

Unresolved Anomalies and Tensions in the Standard Cosmological Model

November 30th 2023
INAF-OAAb colloquia

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



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The Λ CDM model

Out of various cosmological models proposed in literature, the **Lambda cold dark matter (Λ CDM) scenario has been chosen as the standard model for its simplicity** and ability to accurately describe a wide range of astrophysical and cosmological observations.

However, Λ CDM still has many unknown areas and lacks the ability to explain fundamental concepts related to the structure and evolution of the universe. These concepts are based on three unknown ingredients that are not supported by theoretical first principles or laboratory experiments but are instead inferred from cosmological and astrophysical observations.

The three unknown ingredients are:
inflation, dark matter (DM), and dark energy (DE).

In Λ CDM, **inflation is given by a single, slow-rolling scalar field;**
DM is assumed to interact only through gravity, be **cold and pressureless**, and lack direct evidence of its existence;
DE is represented by the **cosmological constant term Λ** , without any strong physical explanation.

The Λ CDM model

Despite its **theoretical shortcomings**, Λ CDM remains the preferred model due to its ability to accurately describe observed phenomena. However, the Λ CDM 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 Λ CDM model are expected to be detected. And in fact, discrepancies in important cosmological parameters, such as H_0 , have already arisen in various 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 Λ CDM model**.

H0 tension

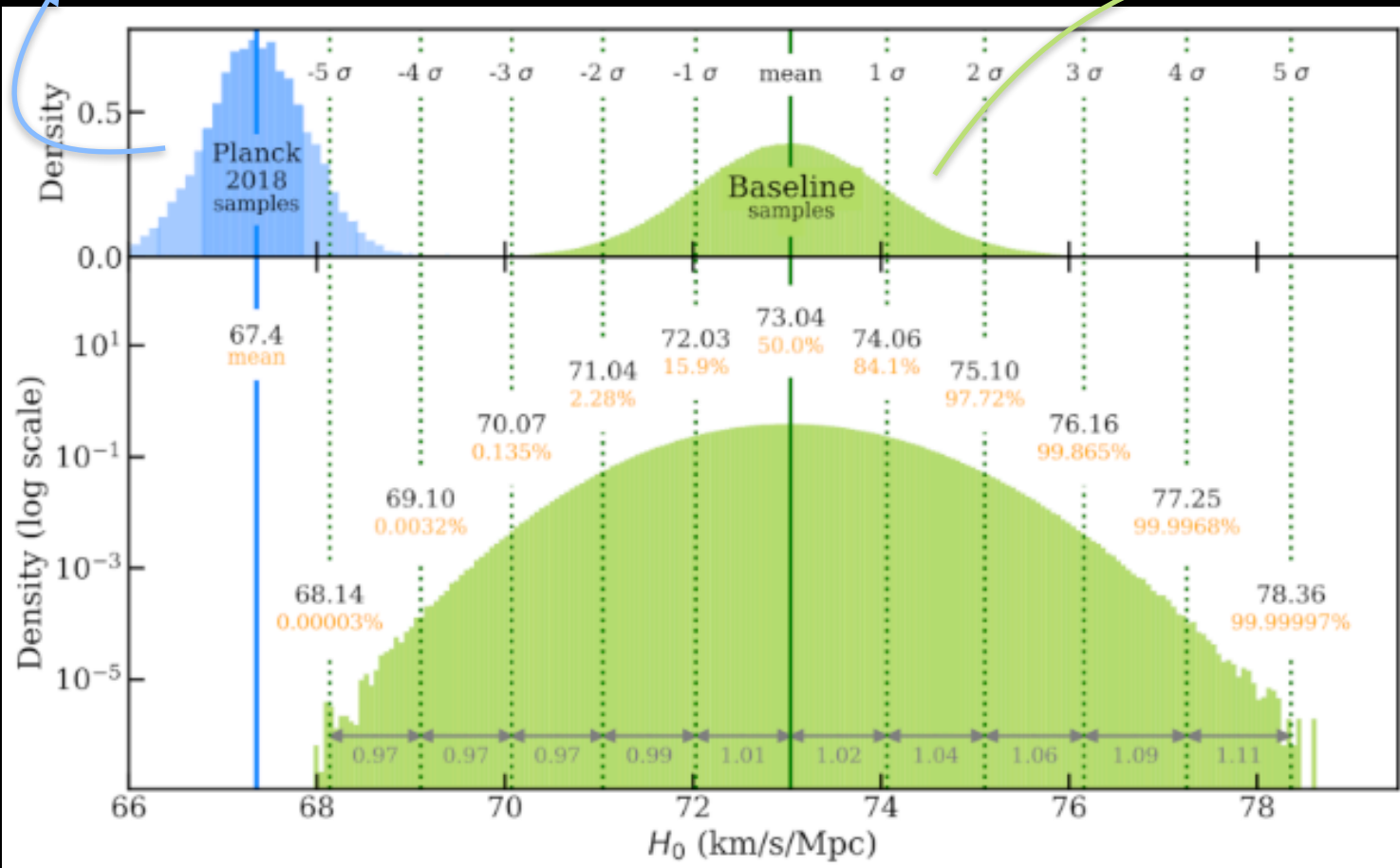
The H0 tension is the most statistically significant, long-lasting and widely persisting disagreement we have currently in cosmology.

The Planck estimate assuming a “vanilla”

Λ CDM cosmological model:

$H_0 = 67.36 \pm 0.54$ km/s/Mpc

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



The latest local measurements obtained by the SH0ES collaboration

$H_0 = 73.04 \pm 1.04$ km/s/Mpc

Riess et al. *arXiv:2112.04510*

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

Distance Ladder

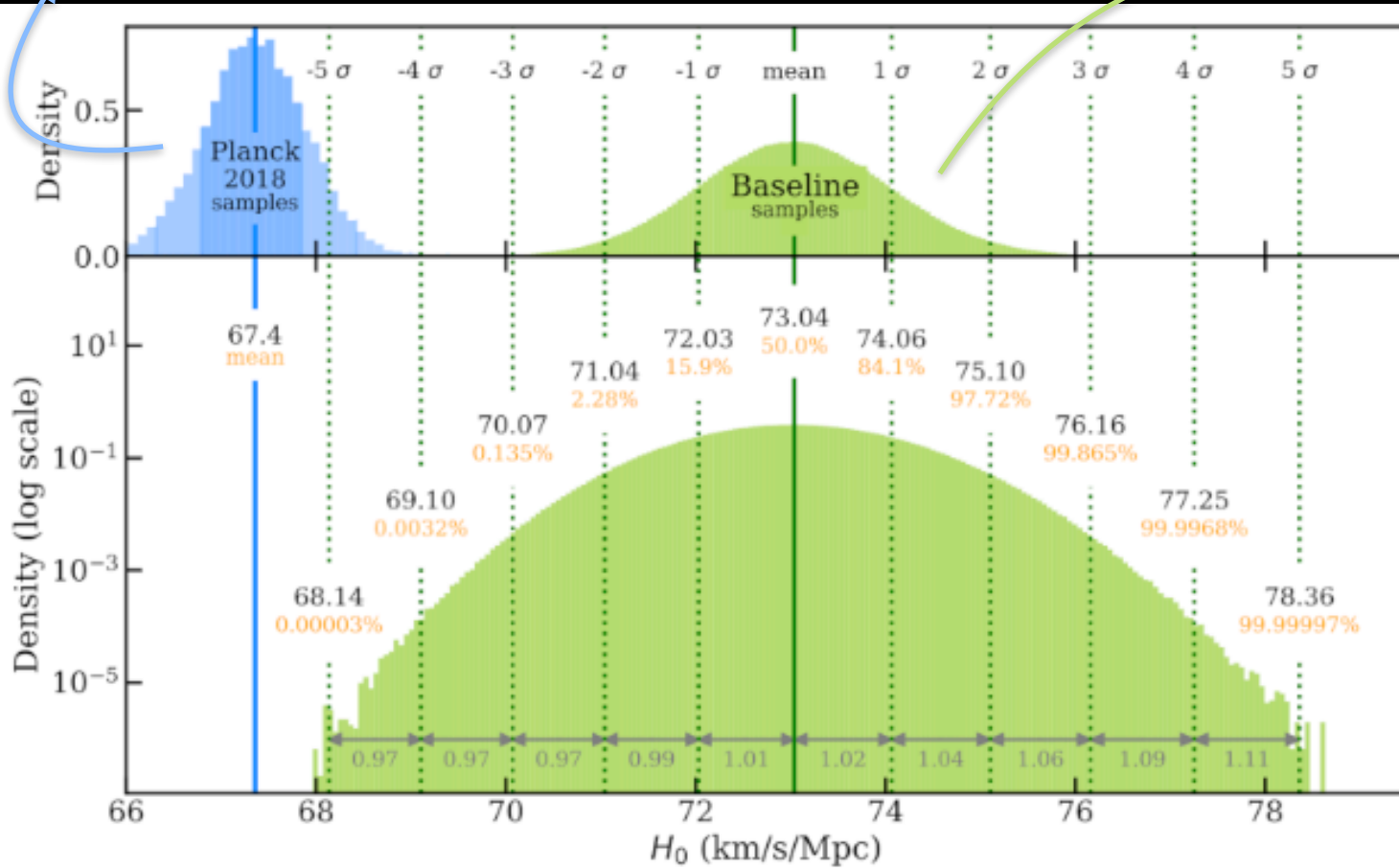


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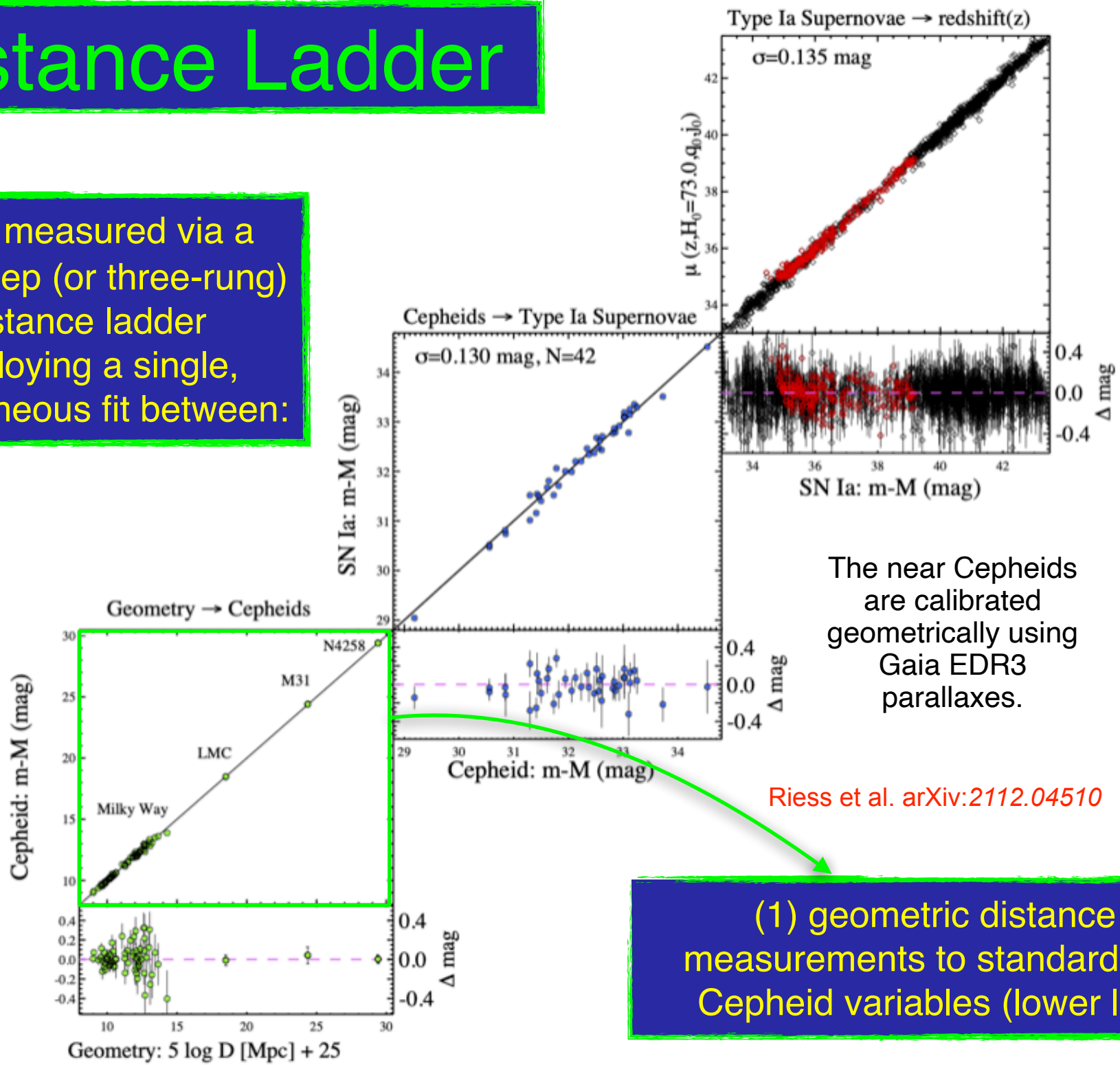
Riess et al. arXiv:2112.04510

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



Distance Ladder

H_0 is measured via a three-step (or three-rung) distance ladder employing a single, simultaneous fit between:



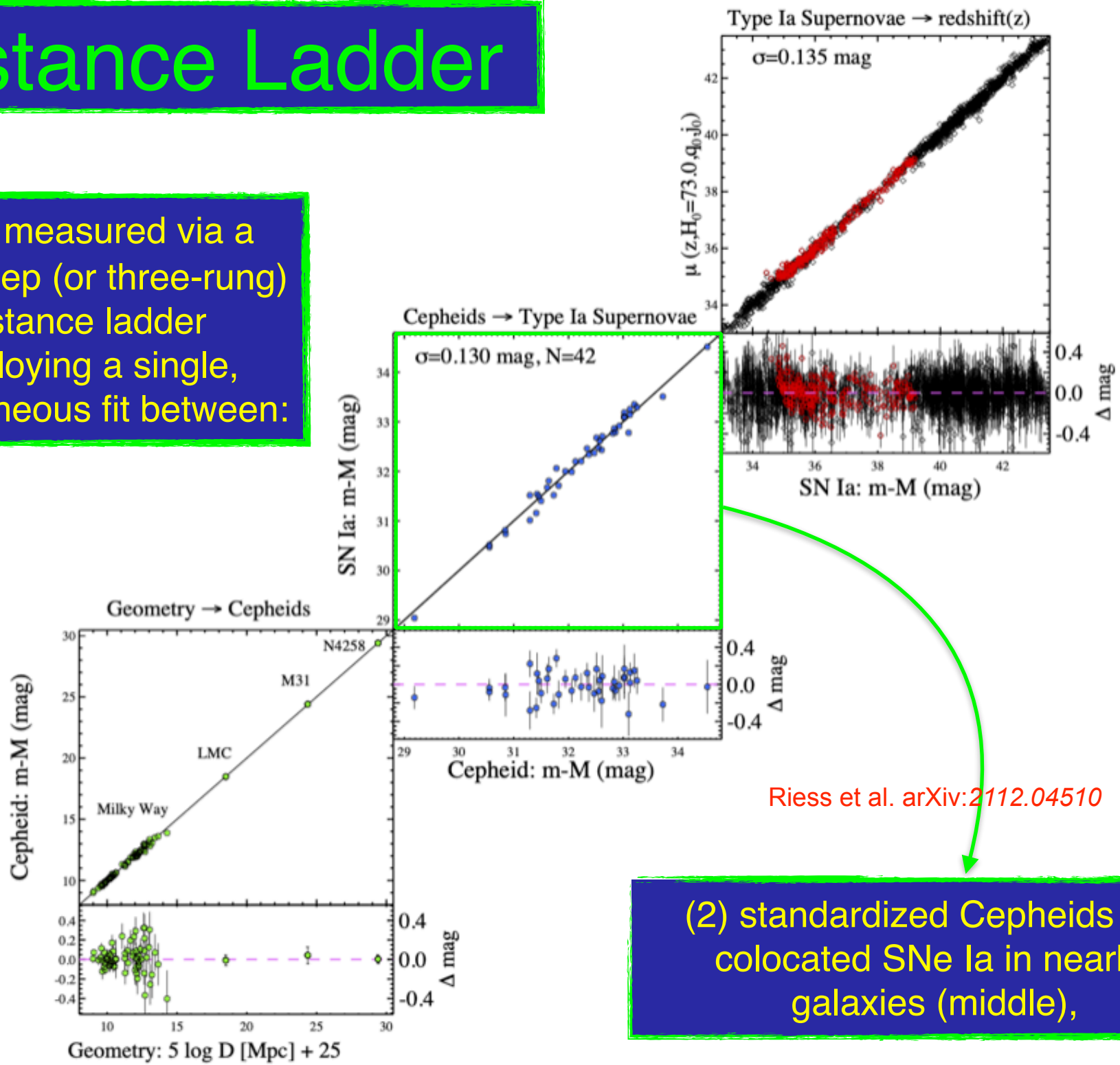
The near Cepheids are calibrated geometrically using Gaia EDR3 parallaxes.

