.0034}$	3.0435 ± 0.0032
ξ	0	$\boxed{-0.48^{+0.16}_{-0.30}}$	> -0.223	> -0.220	> -0.195

Di Valentino & Mena, Mon.Not.Roy.Astron.Soc. 500 (2020) 1, L22-L26, arXiv:2009.12620

For a mock Planck-like experiment,
due to the strong correlation present between the standard and the exotic physics parameters, there is a dangerous detection at more than 3σ for a coupling between dark matter and dark energy different from zero, even if the fiducial model has $\xi = 0$:

$-0.85 < \xi < -0.02$ at 99% CL



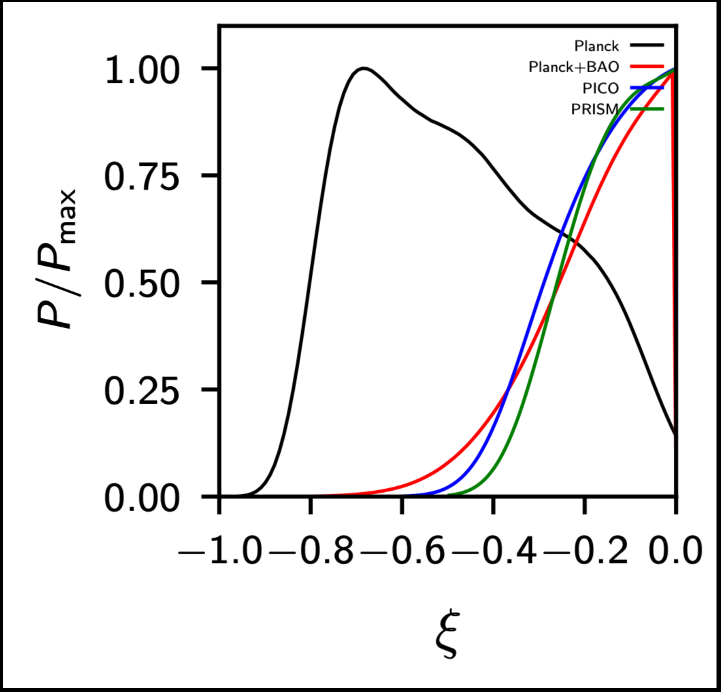
Mock experiments

fake IDE detection

Parameters	Fiducial model	Planck	Planck+BAO	PICO	PRISM
$\Omega_b h^2$	0.02236	0.02238 ± 0.00015	0.02230 ± 0.00014	0.022364 ± 0.000029	0.022361 ± 0.000019
$\Omega_c h^2$	0.1202	$0.056^{+0.025}_{-0.047}$	$0.101^{+0.019}_{-0.006}$	$0.100^{+0.019}_{-0.008}$	$0.103^{+0.016}_{-0.007}$
$100\theta_{MC}$	1.04090	$1.0451^{+0.0021}_{-0.0032}$	$1.0419^{+0.0005}_{-0.0011}$	$1.04206^{+0.0005}_{-0.0011}$	$1.04191^{+0.00042}_{-0.00094}$
τ	0.0544	$0.0528^{+0.010}_{-0.009}$	0.0517 ± 0.0098	$0.0543^{+0.0016}_{-0.0019}$	$0.0542^{+0.0017}_{-0.0019}$
n_s	0.9649	0.9652 ± 0.0041	0.9624 ± 0.0036	0.9571 ± 0.0014	0.9657 ± 0.0012
$\ln(10^{10}A_s)$	3.045	$3.041^{+0.020}_{-0.018}$	3.042 ± 0.019	$3.0436^{+0.0030}_{-0.0034}$	3.0435 ± 0.0032
ξ	0	$-0.48^{+0.16}_{-0.30}$	$\boxed{> -0.223}$	> -0.220	> -0.195

Di Valentino & Mena, Mon.Not.Roy.Astron.Soc. 500 (2020) 1, L22-L26, arXiv:2009.12620

The inclusion of mock BAO data,
a mock dataset built using the same fiducial cosmological model than that of the CMB,
helps in breaking the degeneracy,
providing a lower limit for the coupling ξ
in perfect agreement with zero.



Mock experiments

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	$\boxed{-0.22^{+0.18}_{-0.09}}$ $[> -0.48]$	> -0.35	> -0.12
H_0 [km/s/Mpc]	$\boxed{69.55^{+0.98}_{-1.60}}$	$69.04^{+0.84}_{-1.10}$	$68.02^{+0.49}_{-0.60}$
Ω_m	$0.243^{+0.054}_{-0.030}$	$0.261^{+0.038}_{-0.025}$	$0.299^{+0.015}_{-0.007}$

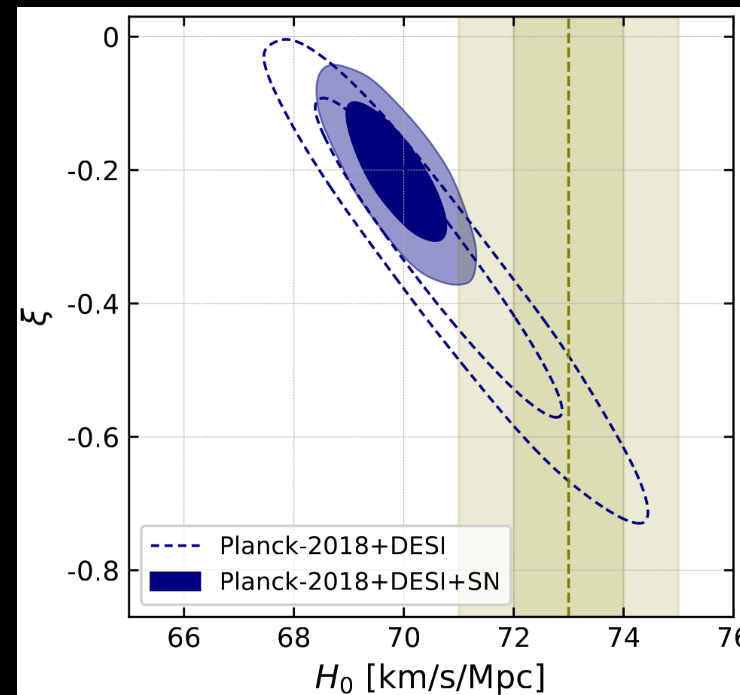
Nunes, Vagnozzi, Kumar, Di Valentino, and Mena, *Phys.Rev.D* 105 (2022) 12, 123506

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



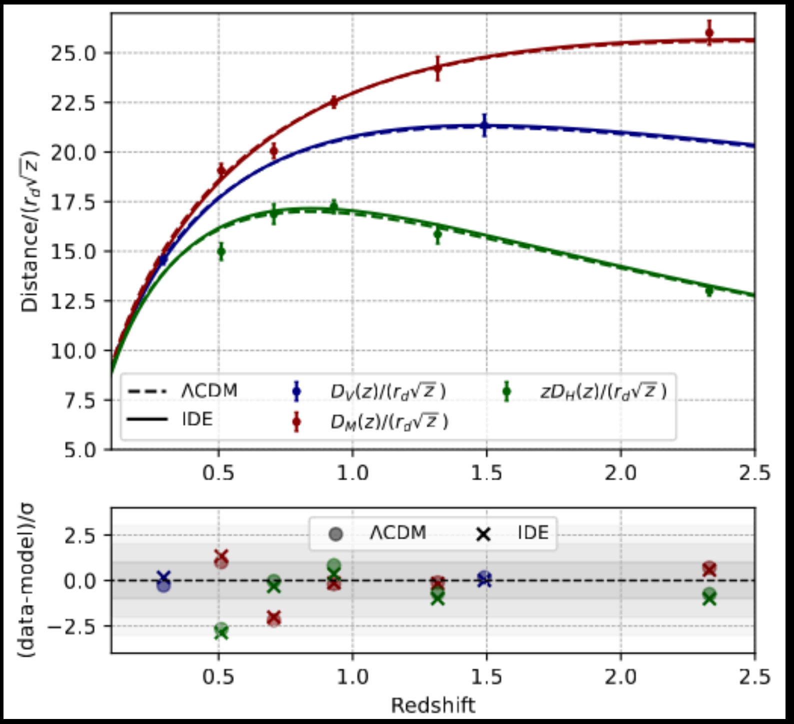
Giarè, Sabogal, Nunes, Di Valentino, *Phys.Rev.Lett.* 133 (2024) 25, 251003

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.

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



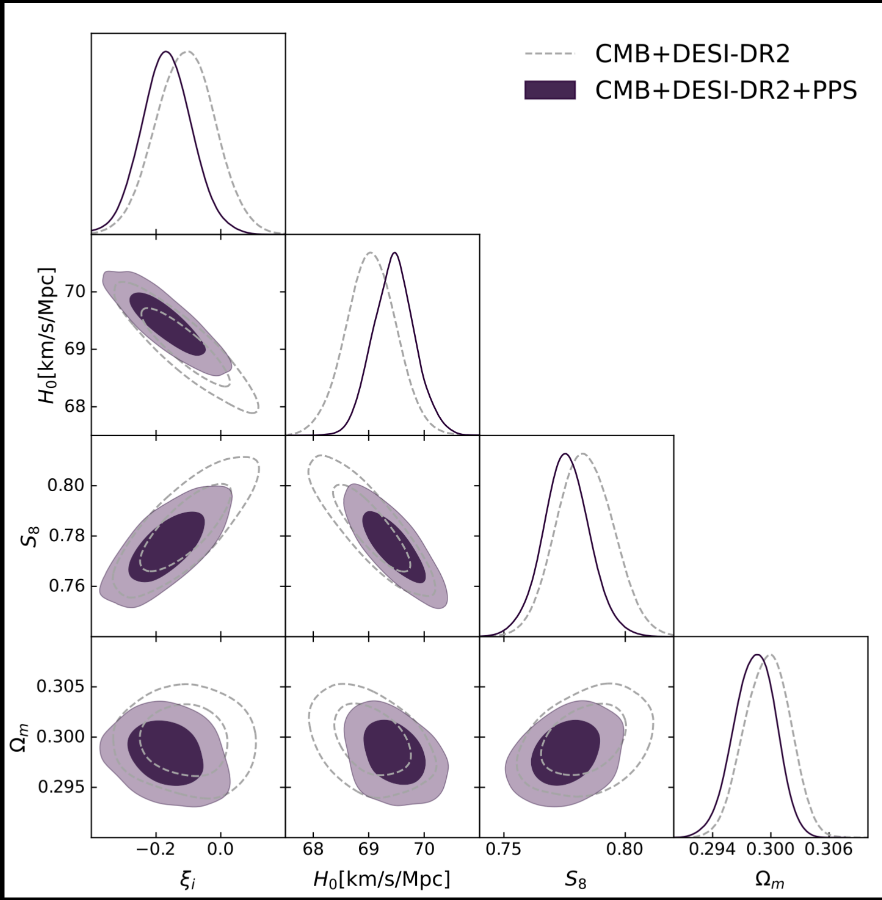
Giarè, Sabogal, Nunes, Di Valentino, *Phys.Rev.Lett.* 133 (2024) 25, 251003