Riess et al. arXiv:2112.04510

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

Distance Ladder

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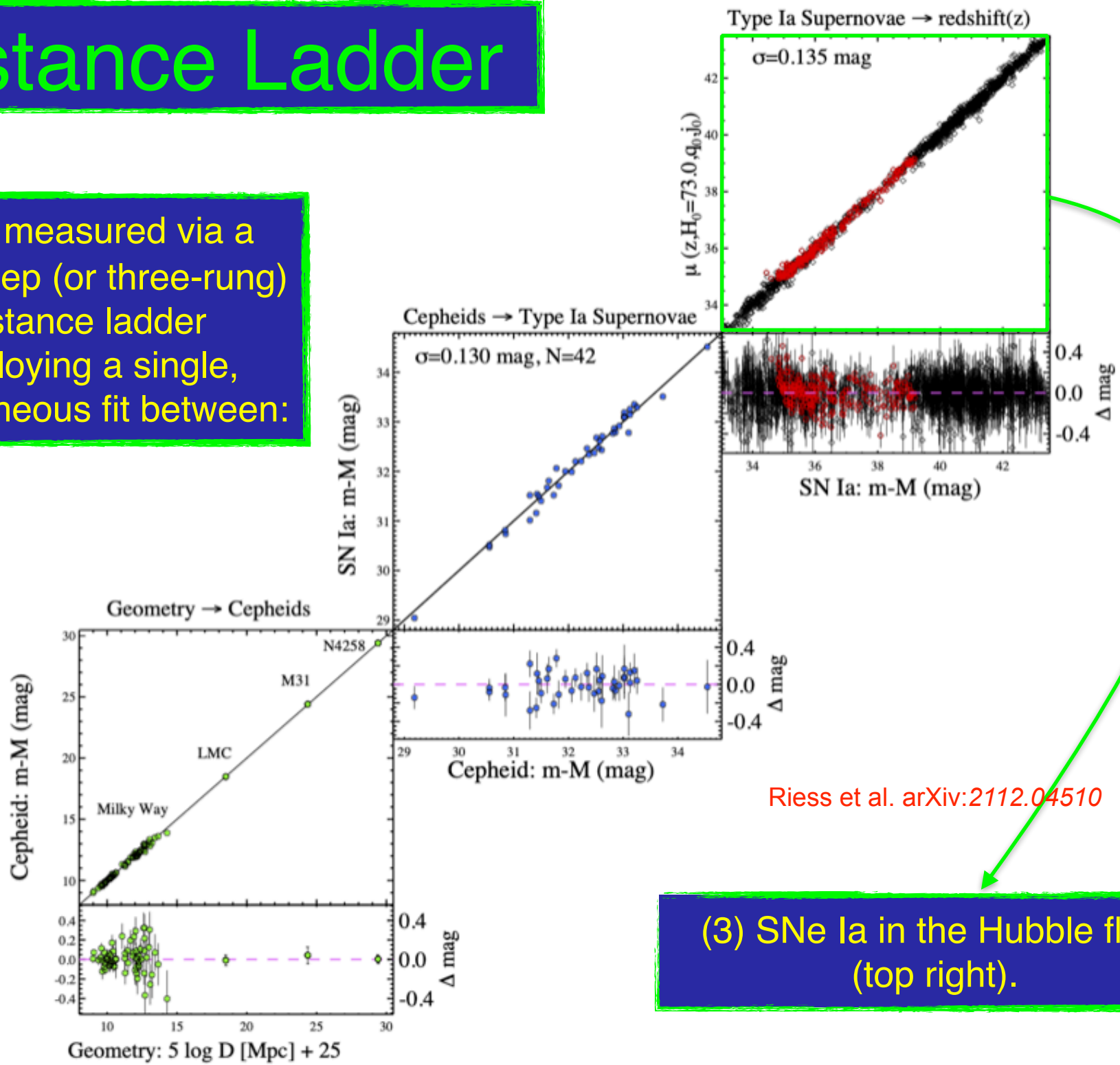


Riess et al. arXiv:2112.04510

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

Distance Ladder

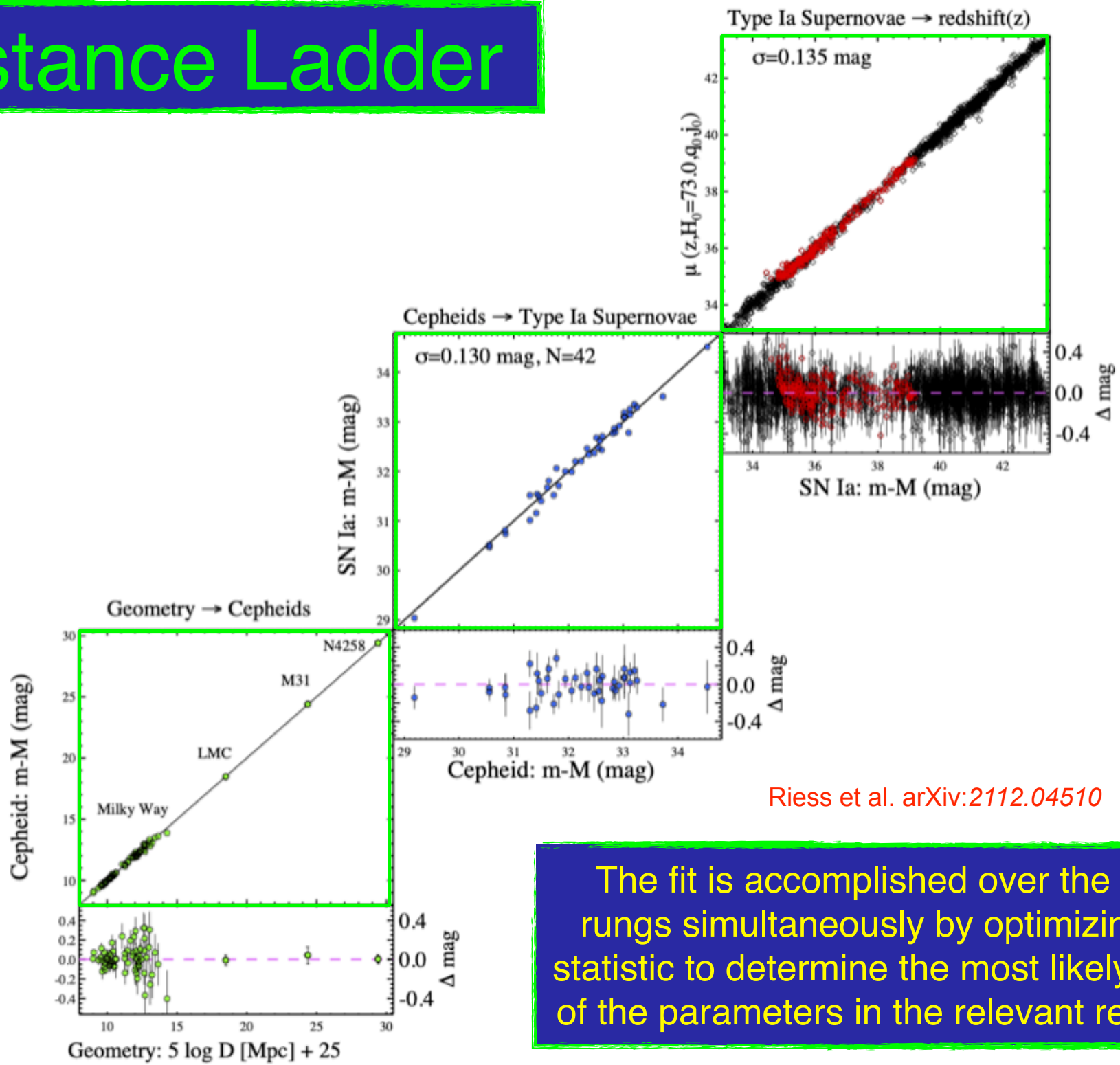
H_0 is measured via a three-step (or three-rung) distance ladder employing a single, simultaneous fit between:



Riess et al. arXiv:2112.04510

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

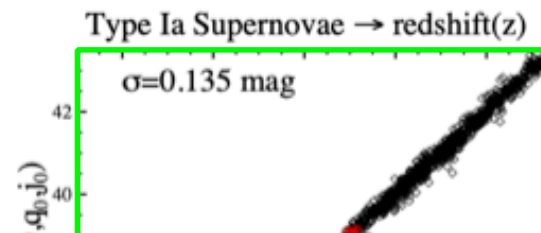
Distance Ladder



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:2306.00070

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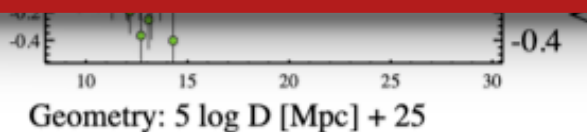
Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 31 May 2023]

Leveraging SN Ia spectroscopic similarity to improve the measurement of H_0

Yukei S. Murakami, Adam G. Riess, Benjamin E. Stahl, W. D'Arcy Kenworthy, Dahne-More A. Pluck, Antonella Macoretta, Dillon Brout, David O. Jones, Dan M. Scolnic, Alexei V. Filippenko

Recent studies suggest spectroscopic differences explain a fraction of the variation in Type Ia supernova (SN Ia) luminosities after light-curve/color standardization. In this work, (i) we empirically characterize the variations of standardized SN Ia luminosities, and (ii) we use a spectroscopically inferred parameter, SIP, to improve the precision of SNe Ia along the distance ladder and the determination of the Hubble constant (H_0). First, we show that the `Pantheon+` covariance model modestly overestimates the uncertainty of standardized magnitudes by $\sim 7\%$, in the parameter space used by the SHOES Team to measure H_0 ; accounting for this alone yields $H_0 = 73.01 \pm 0.92 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Furthermore, accounting for spectroscopic similarity between SNe Ia on the distance ladder reduces their relative scatter to $\sim 0.12 \text{ mag}$ per object (compared to $\sim 0.14 \text{ mag}$ previously). Combining these two findings in the model of SN covariance, we find an overall 14% reduction (to $\pm 0.85 \text{ km s}^{-1} \text{ Mpc}^{-1}$) of the uncertainty in the Hubble constant and a modest increase in its value. Including a budget for systematic uncertainties itemized by Riess et al. (2022a), we report an updated local Hubble constant with $\sim 1.2\%$ uncertainty, $H_0 = 73.29 \pm 0.90 \text{ km s}^{-1} \text{ Mpc}^{-1}$. We conclude that spectroscopic differences among photometrically standardized SNe Ia do not explain the "Hubble tension." Rather, accounting for such differences increases its significance, as the discrepancy against Λ CDM calibrated by the *Planck* 2018 measurement rises to 5.7σ .



CMB constraints

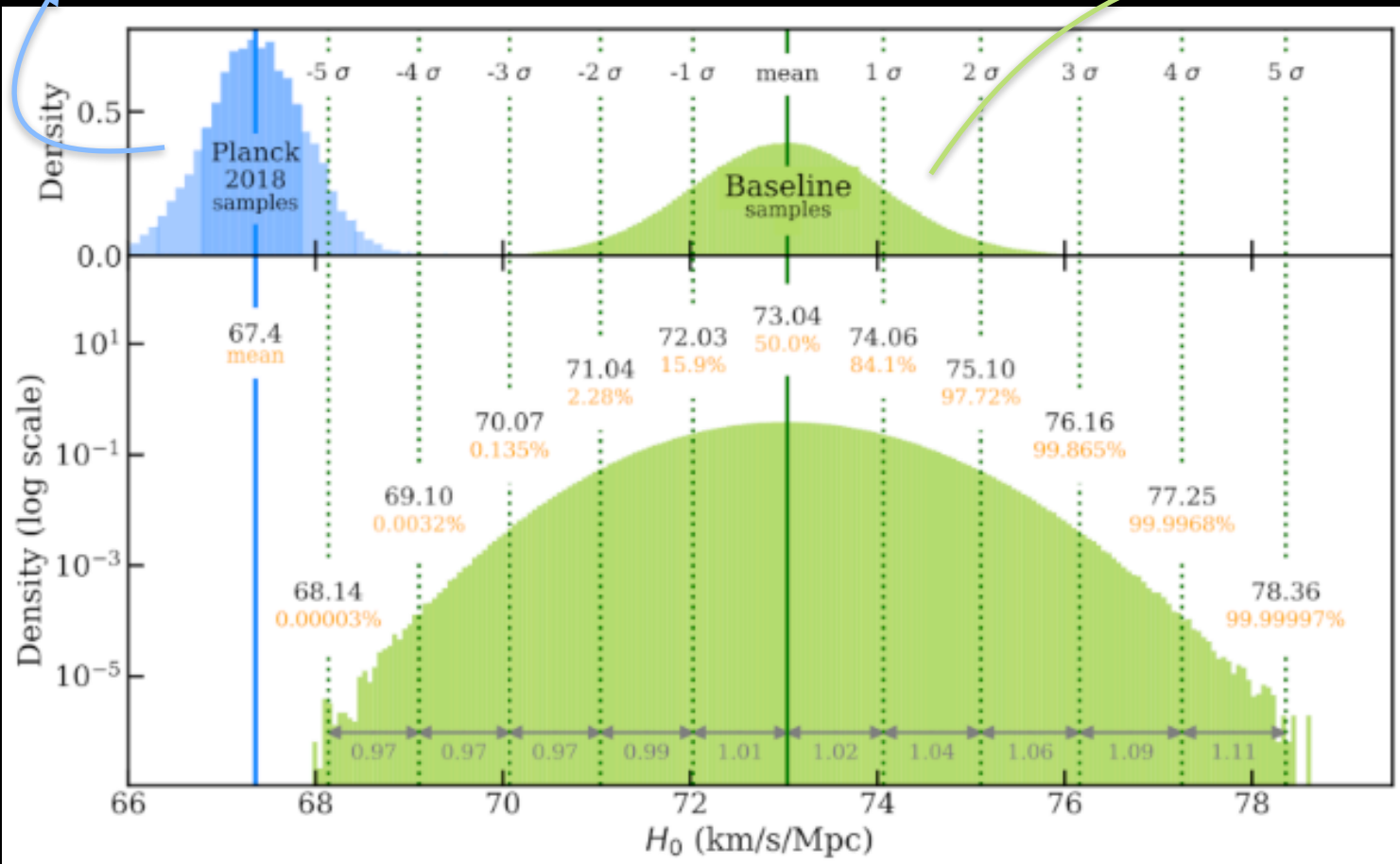


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Λ CDM cosmological model:

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

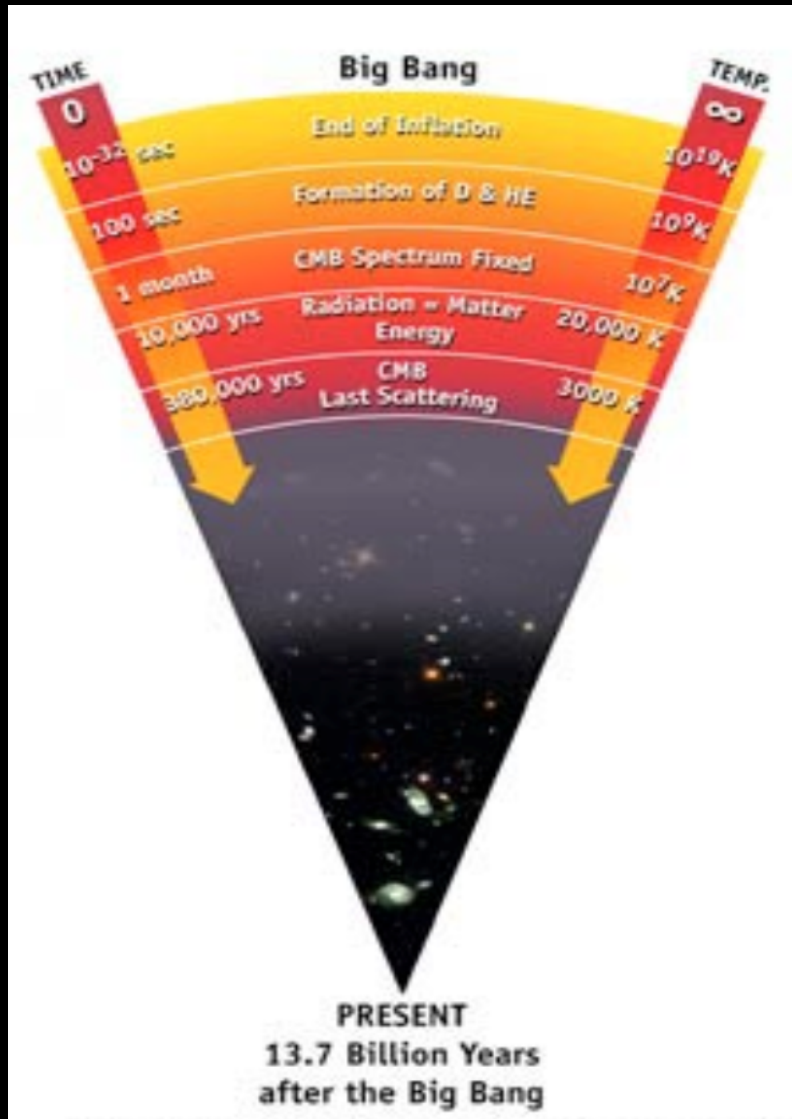


The latest local measurements obtained by the SH0ES collaboration

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

Riess et al. [arXiv:2112.04510](https://arxiv.org/abs/2112.04510)