Overall, high and low redshift data can be equally or better explained within the IDE framework compared to ΛCDM, while also yielding higher values of H0 in better agreement with the local distance ladder estimate.

Constraints at 68% cl.

The IDE case

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



Silva, Sabogal, Souza, Nunes, Di Valentino & Kumar, *Phys.Rev.D* 111 (2025) 12, 123511

It can alleviate the H0 tension to approximately 3σ.

Let’s see another example at late time…

Omnipotent DE

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

Adil, Akarsu, Di Valentino et al., *Phys.Rev.D* 109 (2024) 2, 023527

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

Omnipotent DE

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

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

So the expansion rate of the Universe will be:

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

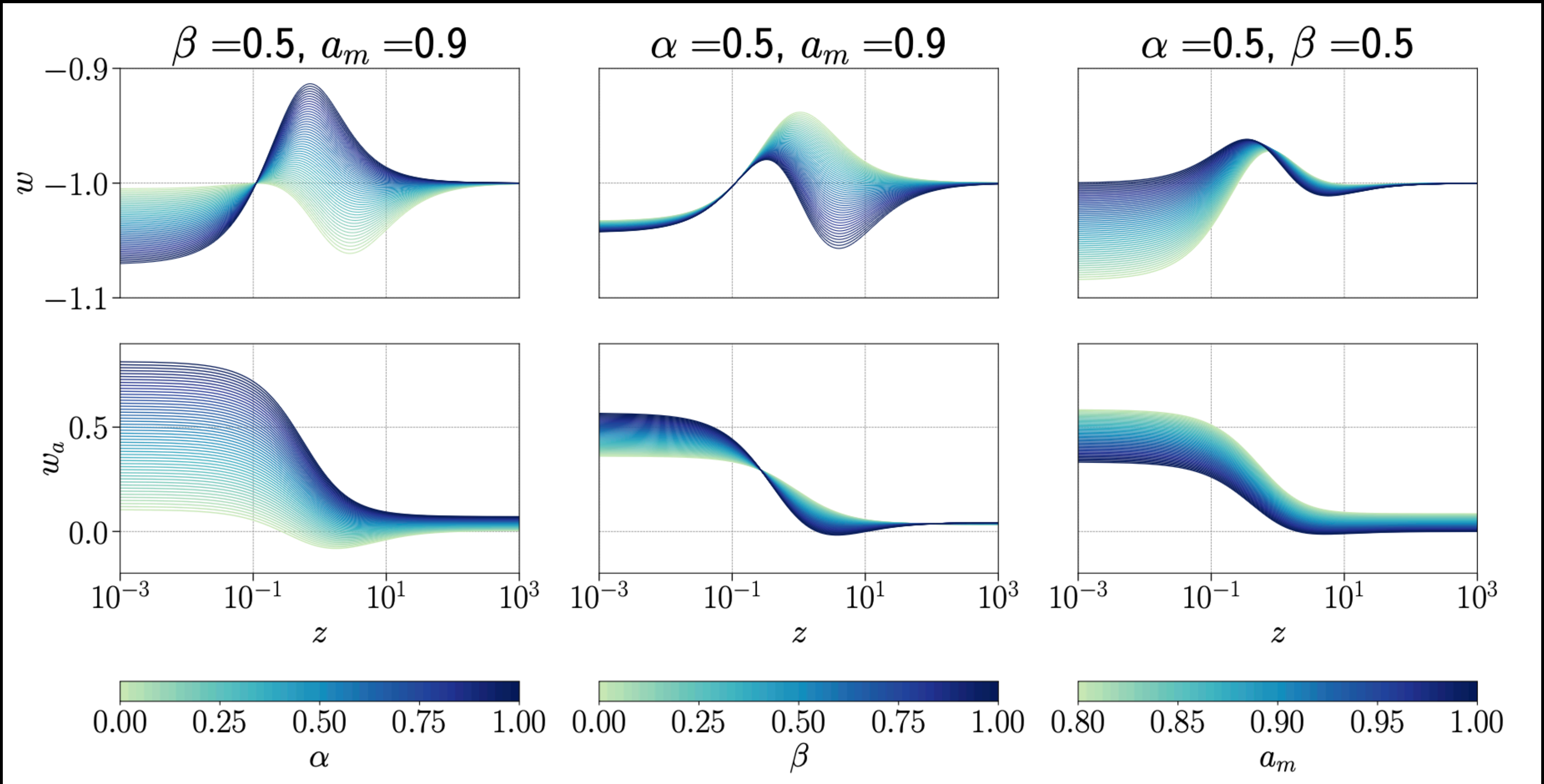
And the dark energy equation of state:

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

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

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

Omnipotent DE



Specogna et al., *arXiv: 2504.17859*

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

Constraints at 68% cl.

Omnipotent DE

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

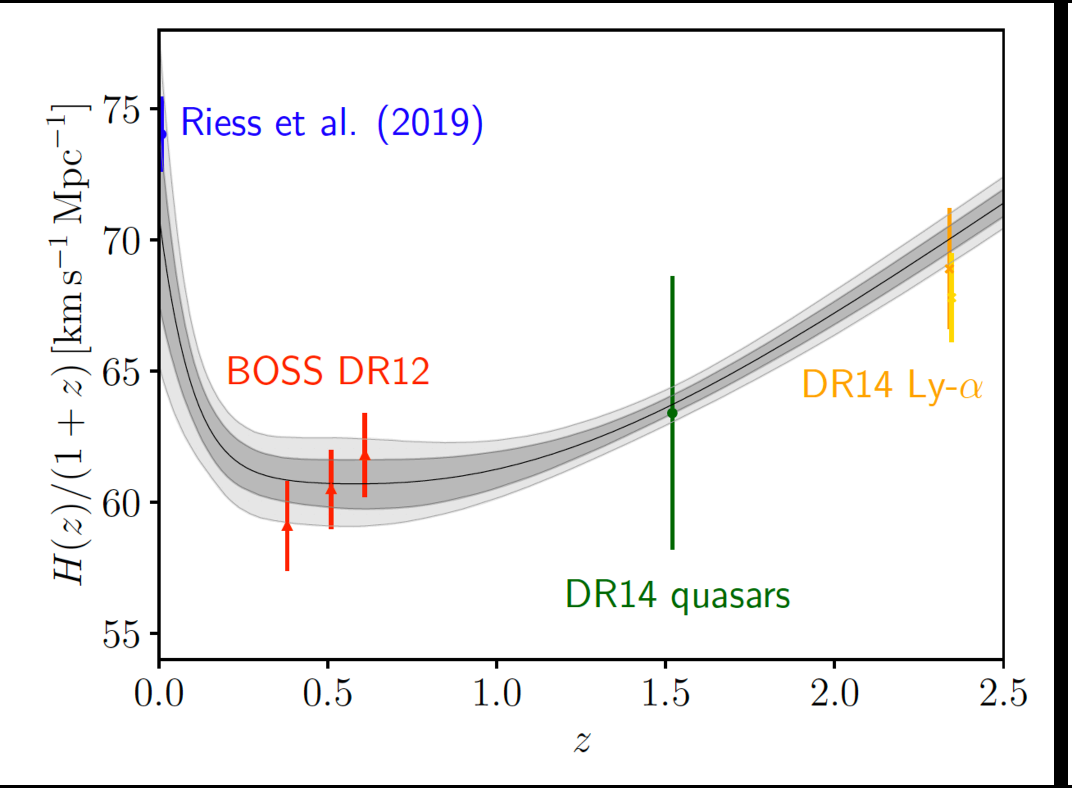
We find that the combination of all the observational data including Planck, in agreement one with each other for this model, is indeed consistent with $a_m < 1$ at more than 2σ.