CMB constraints



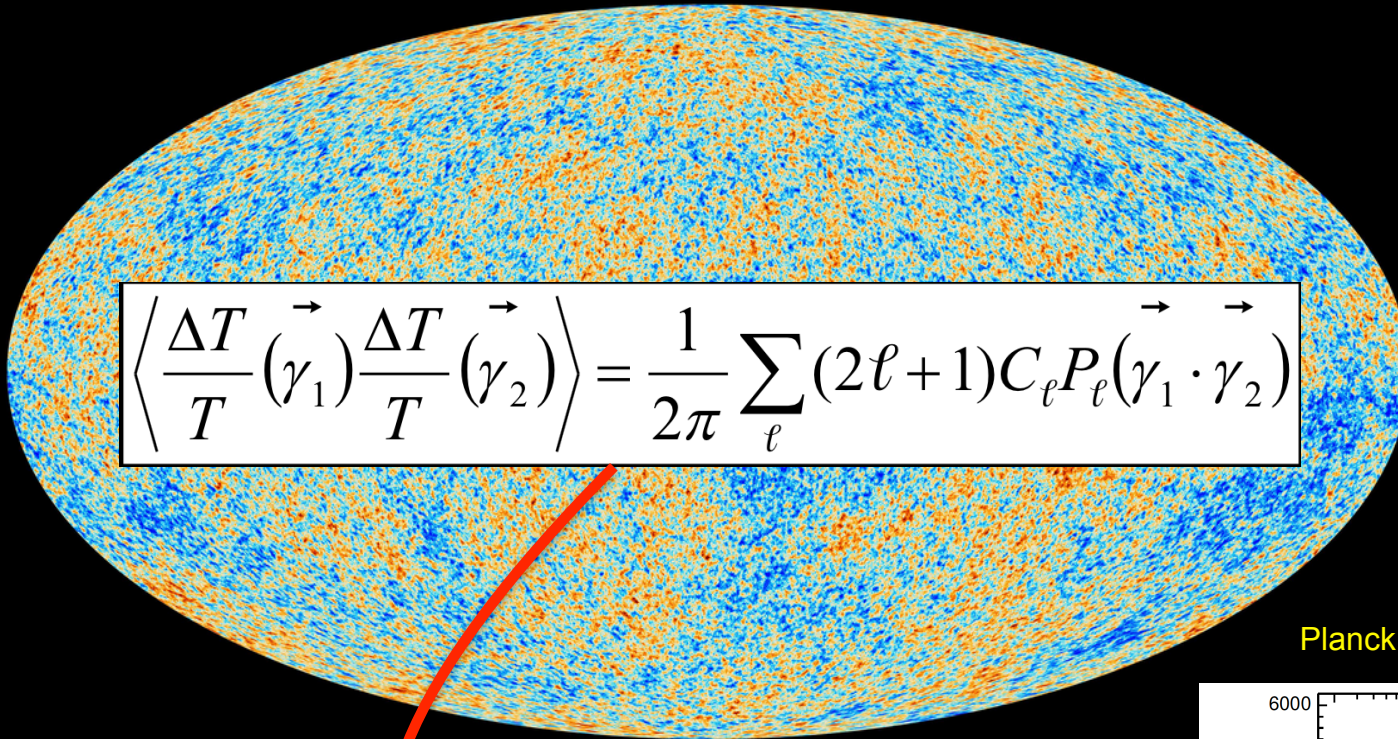
The Universe originates from a hot Big Bang.

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 from recombination, emitted about 13 billion years ago, just 400,000 years after the Big Bang.

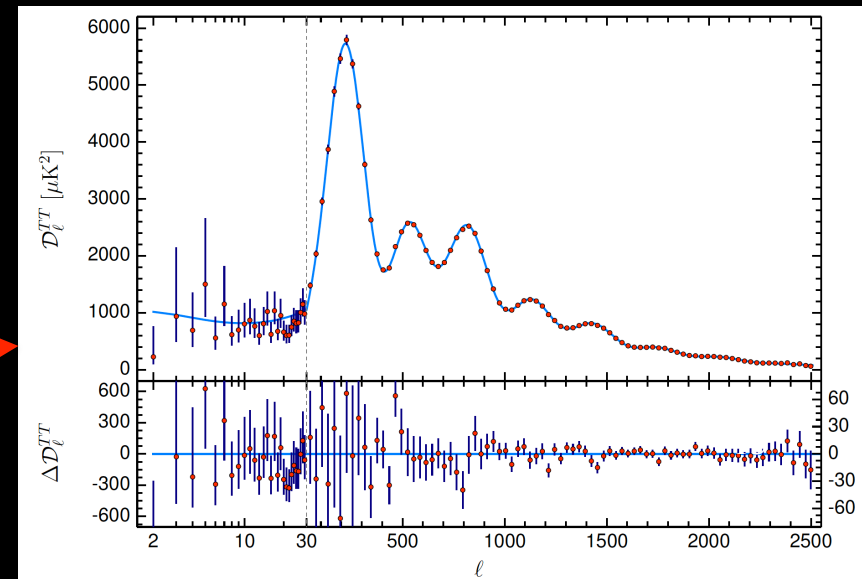
The CMB provides an unparalleled probe of the early Universe and today it is a black body a temperature $T=2.726$ K.

CMB constraints



From the map of the CMB anisotropies we can extract the temperature angular power spectrum.

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



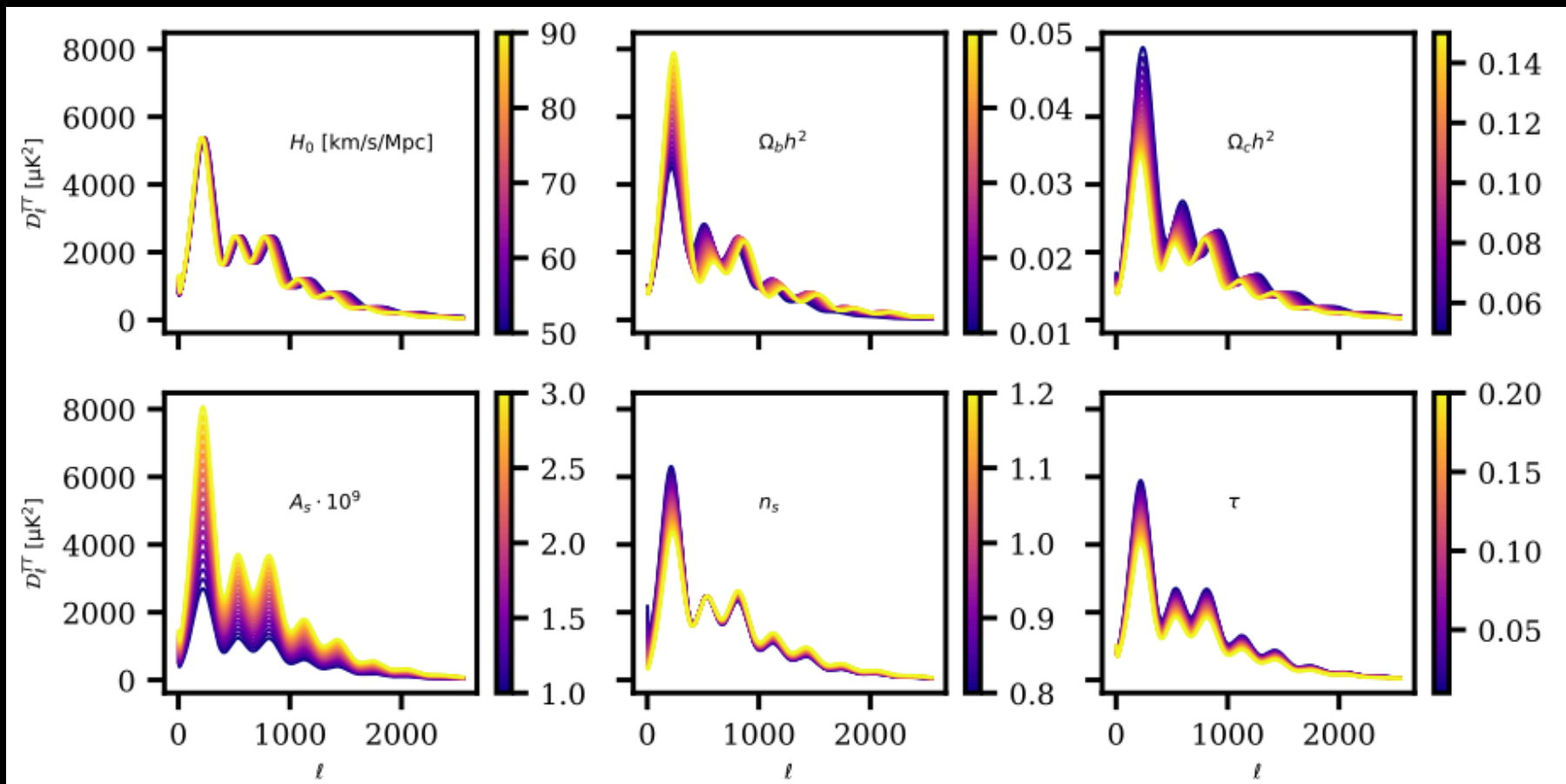
Cosmological parameters:
($\Omega_b h^2$, $\Omega_m h^2$, H_0 , n_s , τ , A_s)



Theoretical model

We choose a set of cosmological parameters that describes our **theoretical model** and compute the angular power spectra.

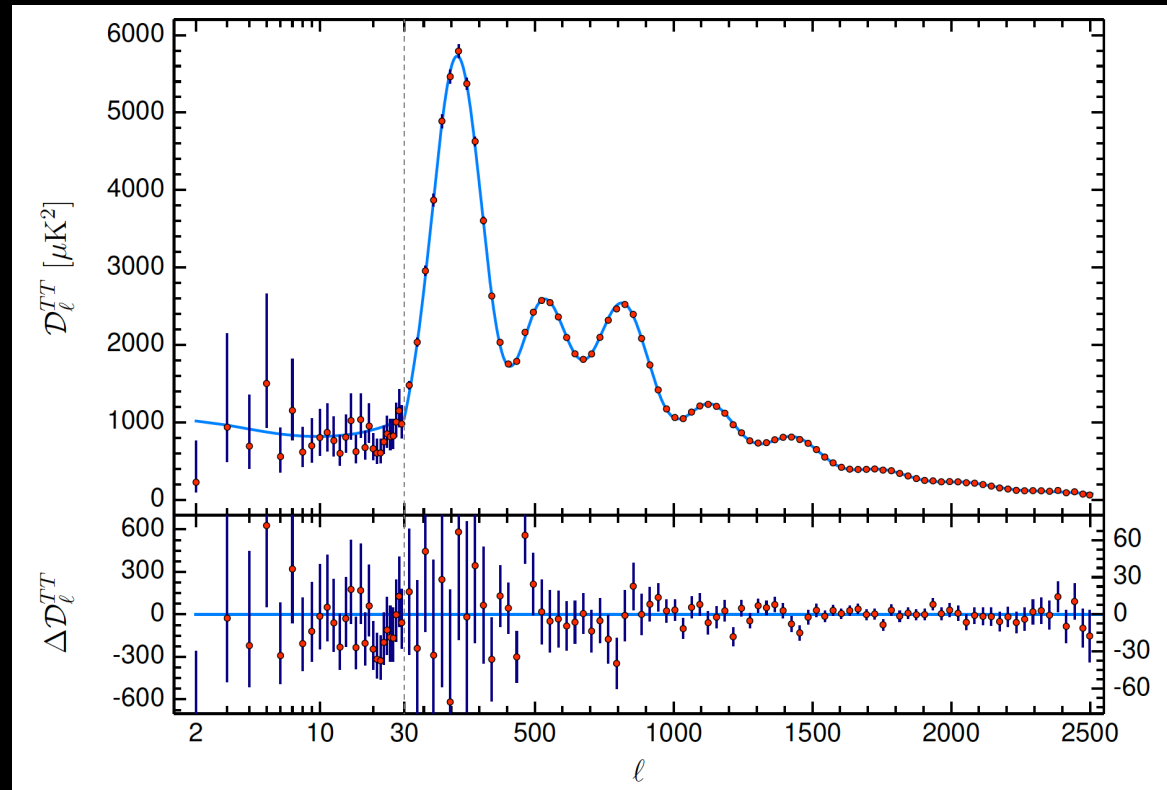
Because of the correlations present between the parameters, variation of different quantities can produce similar effects on the CMB.



Cosmological parameters:
($\Omega_b h^2$, $\Omega_m h^2$, H_0 , n_s , τ , A_s)

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.

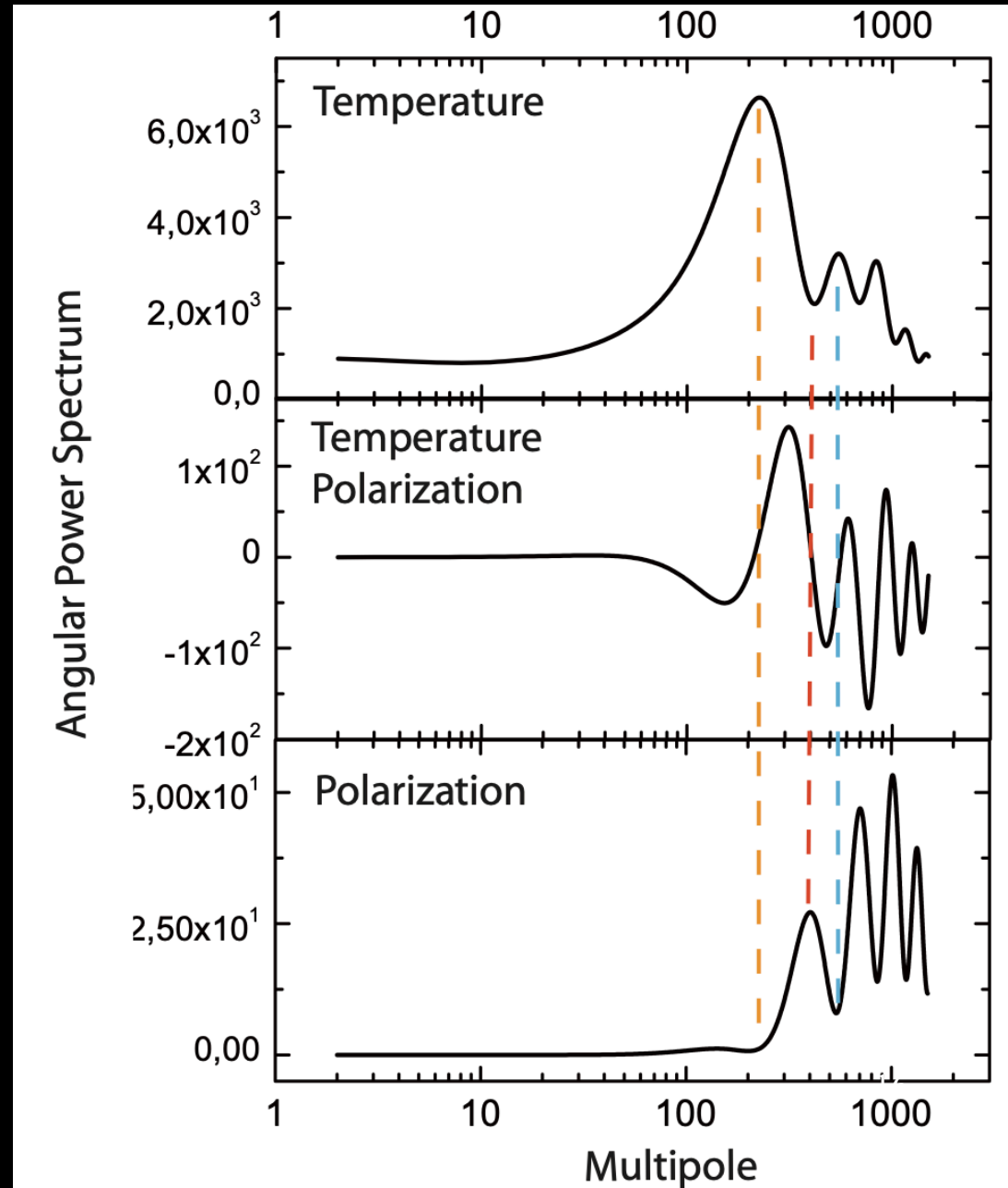


Planck 2018, *Astron.Astrophys.* 641 (2020) A6

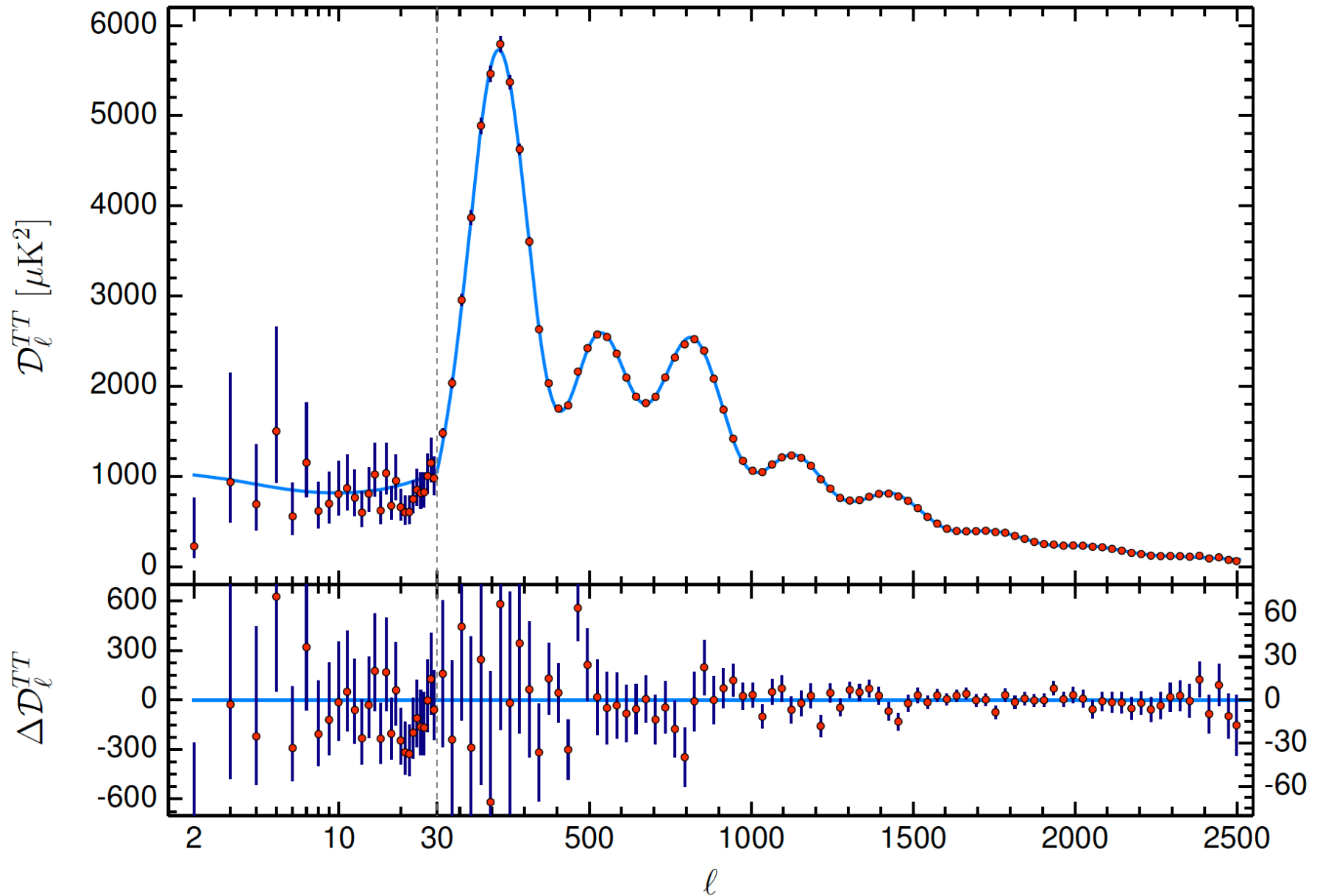
Parameter constraints

We can extract 4 independent angular spectra from the CMB:

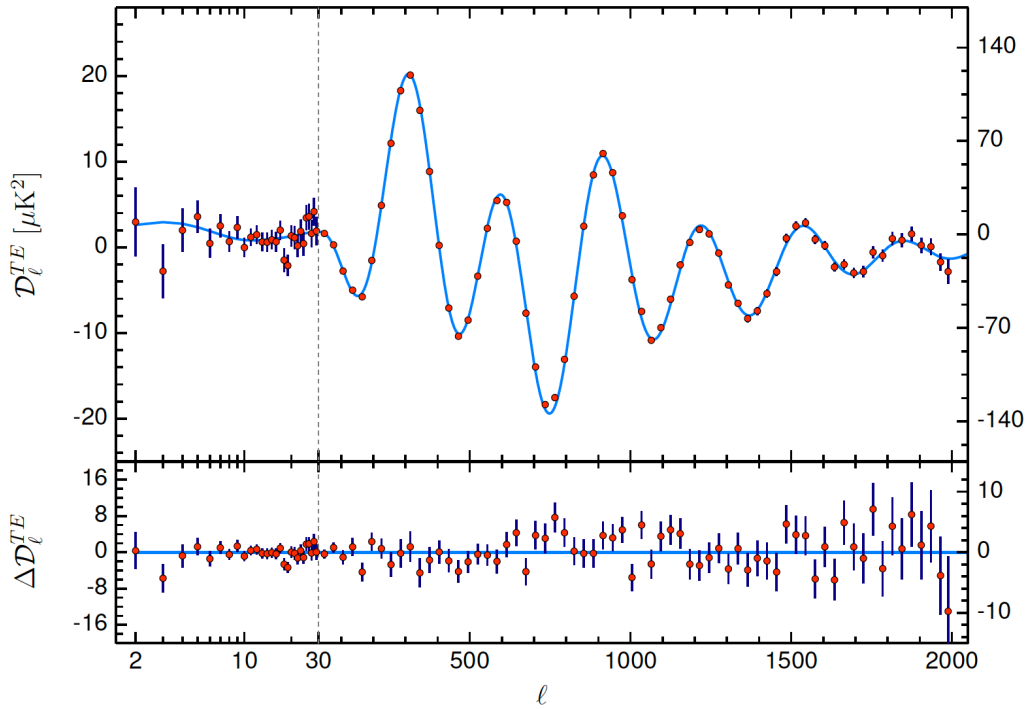
- Temperature
- Cross Temperature Polarization E
- Polarization type E (density fluctuations)
- Polarization type B (gravitational waves)



Planck satellite experiment



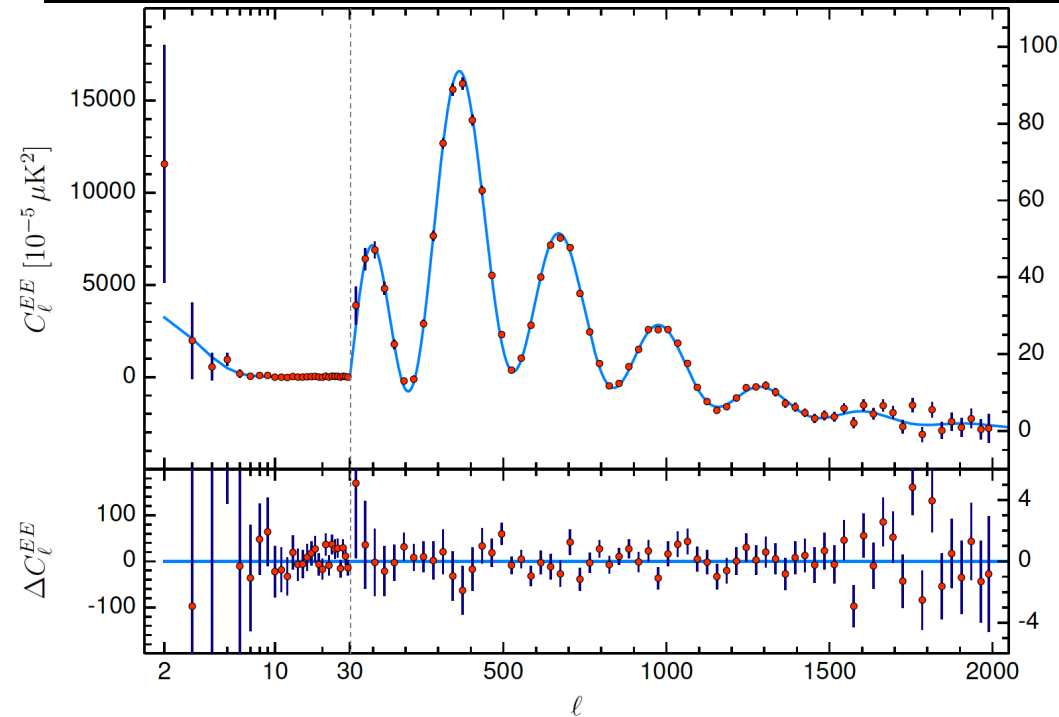
Planck satellite experiment



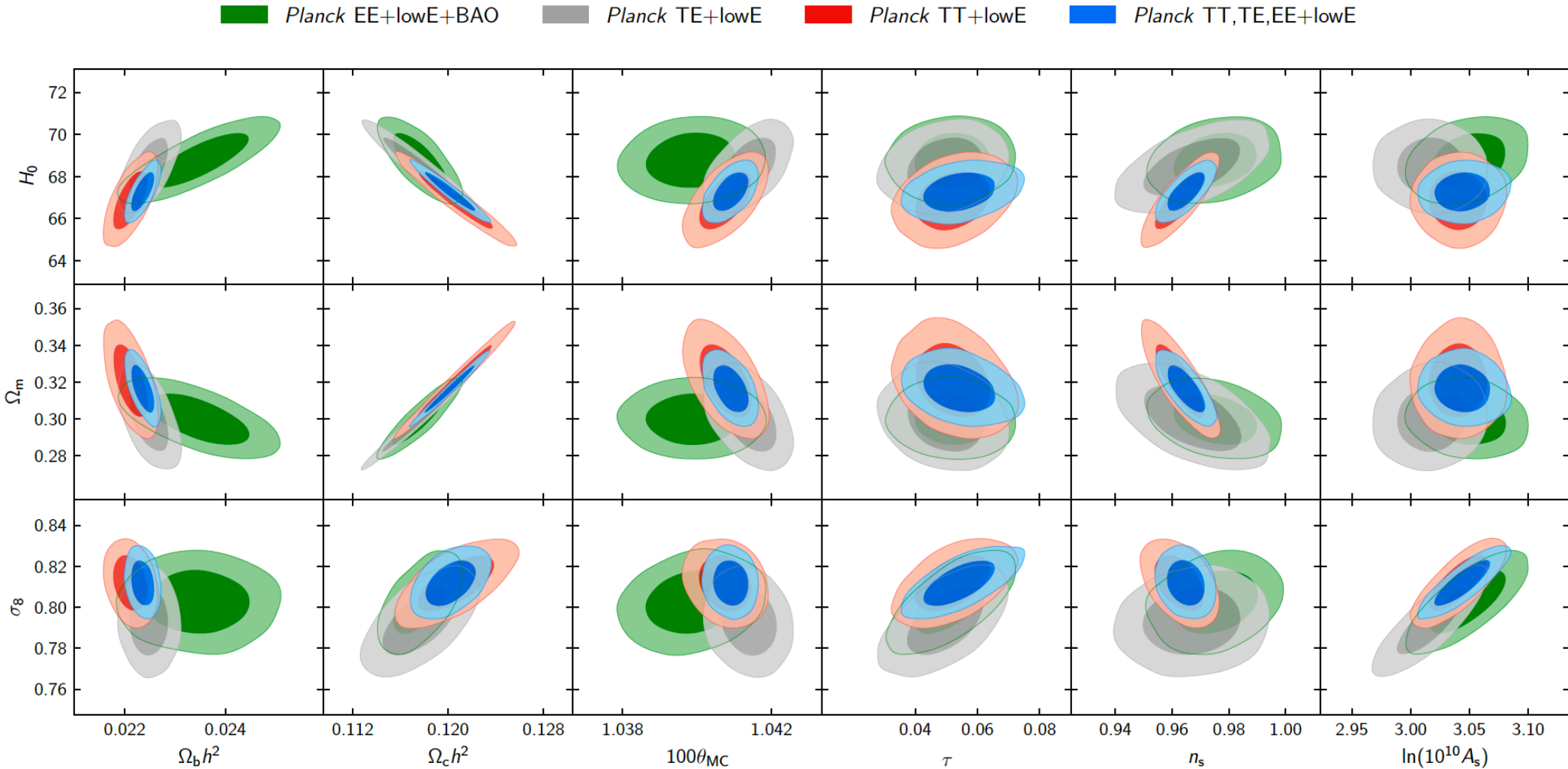
The theoretical spectra in light blues are computed from the best-fit base- Λ CDM theoretical spectrum fit to the Planck TT,TE,EE+lowE+lensing likelihood.

Residuals with respect to this theoretical model are shown in the lower panel in each plot.

Polarization spectra



Planck satellite experiment



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

Constraints on parameters of the LCDM model from the separate Planck EE, TE, and TT high- l spectra combined with low- l polarization (lowE), and, in the case of EE also with BAO, compared to the joint result using Planck TT,TE,EE+lowE.

CMB constraints

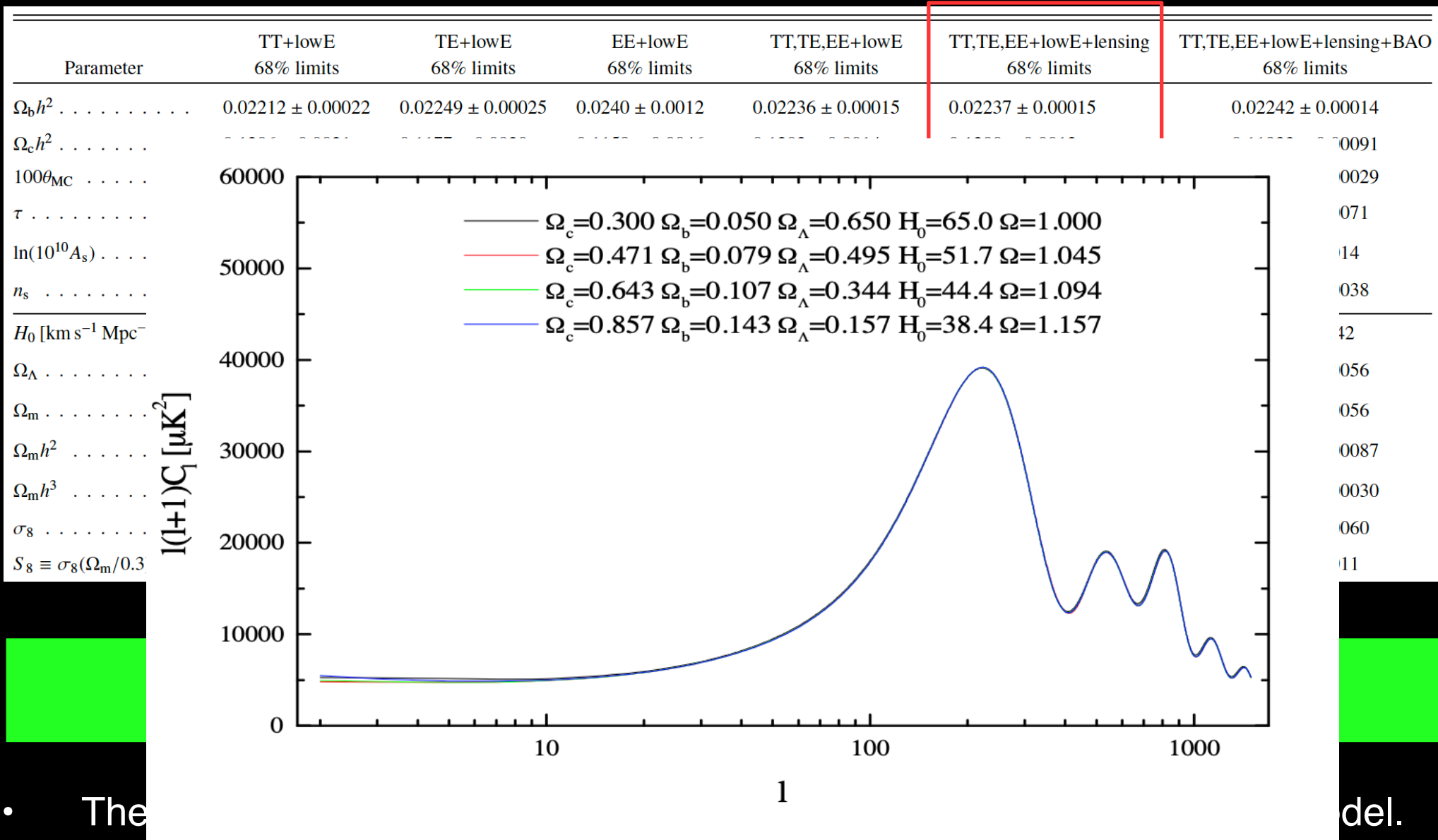
Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [km s ⁻¹ Mpc ⁻¹]	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1434 ± 0.0020	0.1408 ± 0.0019	$0.1404^{+0.0034}_{-0.0039}$	0.1432 ± 0.0013	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09589 ± 0.00046	0.09635 ± 0.00051	$0.0981^{+0.0016}_{-0.0018}$	0.09633 ± 0.00029	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8118 ± 0.0089	0.793 ± 0.011	0.796 ± 0.018	0.8120 ± 0.0073	0.8111 ± 0.0060	0.8102 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.840 ± 0.024	0.794 ± 0.024	$0.781^{+0.052}_{-0.060}$	0.834 ± 0.016	0.832 ± 0.013	0.825 ± 0.011

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

2018 Planck results are a wonderful confirmation of the flat standard Λ CDM cosmological model, but are **model dependent!**

- 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.