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

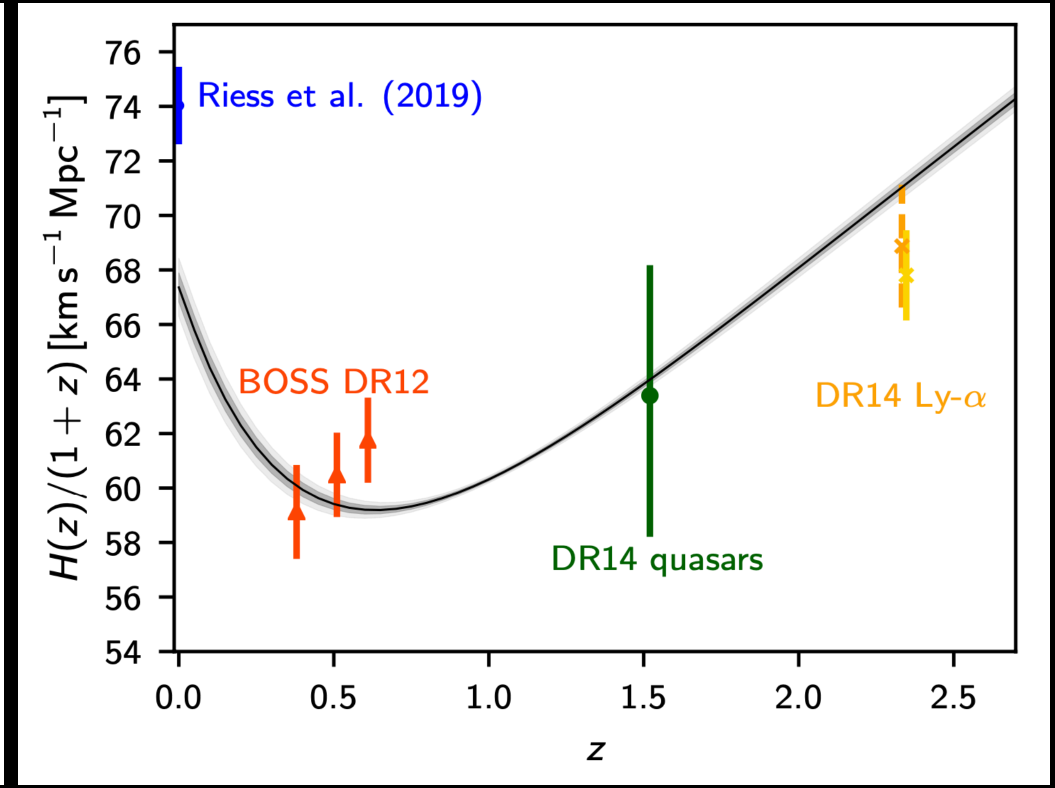
Di Valentino et al., *Entropy* 23 (2021) 4, 404

Constraints at 68% cl.

Omnipotent DE



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



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

The CMB+BAO combination it is in better agreement with the phantom crossing than with the ΛCDM model.

Constraints at 68% cl.

Omnipotent DE: DESI

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

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

Specogna et al., *arXiv: 2504.17859*

What is the solution is instead at recombination?

Universe with a varying electron mass

Solutions that modify the recombination history usually attempt to have an earlier recombination in order to infer a smaller sound horizon, which is compatible with a larger Hubble parameter.

A model with a varying electron mass modifies the recombination epoch and the drag epoch, keeping CMB power spectra almost unchanged, because the parameter dependencies exactly cancel out

(See Hart & Chluba, *MNRAS 493, 3255 (2020) and* Sekiguchi & Takahashi, *Phys.Rev.D* 103 (2021) 8, 083507).

The inclusion of a variation of the effective rest mass of an electron

$$\delta m_e \equiv \frac{m_{\mathrm{e,early}}}{m_{\mathrm{e,late}}} - 1$$

shifts the atomic energy levels of hydrogen in the early Universe, allowing for a larger energy gap between the various orbitals, which also increases the required photo-ionization temperature.

As such, recombination will already be possible at higher temperatures and correspondingly higher redshift (earlier times), while also altering the reionization history.

Universe with a varying electron mass

Constraints at 68% cl.

Parameter	*Planck* 2018 + varying m_e	*Planck* 2018 + BAO + varying m_e
$\Omega_b h^2$	$0.0199^{+0.0012}_{-0.0014}$	0.02255 ± 0.00016
$\Omega_c h^2$	0.1058 ± 0.0076	0.1208 ± 0.0018
$100\theta_{MC}$	0.958 ± 0.045	1.0464 ± 0.0047
τ	0.0512 ± 0.0077	0.0549 ± 0.0074
$\ln(10^{10} A_s)$	3.029 ± 0.017	3.045 ± 0.014
n_s	0.9640 ± 0.0040	0.9654 ± 0.0040
$\alpha_{EM}/\alpha_{EM,0}$	– –	– –
$m_e/m_{e,0}$	0.888 ± 0.059	1.0078 ± 0.0067
H_0	46^{+9}_{-10}	69.1 ± 1.2