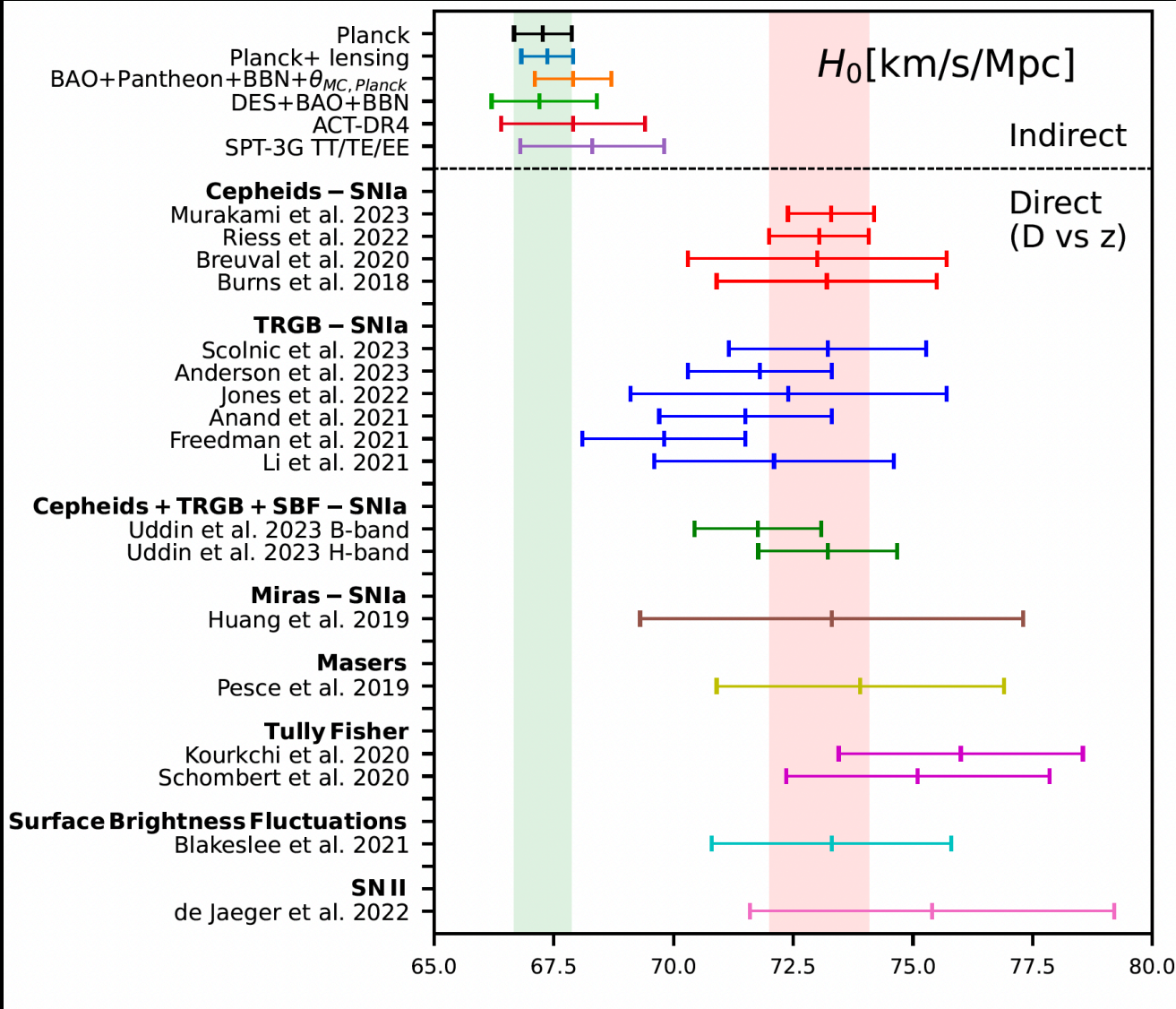
CMB constraints



- The results are affected by the degeneracy between the parameters that induce similar effects on the observables.

Are there other H_0 estimates?

Latest H0 measurements



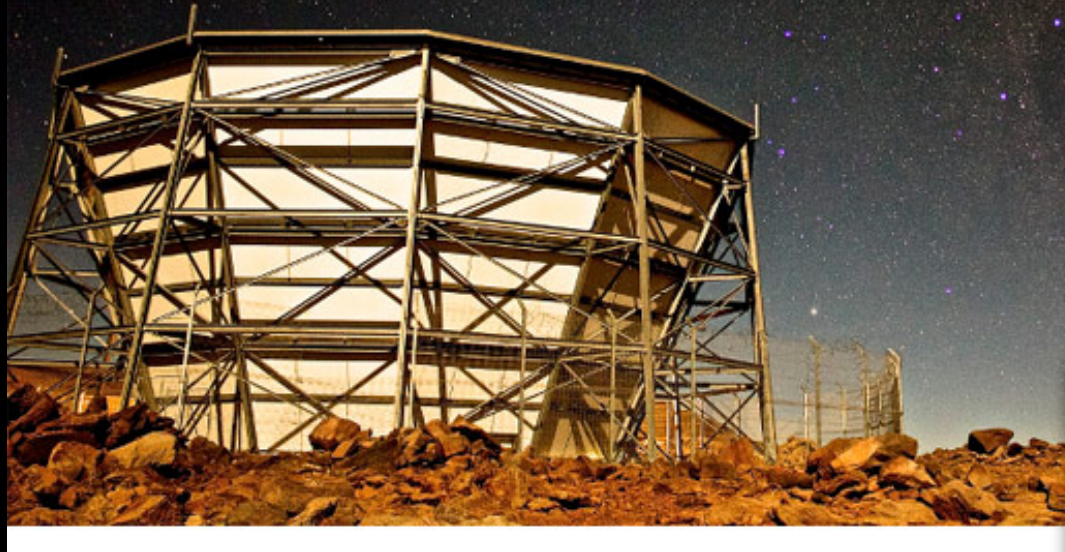
Hubble constant measurements made by different astronomical missions and groups over the years.

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

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

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

Ground based CMB telescope



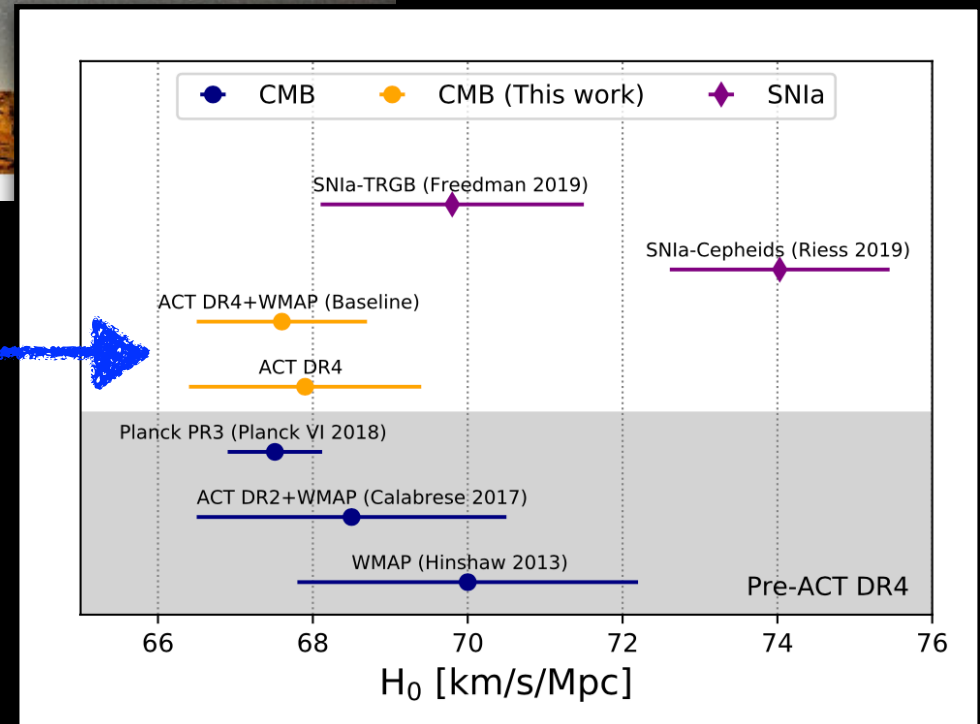
ACT-DR4:

$H_0 = 67.9 \pm 1.5$ km/s/Mpc in Λ CDM

ACT-DR4 + WMAP:

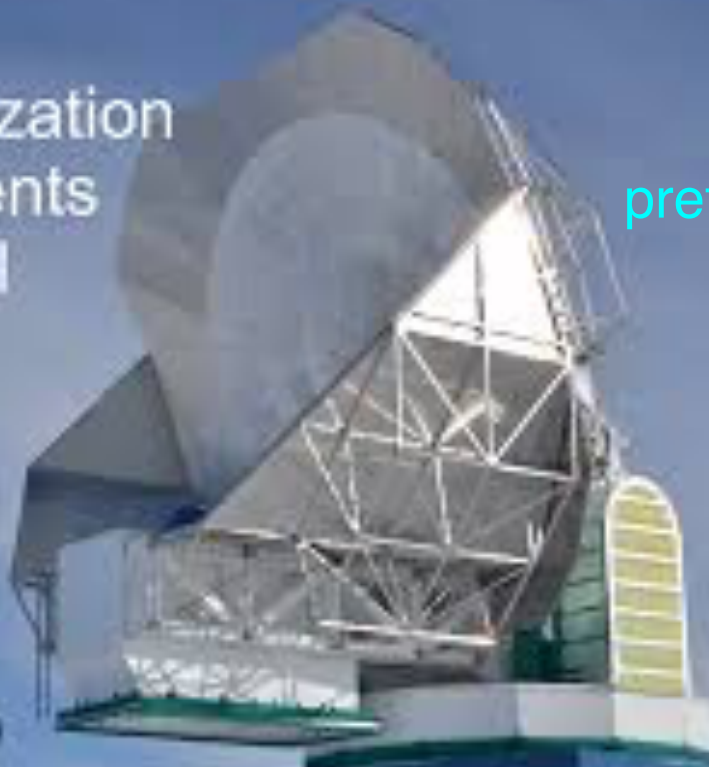
$H_0 = 67.6 \pm 1.1$ km/s/Mpc in Λ CDM

Λ CDM - dependent



CMB Polarization Measurements with SPTpol

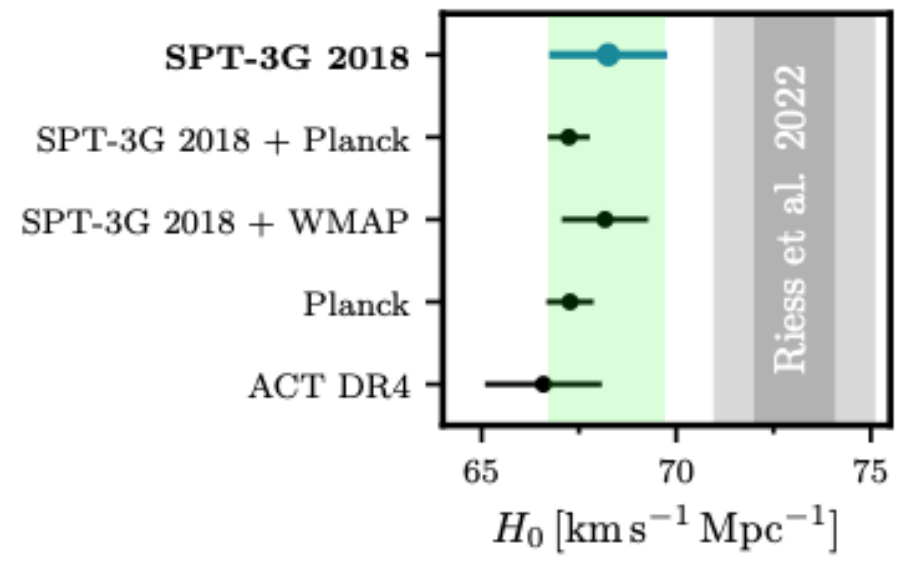
Nicholas Harrington
UC Berkeley



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

Ground based CMB telescope

SPT-3G TT/TE/EE:
 $H_0 = 68.3 \pm 1.5 \text{ km/s/Mpc}$ in ΛCDM

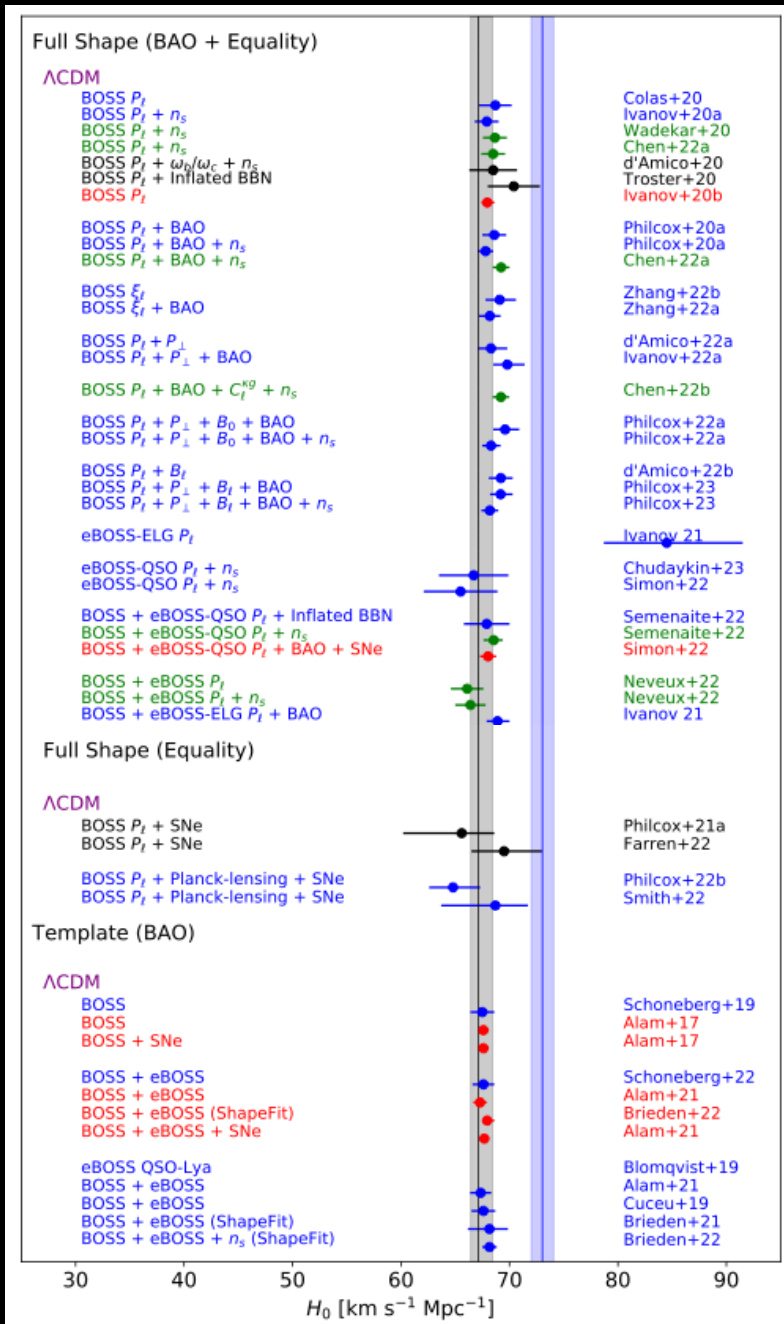


ΛCDM - dependent

SPT-3G collaboration, arXiv:2212.05642

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

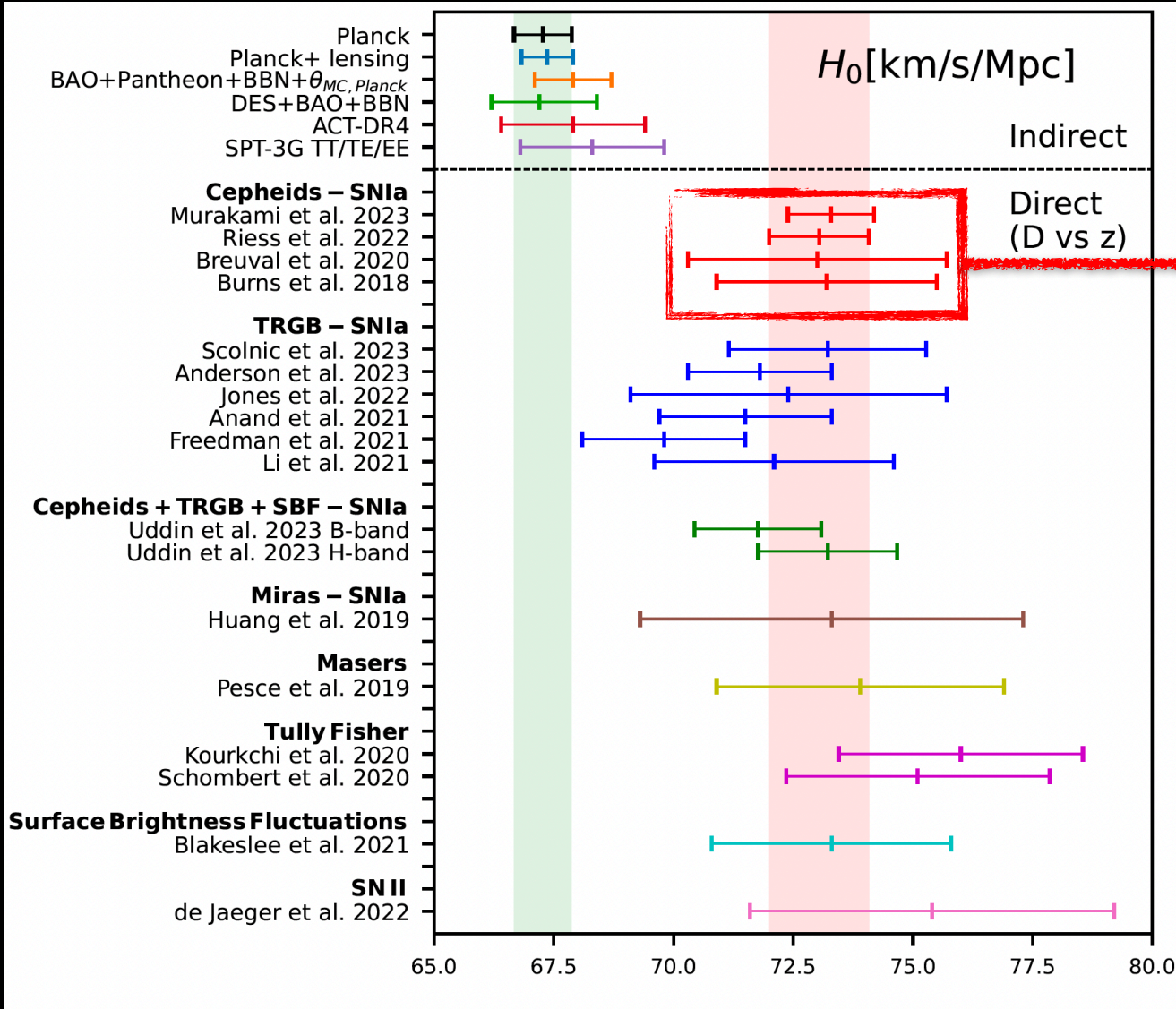
Spectroscopic Surveys BAO and Full Shape from BOSS and eBOSS



Results shown in blue include a BBN prior on ω_b ,
in green use an ω_b prior from *Planck*,
in red are combined with the full *Planck* dataset.

Λ CDM - dependent

Latest H0 measurements



Cepheids-SN Ia:

$$H_0 = 73.29 \pm 0.90 \text{ km/s/Mpc}$$

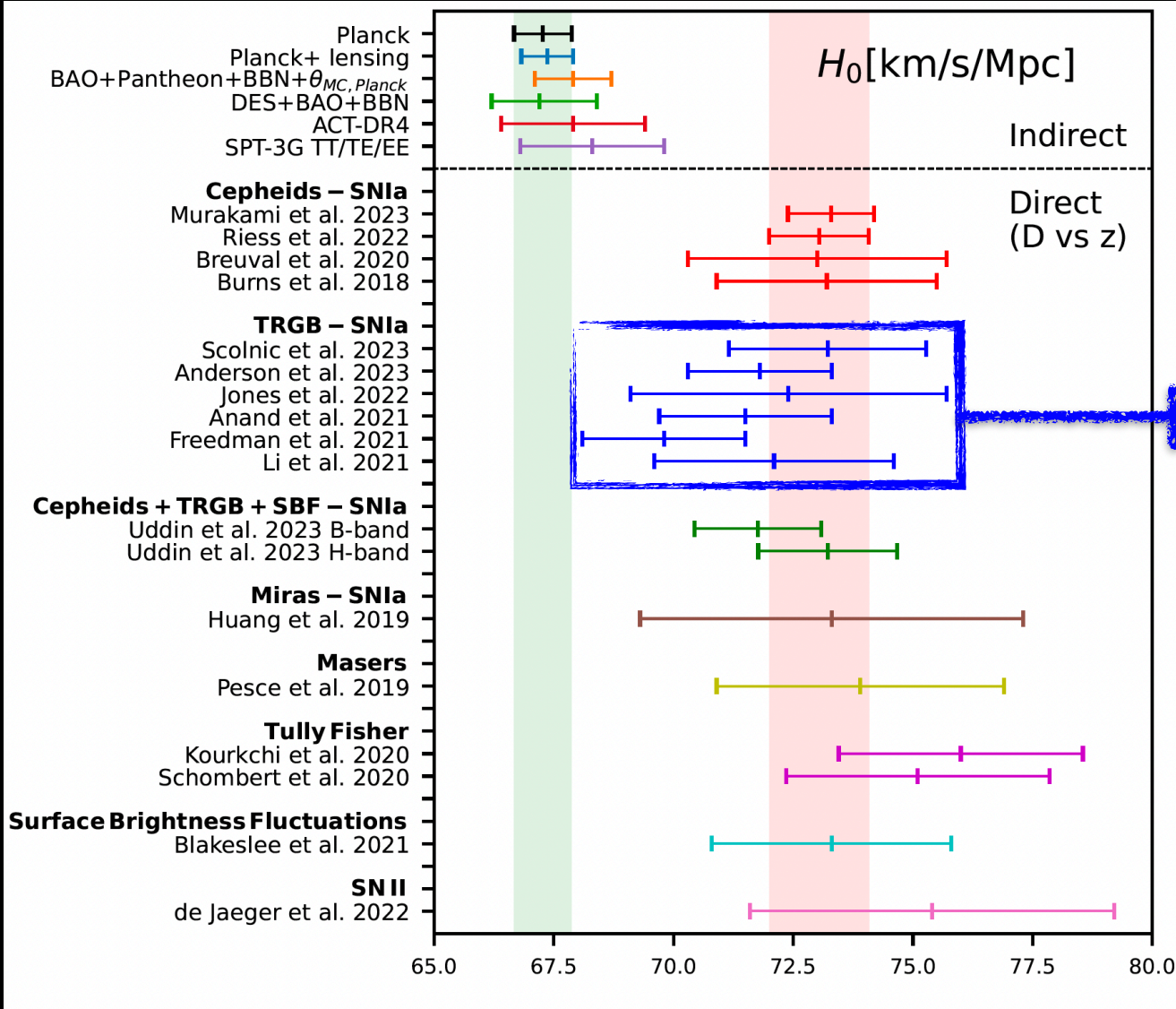
Murakami et al., arXiv:2306.00070

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

Riess et al., arXiv:2112.04510

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

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.

$$H_0 = 73.22 \pm 2.06 \text{ km/s/Mpc}$$

Scolnic et al., arXiv:2304.06693

$$H_0 = 71.8 \pm 1.5 \text{ km/s/Mpc}$$

Anderson et al., arXiv:2303.04790

$$H_0 = 72.4 \pm 3.3 \text{ km/s/Mpc}$$

Jones et al., arXiv:2201.07801

$$H_0 = 71.5 \pm 1.8 \text{ km/s/Mpc}$$

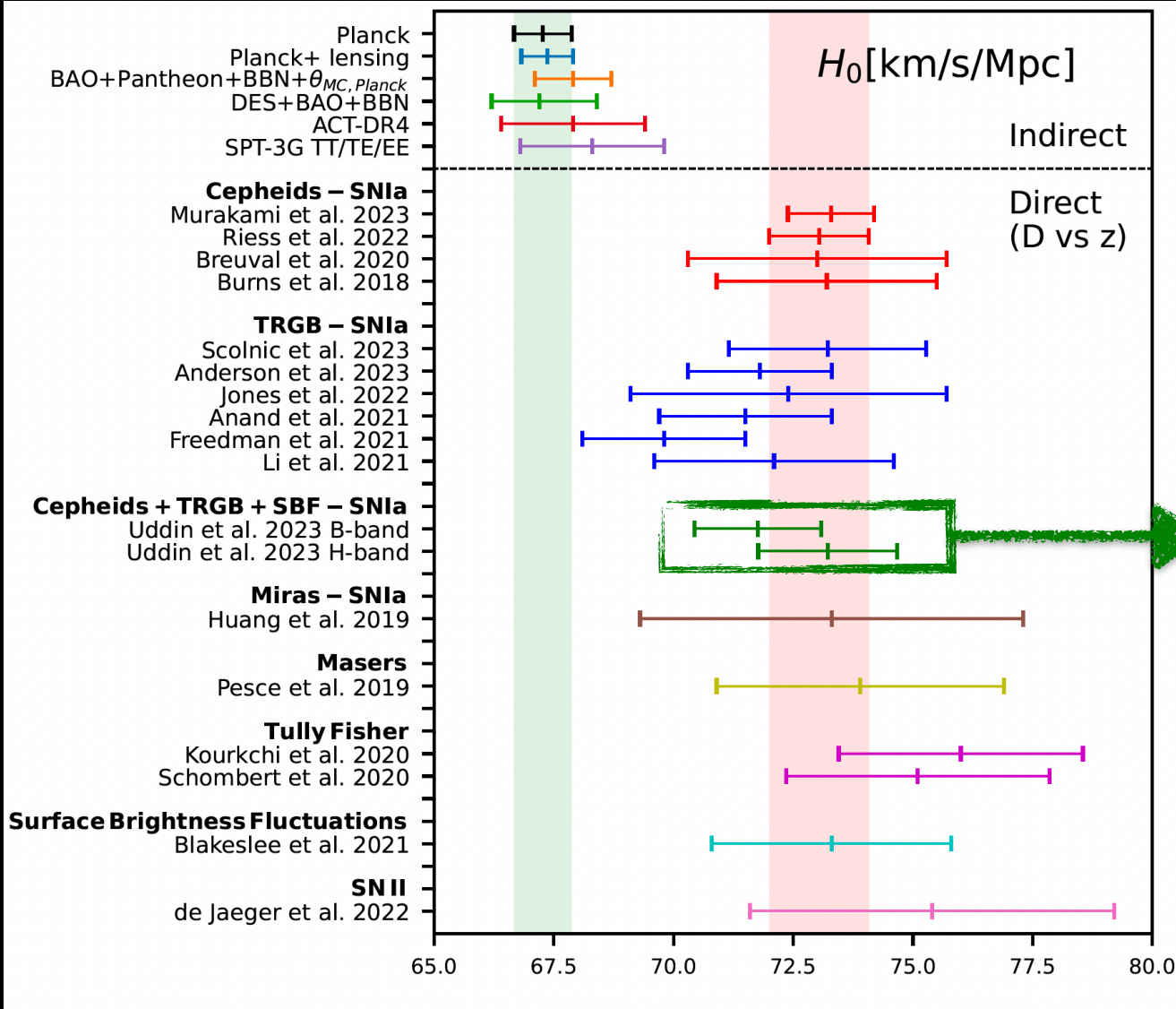
Anand et al., arXiv:2108.00007

$$H_0 = 69.8 \pm 1.7 \text{ km/s/Mpc}$$

Freedman, arXiv:2106.15656

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

Latest H0 measurements



Carnegie Supernova Project:
 Measurements of H0 using
 Cepheids, TRGB, and SBF
 Distance Calibration
 to Type Ia Supernovae

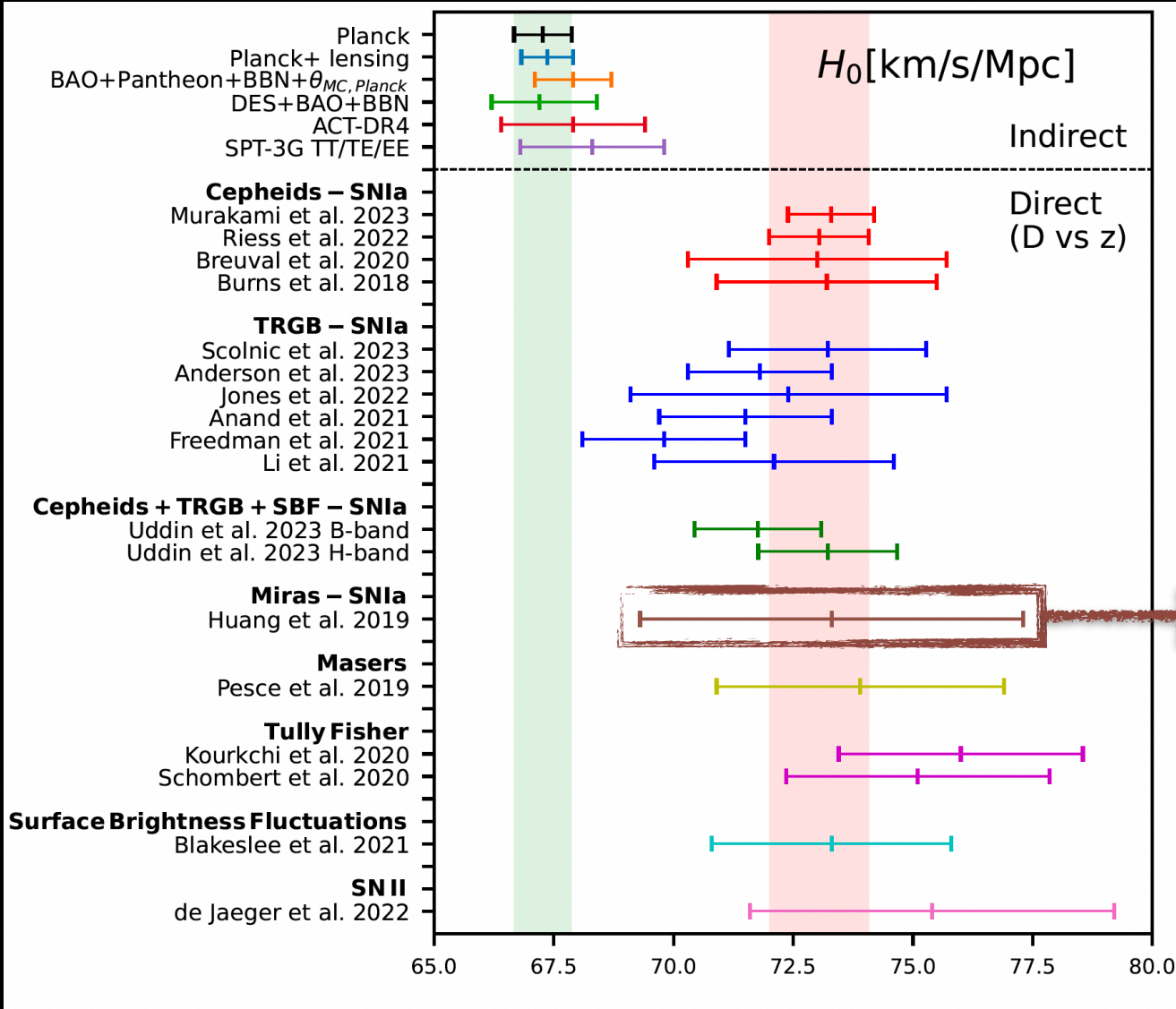
$$H_0 = 71.76 \pm 1.32 \text{ km/s/Mpc}$$

$$H_0 = 73.22 \pm 1.45 \text{ km/s/Mpc}$$

Uddin et al., arXiv:2308.01875 [astro-ph.CO]