Hart & Chluba, *MNRAS 493, 3255 (2020)*

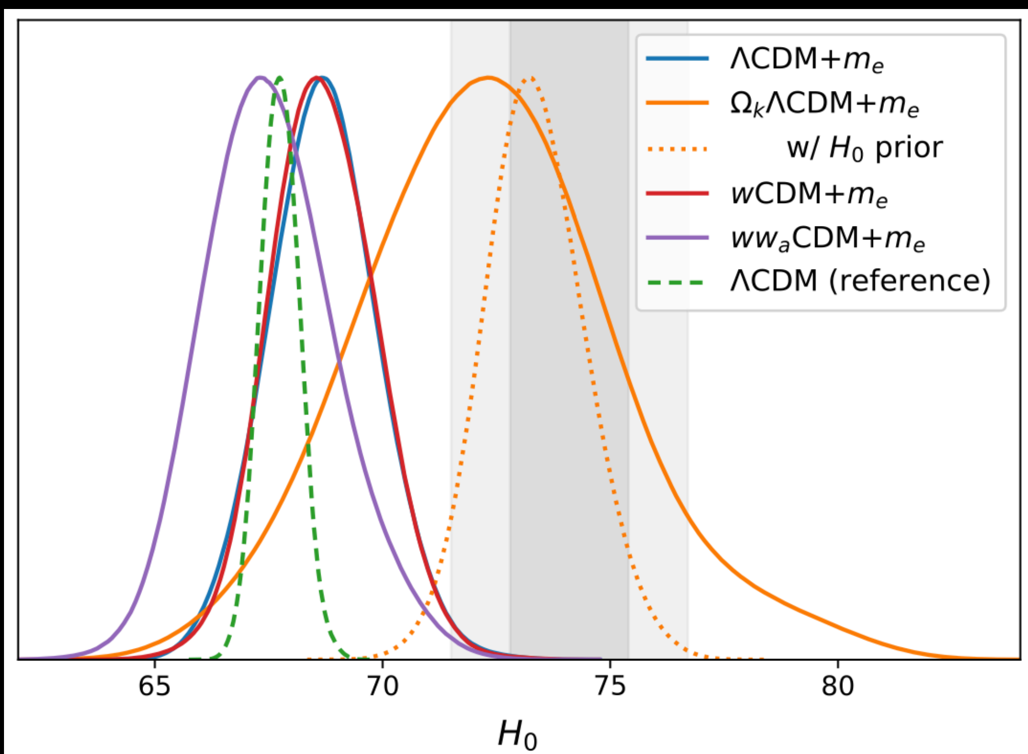
A model with a time-varying electron mass gives H0 in agreement with SH0ES at about 2.5σ.

Closed universe with a varying electron mass

Constraints at 68% cl.

	varying m_e				constant m_e
	ΛCDM	$\Omega_k\Lambda$CDM	wCDM	ww_aCDM	ΛCDM (reference)
H_0 [km/sec/Mpc] (mean with 68% errors)					
based on CMB+BAO+SNeIa	$68.7^{+1.2}_{-1.2}$	$72.3^{+2.7}_{-2.8}$	$68.7^{+1.1}_{-1.2}$	$67.5^{+1.3}_{-1.6}$	$67.7^{+0.4}_{-0.4}$
based on CMB+BAO+SNeIa+H0	$71.2^{+0.9}_{-0.9}$	$72.9^{+1.0}_{-1.0}$	$71.0^{+1.0}_{-1.0}$	$71.5^{+1.1}_{-0.9}$	$68.4^{+0.4}_{-0.4}$
$\Delta\chi^2_{\rm eff}$ relative to the reference					
based on CMB+BAO+SNeIa+H0	-12.2	-23.5	-12.5	-13.2	0

Sekiguchi & Takahashi, *Phys.Rev.D* 103 (2021) 8, 083507



A model with a time-varying electron mass gives H0 in agreement with SH0ES within 1σ if the universe is closed, in agreement with the low redshift data.

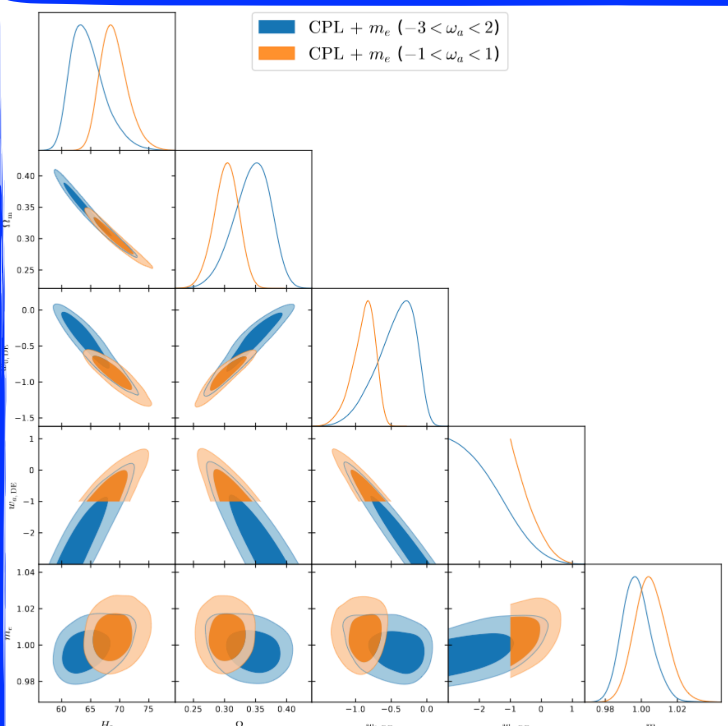
Universe with a varying electron mass: DESI