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

Latest H0 measurements

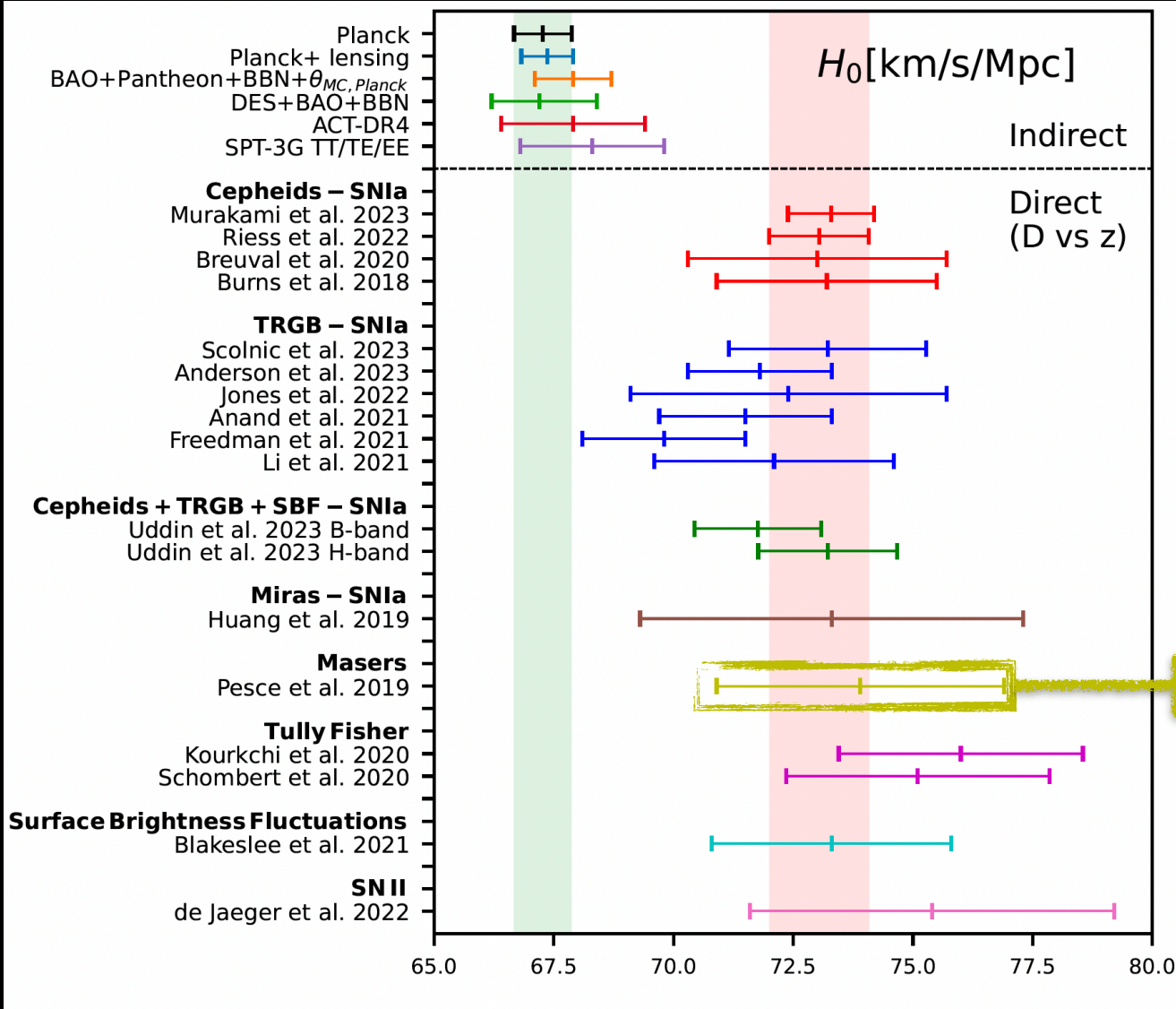


MIRAS
variable red giant stars from
older stellar populations

$H_0 = 73.3 \pm 4.0$ km/s/Mpc
Huang et al., arXiv:1908.10883 [astro-ph.CO]

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

Latest H0 measurements

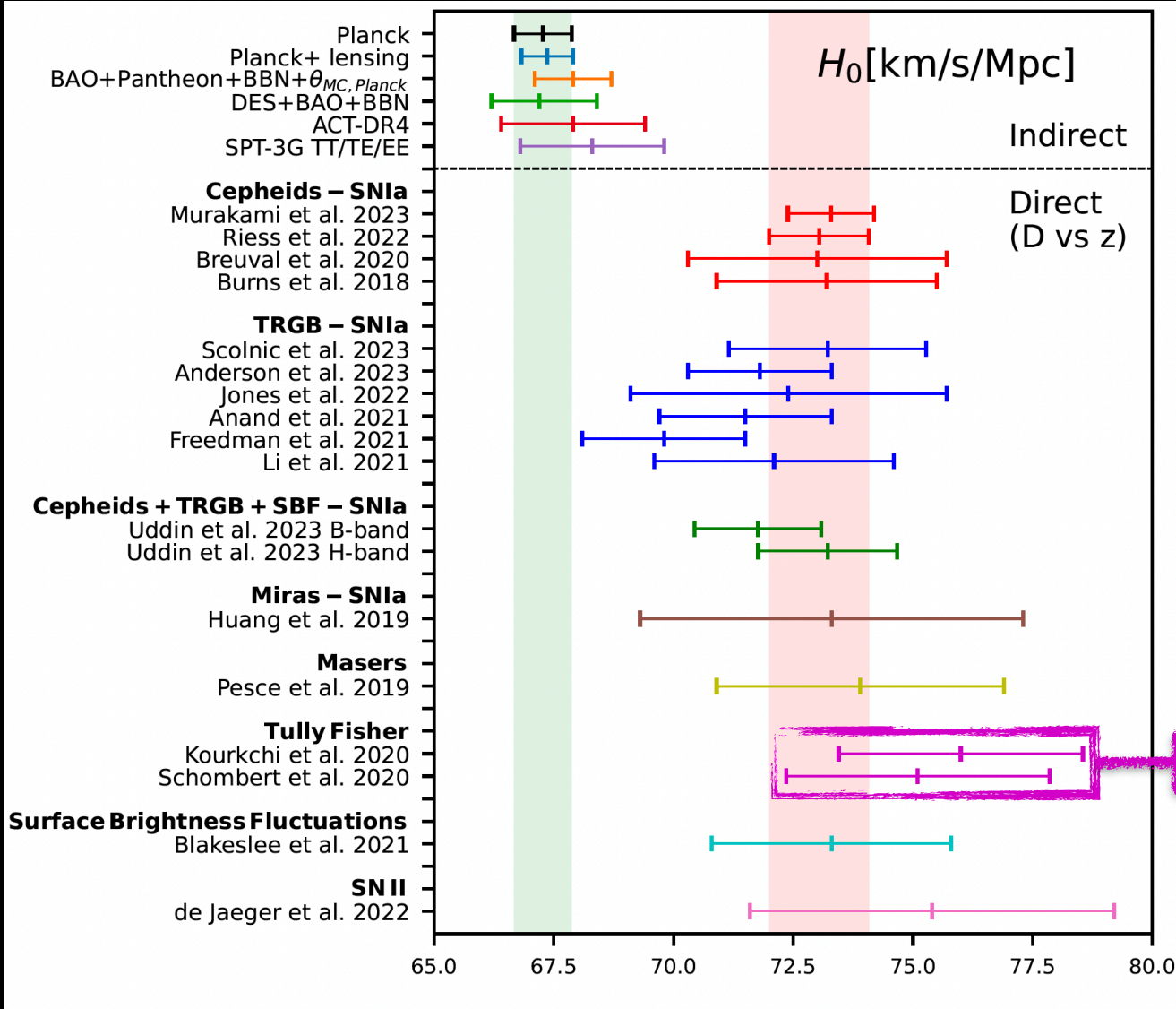


$H_0 = 73.9 \pm 3.0$ km/s/Mpc
 Pesce et al. arXiv:2001.09213

The Megamaser Cosmology Project measures H_0 using geometric distance measurements to six Megamaser - hosting galaxies. This approach avoids any distance ladder by providing geometric distance directly into the Hubble flow.

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

Latest H0 measurements



$$H_0 = 76.00 \pm 2.55 \text{ km/s/Mpc}$$

Kourkchi et al. [arXiv:2004.14499](https://arxiv.org/abs/2004.14499)

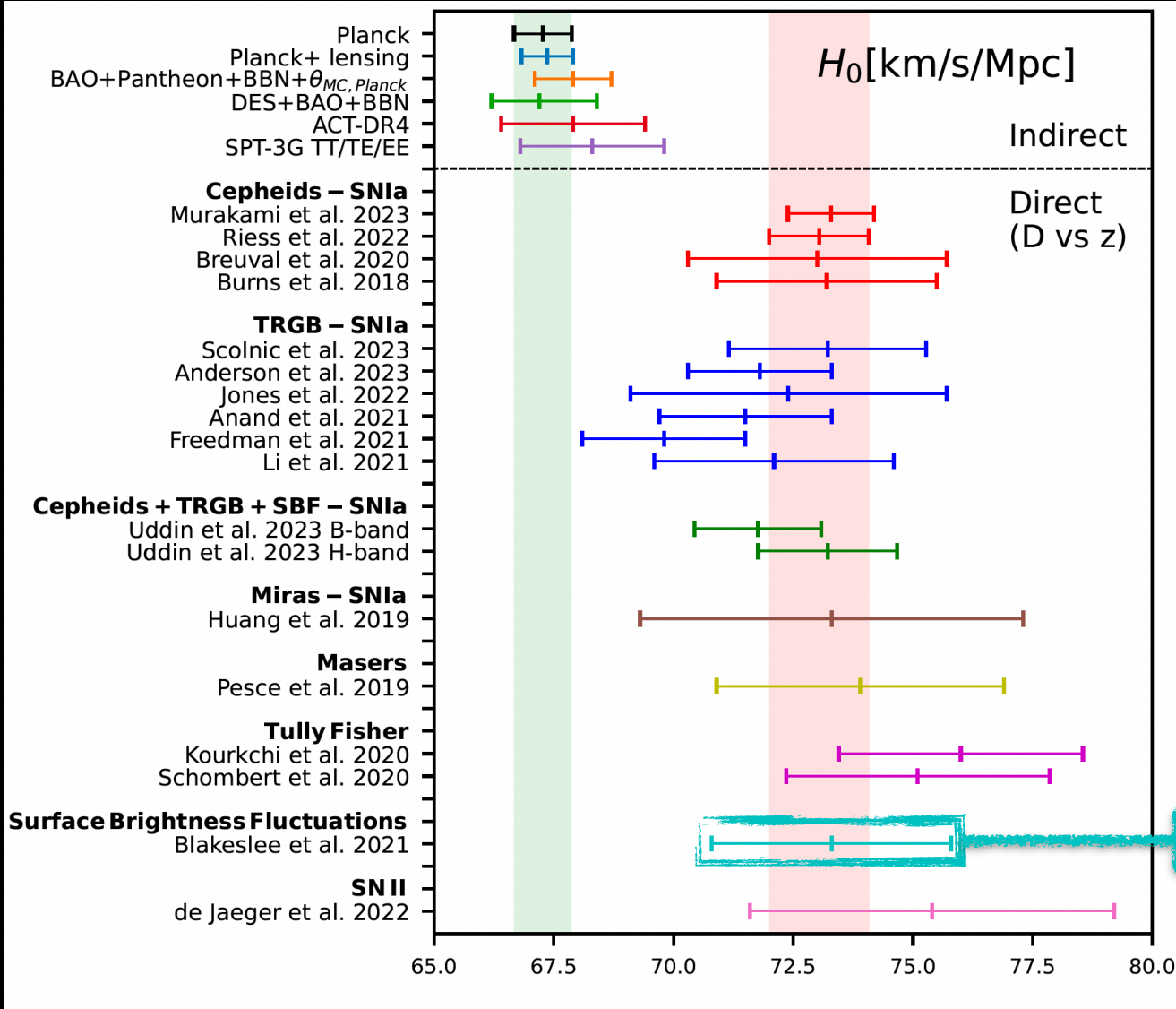
$$H_0 = 75.10 \pm 2.75 \text{ km/s/Mpc}$$

Schombert et al. [arXiv:2006.08615](https://arxiv.org/abs/2006.08615)

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

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

Latest H0 measurements



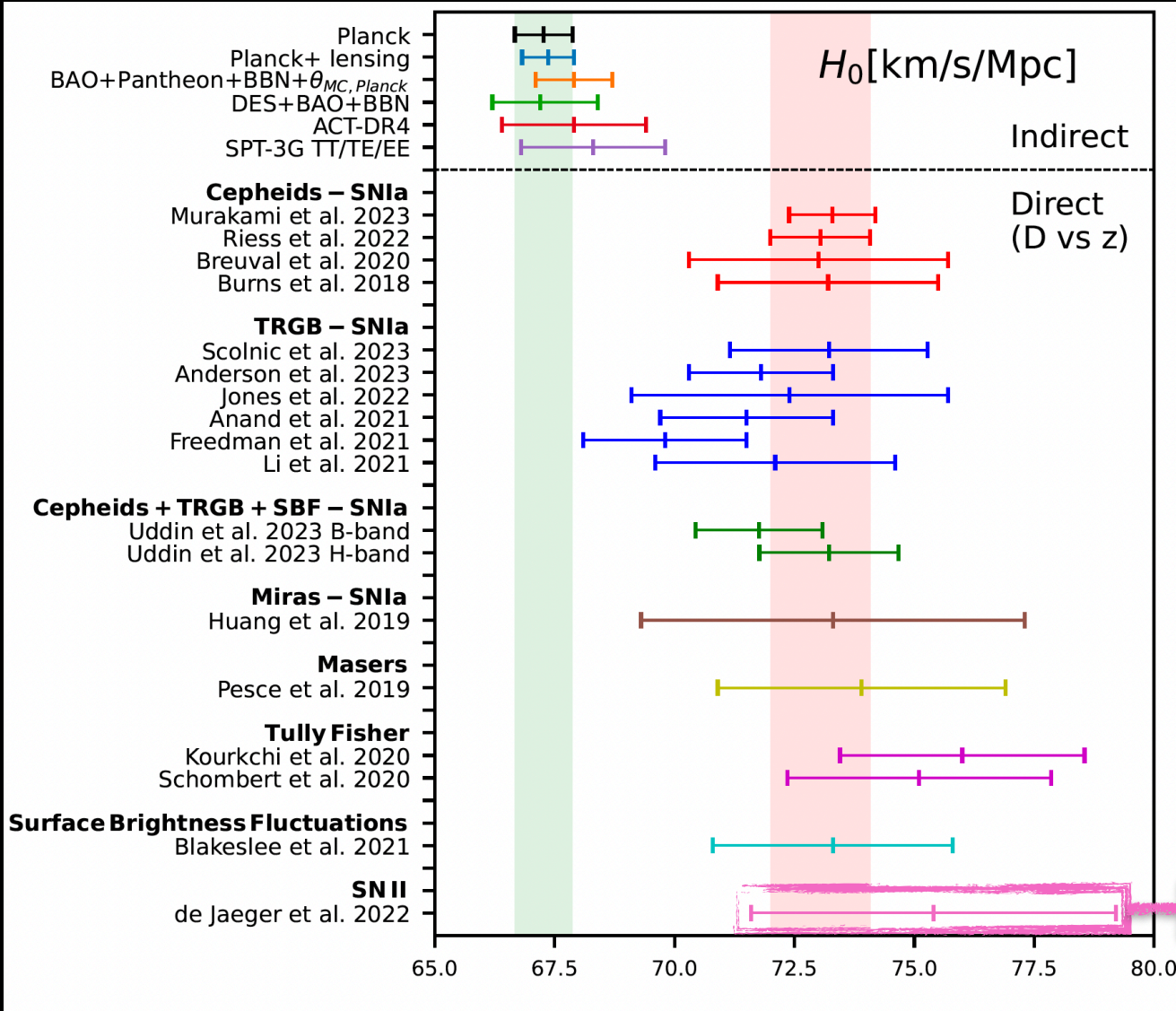
$H_0 = 73.3 \pm 2.5$ km/s/Mpc

Blakeslee et al., arXiv:2101.02221

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

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

Latest H0 measurements

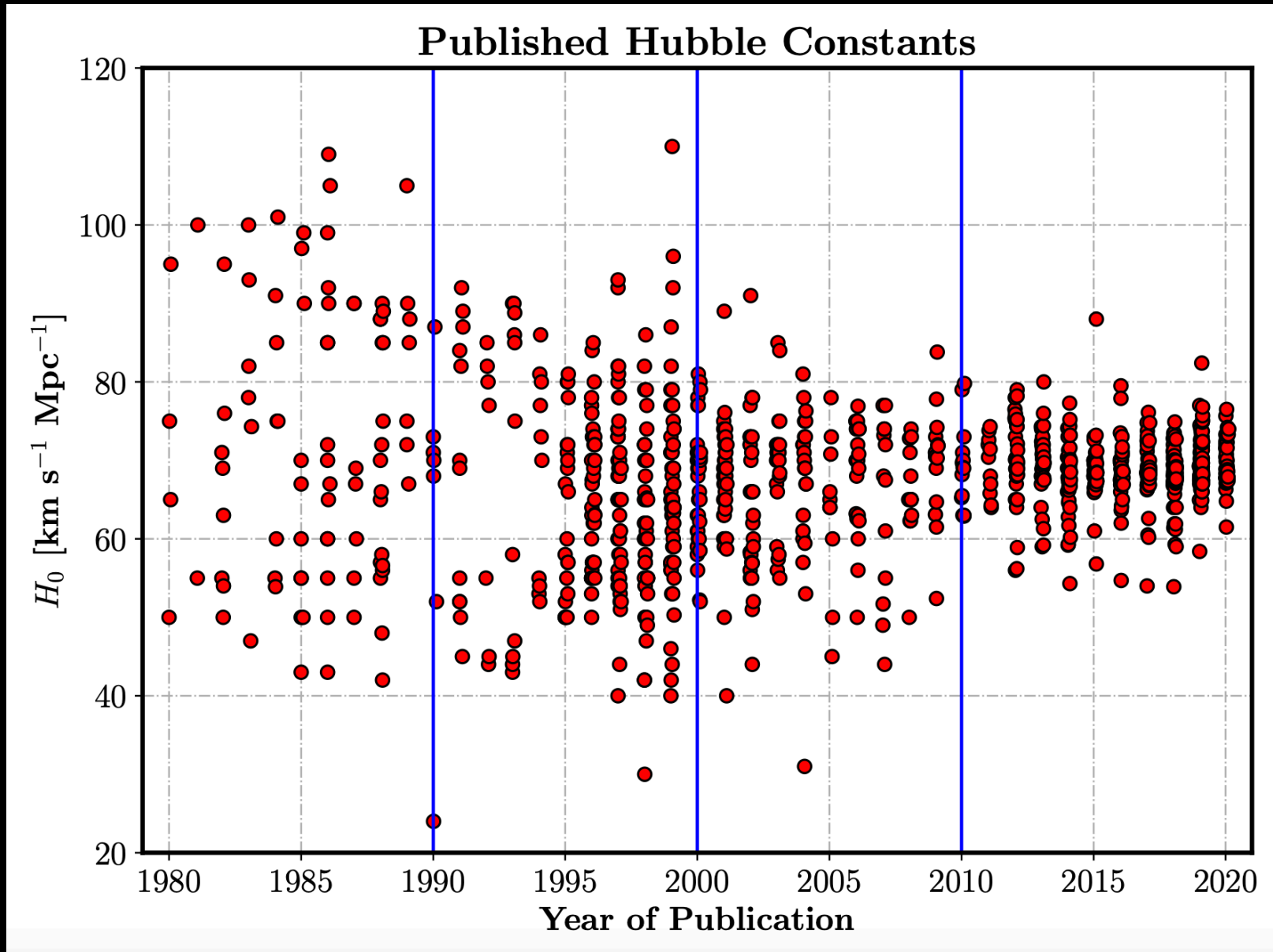


$$H_0 = 75.4^{+3.8}_{-3.7} \text{ km/s/Mpc}$$

de Jaeger et al., arXiv:2203.08974

Type II supernovae
used as standardisable
candles and calibrated by
both Cepheids and TRGB