Model	Data	$10^2\Delta m_e/m_e$	H_0 [km/s/Mpc]	GT
$\Delta m_e/m_e$	P15	$-3.9^{+4.6}_{-7.2}$	60^{+8}_{-16}	1.6
$\Delta m_e/m_e$	P15 + SDSS	$0.39^{+0.74}_{-0.74}$	68.1 ± 1.3	3.0
$\Delta m_e/m_e + \Delta\alpha/\alpha$	P15 + SDSS	0.56 ± 0.80	68.1 ± 1.3	3.0
$\Delta m_e/m_e$	P18	-11.2 ± 5.9	46^{+9}_{-10}	3.0
$\Delta m_e/m_e$	P18 + SDSS	0.47 ± 0.66	68.46 ± 1.26	2.8
$\Delta m_e/m_e + \Omega_k$	P18 + SDSS	1.5 ± 1.8	69.29 ± 2.11	1.6
$\Delta m_e/m_e$	SPT+P18+SDSS+Pan	0.3 ± 0.6	68.0 ± 1.1	3.3
$\Delta m_e/m_e + \Omega_k$	SPT+P18+SDSS+Pan	0.35 ± 1.64	68.2 ± 1.6	2.5
$\Delta m_e/m_e + \Omega_k + m_\nu$	SPT+P18+SDSS+Pan	3 ± 3	$69.8^{+1.8}_{-2.9}$	1.6
$\Delta m_e/m_e$	P18+DESI+SDSS+Pan	0.92 ± 0.55	69.44 ± 0.84	2.7
$\Delta m_e/m_e + \Omega_k$	P18+DESI+SDSS+Pan	1.3 ± 1.4	69.7 ± 1.4	1.9
$\Delta m_e/m_e$	P18+Pan	$0.69^{+1.44}_{-1.36}$	$68.75^{+3.01}_{-2.81}$	1.4
$\Delta m_e/m_e$	P18+PanPLUS	$-1.00^{+1.09}_{-1.04}$	$65.08^{+2.18}_{-2.03}$	3.4
$\Delta m_e/m_e$	P18+DESI	1.21 ± 0.63	70.03 ± 1.06	2.0
$\Delta m_e/m_e + \Omega_k$	P18+DESI	2.52 ± 1.85	70.94 ± 1.23	1.3
$\Delta m_e/m_e + \Omega_k$	P18+DESI+PanPLUS	1.88 ± 0.52	71.61 ± 1.00	1.0
$\Delta m_e/m_e + w_0/w_a$	P18+DESI	1.53 ± 0.63	70.30 ± 1.34	1.6
$\Delta m_e/m_e + w_0/w_a$	P18+DESI+PanPLUS	0.72 ± 0.84	69.38 ± 2.17	1.5

Schoneberg & Vacher, *arXiv:2407.16845*

A model with a time-varying electron mass gives H0 in agreement with SH0ES below 2σ, if combined with a DDE or curvature.

Universe with a varying electron mass: DESI



Parameter	CPL + m_e ($-3 < w_a < 2$)	CPL + m_e ($-1 < w_a < 1$)
m_e	$0.9976^{+0.0070}_{-0.0089}$	$1.0052^{+0.0081}_{-0.0093}$
$w_{0,\mathrm{DE}}$	$-0.45^{+0.34}_{-0.18}$	$-0.89^{+0.19}_{-0.12}$
$w_{a,\mathrm{DE}}$	< -1.56	< -0.359
H_0	$64.6^{+2.0}_{-3.5}$	$69.0^{+1.9}_{-2.7}$
$\Omega_\mathrm{m} h^2$	$0.1425^{+0.0020}_{-0.0023}$	0.1437 ± 0.0023
σ_8	$0.793^{+0.022}_{-0.030}$	$0.824^{+0.022}_{-0.025}$
χ^2	2790.7 ± 6.4	2794.4 ± 6.3

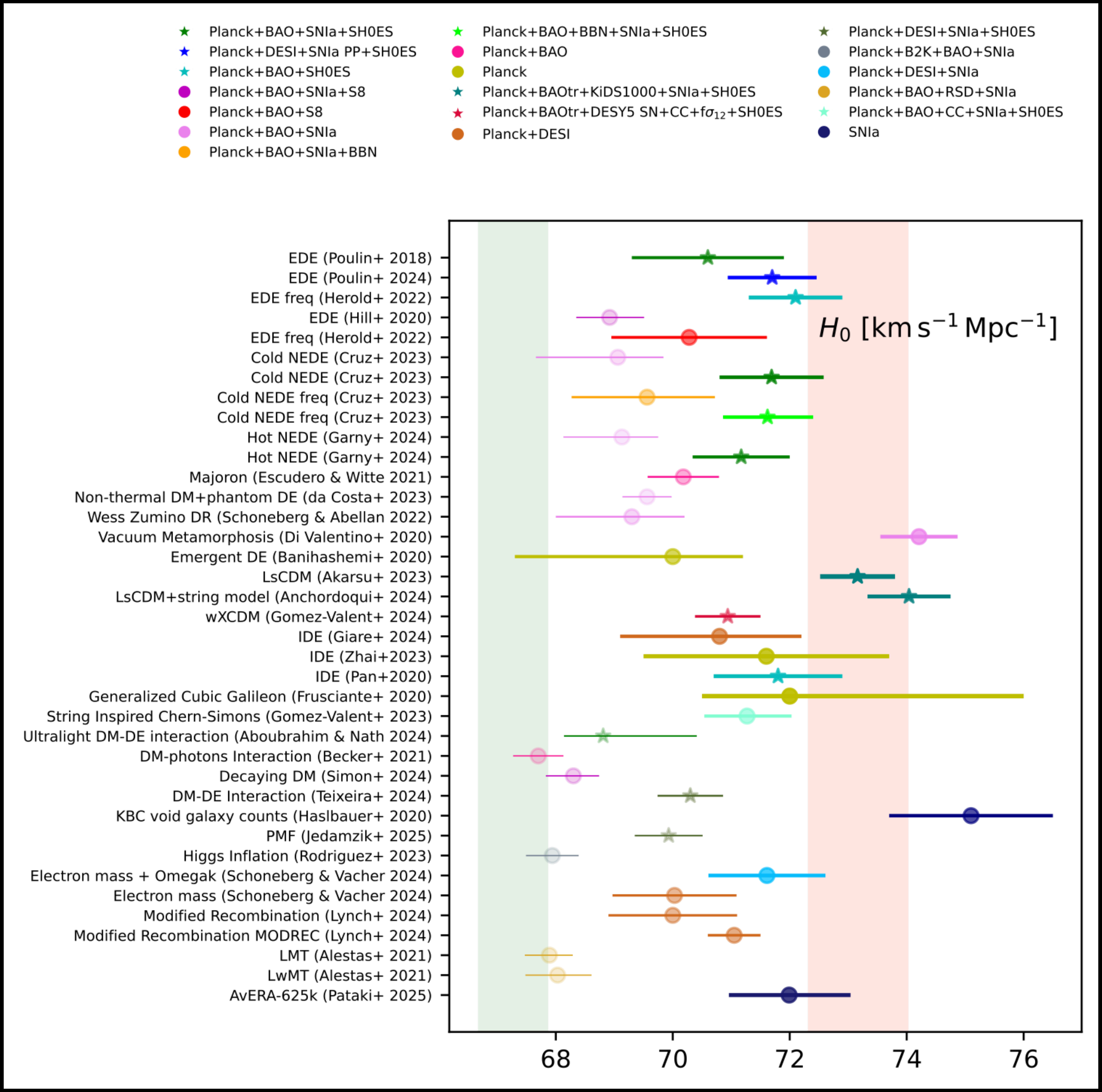
Smith, Ozulker, Di Valentino & van de Bruck, in preparation.

	Data	$10^2\Delta m_e/m_e$	H_0 [km/s/Mpc]	GT
	P15	$3.0^{+4.6}$	69^{+8}	1.6
	+DESI+SDSS+Pan	0.92 ± 0.55	69.44 ± 0.84	2.7
$\Delta m_e/m_e$	P18+Pan	$0.69^{+1.44}_{-1.36}$	$68.75^{+3.01}_{-2.81}$	1.4
$\Delta m_e/m_e$	P18+PanPLUS	$-1.00^{+1.09}_{-1.04}$	$65.08^{+2.18}_{-2.03}$	3.4
$\Delta m_e/m_e$	P18+DESI	1.21 ± 0.63	70.03 ± 1.06	2.0
$\Delta m_e/m_e + \Omega_k$	P18+DESI	2.52 ± 1.85	70.94 ± 1.23	1.3
$\Delta m_e/m_e + \Omega_k$	P18+DESI+PanPLUS	1.88 ± 0.52	71.61 ± 1.00	1.0
$\Delta m_e/m_e + w_0/w_a$	P18+DESI	1.53 ± 0.63	70.30 ± 1.34	1.6
$\Delta m_e/m_e + w_0/w_a$	P18+DESI+PanPLUS	0.72 ± 0.84	69.38 ± 2.17	1.5

Schoneberg & Vacher, *arXiv:2407.16845*

However this results depends strongly
on the prior adopted on the DDE parameters.

Successful models?



CosmoVerse, Di Valentino et al., arXiv:2504.01669

Summary – Where Do We Stand?

The Hubble tension remains one of the most significant challenges in modern cosmology, with a >6σ discrepancy between early- and late-universe measurements.

The standard model, ΛCDM, still fits each dataset individually, but it fails to fit all datasets simultaneously. This signals potential limits of its validity.

A wide range of proposed solutions (both early- and late-time modifications) have been explored:

- Some models (e.g. EDE, IDE, Omnipotent DE, electron mass) show promise in alleviating the tension, but often introduce new challenges or tensions with other data.
- New measurements (DESI, SPT-3G, ACT-DR6, etc.) have not resolved the discrepancy, but they confirmed and sharpened it.

This persistent inconsistency suggests we are either facing unaccounted systematics or new physics beyond ΛCDM.

Precision without consistency is misleading. To make trustworthy cosmological inferences, we must ensure the internal coherence of our datasets.

Going forward, resolving the Hubble tension is not just about H0, it's about testing the very foundations of our cosmological model.

Thank you!

e.divalentino@sheffield.ac.uk

MENU

COSMOVERSE • COST ACTION CA21136

Addressing observational tensions in cosmology with systematics and fundamental physics

https://cosmoversetensions.eu/

WG1 – Observational Cosmology and systematics

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

READ MORE

WG2 – Data Analysis in Cosmology

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

READ MORE

WG3 – Fundamental Physics

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

READ MORE

Bayes factor

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

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

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

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

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