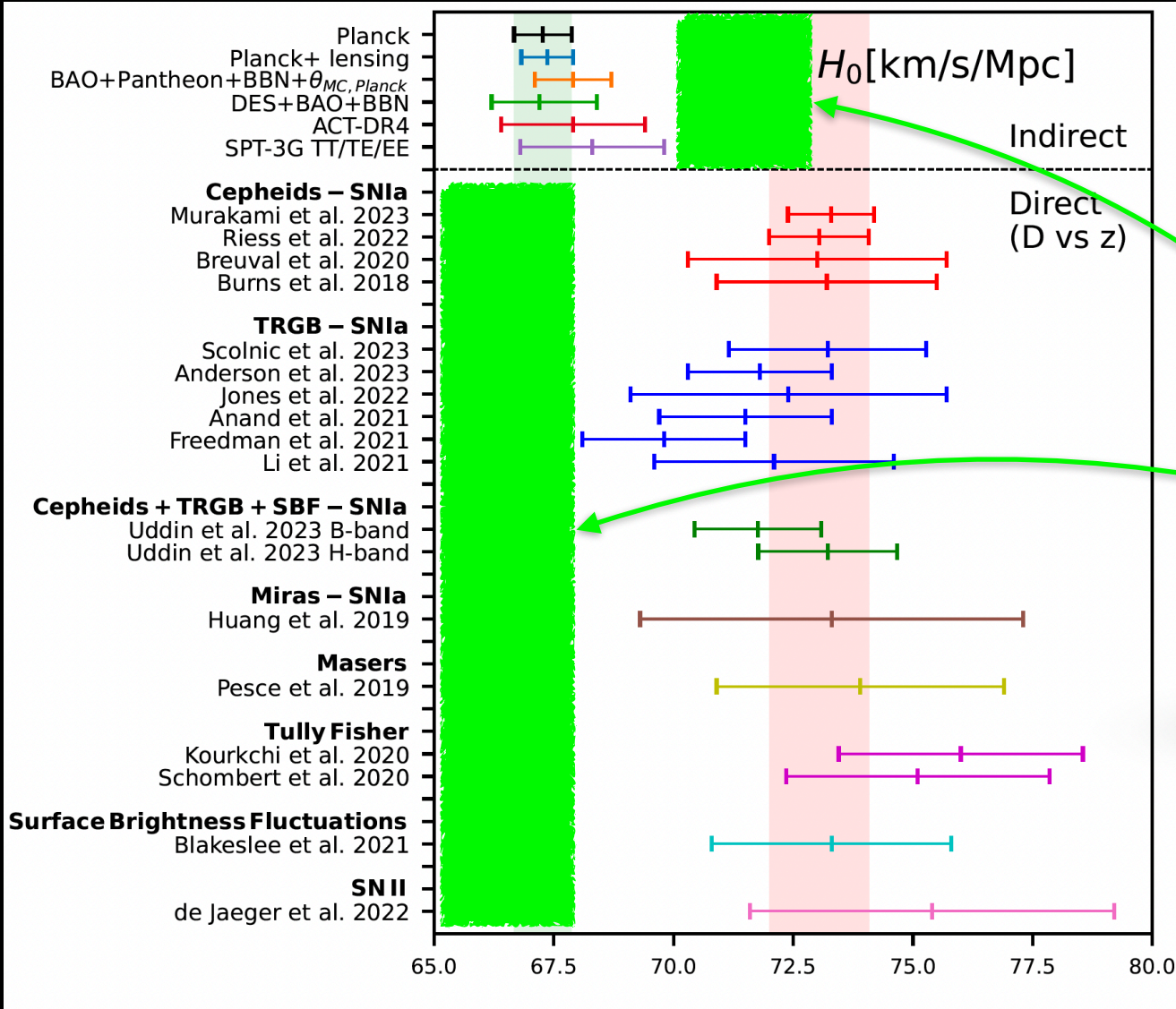
Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073



Freedman, *Astrophys.J.* 919 (2021) 1, 16

In the past the tension was within the same types of measurements and at the same redshifts and thus pointing directly to systematics.

Latest H0 measurements



There are no late universe measurements below the early ones and vice versa.

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

It is difficult to imagine a single systematic error that would consistently explain the discrepancies observed in the diverse range of phenomena that we have encountered earlier, thereby resolving the Hubble constant tension.

Since this tension persists in the $5 - 6.3\sigma$ range

(Riess, *Nature Reviews Physics* (2019); Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073; Di Valentino, *Universe* 2022, 8(8), 399)

even after eliminating the measurements of any individual type of object, team, or calibration,

it is challenging to identify a single error that could account for it.

While multiple independent systematic errors could offer more flexibility in resolving the tension, they are less likely to occur.

Given that the indirect constraints are model-dependent, we can explore the possibility of **expanding the cosmological scenario** and examining which extensions can resolve the discrepancies between the various cosmological probes.

Let's modify the Λ CDM model with a few examples...

(Di Valentino et al. *Class.Quant.Grav.* 38 (2021) 15, 153001 and Abdalla et al., *JHEAp* 34 (2022) 49-211)

The Neutrino effective number

We can consider modifications in the
dark matter sector.

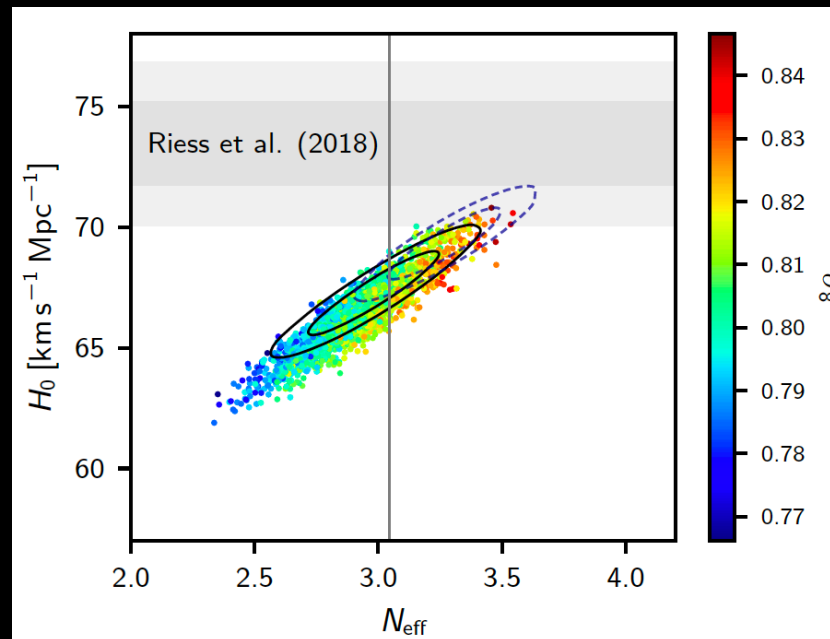
A classical extension is the
effective number of relativistic degrees of freedom,
i.e. additional relativistic matter at recombination,
corresponding to a modification of the expansion history
of the universe at early times.

The Neutrino effective number

The expected value is $N_{\text{eff}} = 3.044$, if we assume standard electroweak interactions and three active massless neutrinos. If we measure a $N_{\text{eff}} > 3.044$, we are in presence of extra radiation.

If we vary N_{eff} , at 68% cl H_0 is equal to $66.4 \pm 1.4 \text{ km/s/Mpc}$, and the tension with SH0ES is still 3.9σ .

$$N_{\text{eff}} = 2.92_{-0.37}^{+0.36} \quad (95\%, \text{Planck TT,TE,EE+lowE}),$$



The Dark energy equation of state

For example, we can consider modifications in the
dark energy sector.

A classical extension is a varying
dark energy equation of state,
that is a modification of the expansion history of the
universe at late times.

The Dark energy equation of state

If we change the cosmological constant with a Dark Energy with equation of state w , we are changing the expansion rate of the Universe:

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

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

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 in 2018 $w = -1.58^{+0.52}_{-0.41}$ with $H_0 > 69.9$ km/s/Mpc at 95% c.l.

Planck data prefer a **phantom dark energy**, with an energy component with $w < -1$, for which the density increases with time in an expanding universe that will **end in a Big Rip**. A phantom dark energy violates the energy condition $\rho \geq |\rho|$, that means that the matter could move faster than light and a comoving observer measure a negative energy density, and the Hamiltonian could have vacuum instabilities due to a negative kinetic energy.

Formally successful models in solving H_0

tension $\leq 1\sigma$ “Excellent models”	tension $\leq 2\sigma$ “Good models”	tension $\leq 3\sigma$ “Promising models”
Dark energy in extended parameter spaces [289] Dynamical Dark Energy [309] Metastable Dark Energy [314] PEDE [392, 394] Elaborated Vacuum Metamorphosis [400–402] IDE [314, 636, 637, 639, 652, 657, 661–663] Self-interacting sterile neutrinos [711] Generalized Chaplygin gas model [744] Galileon gravity [876, 882] Power Law Inflation [966] $f(\mathcal{T})$ [818]	Early Dark Energy [235] Phantom Dark Energy [11] Dynamical Dark Energy [11, 281, 309] GEDE [397] Vacuum Metamorphosis [402] IDE [314, 653, 656, 661, 663, 670] Critically Emergent Dark Energy [997] $f(\mathcal{T})$ gravity [814] Über-gravity [59] Reconstructed PPS [978]	Early Dark Energy [229] Decaying Warm DM [474] Neutrino-DM Interaction [506] Interacting dark radiation [517] Self-Interacting Neutrinos [700, 701] IDE [656] Unified Cosmologies [747] Scalar-tensor gravity [856] Modified recombination [986] Super Λ CDM [1007] Coupled Dark Energy [650]

Table B1. Models solving the H_0 tension with R20 within the 1σ , 2σ and 3σ confidence levels considering the *Planck* dataset only.

Di Valentino et al., *Class.Quant.Grav.* (2021), arXiv:2103.01183 [astro-ph.CO]

Planck only

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., arXiv: 2307.14802

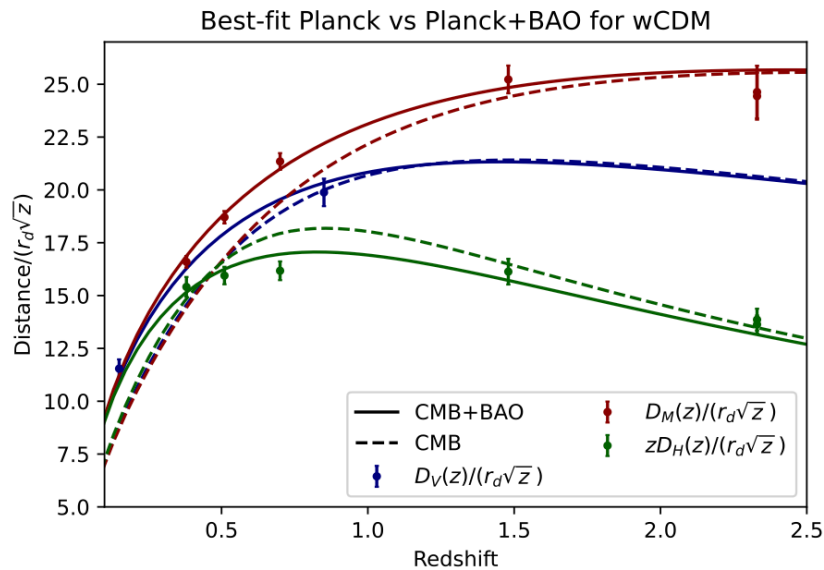


FIG. 5. Best-fit predictions for (rescaled) distance-redshift relations from a w CDM fit to *Planck* CMB data alone (dashed curves) and the CMB+BAO dataset (solid curves). These predictions are presented for the three different types of distances probed by BAO measurements (rescaled as per the y label),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

However, if BAO data are included, the w CDM 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 Λ CDM one and the H_0 tension is restored.

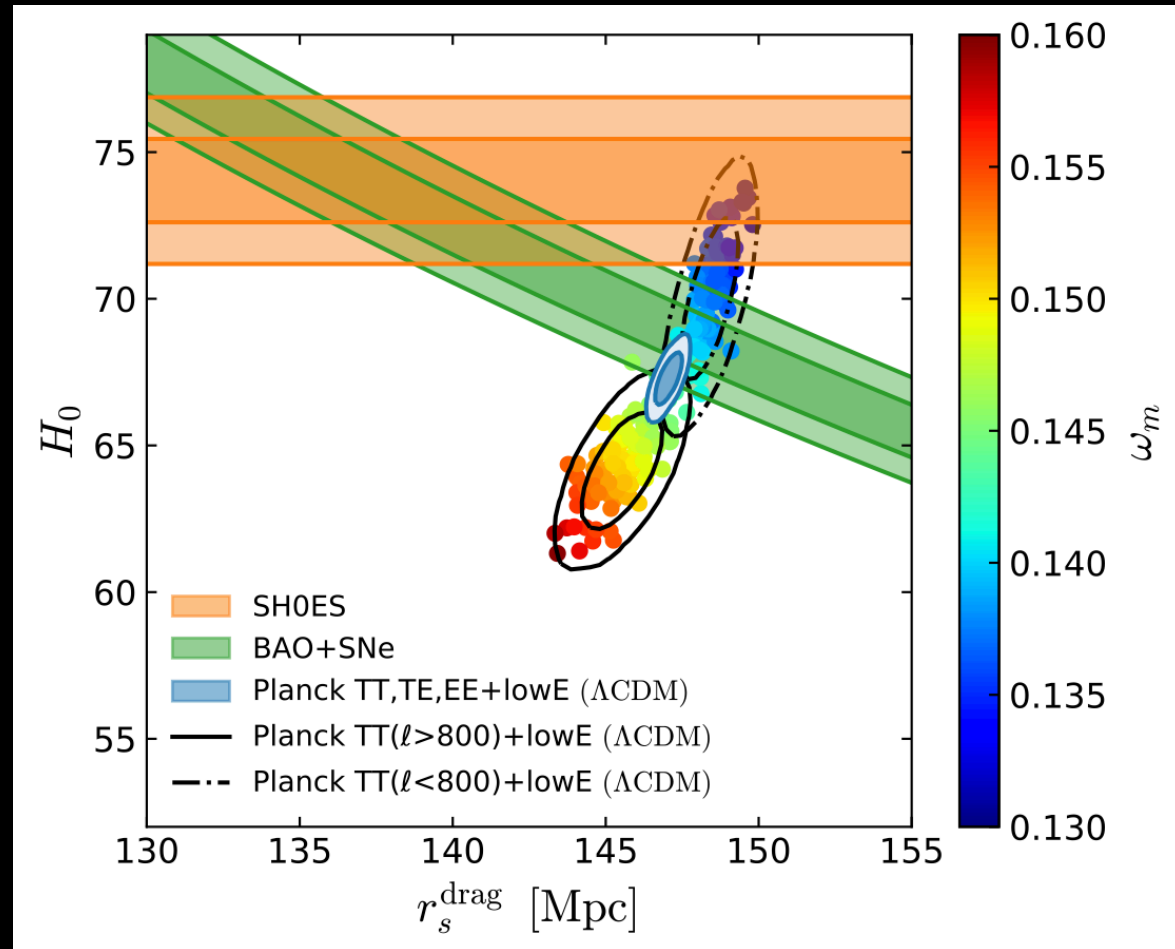
Complication: the sound horizon problem

What about BAO+Pantheon?

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 Λ 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.

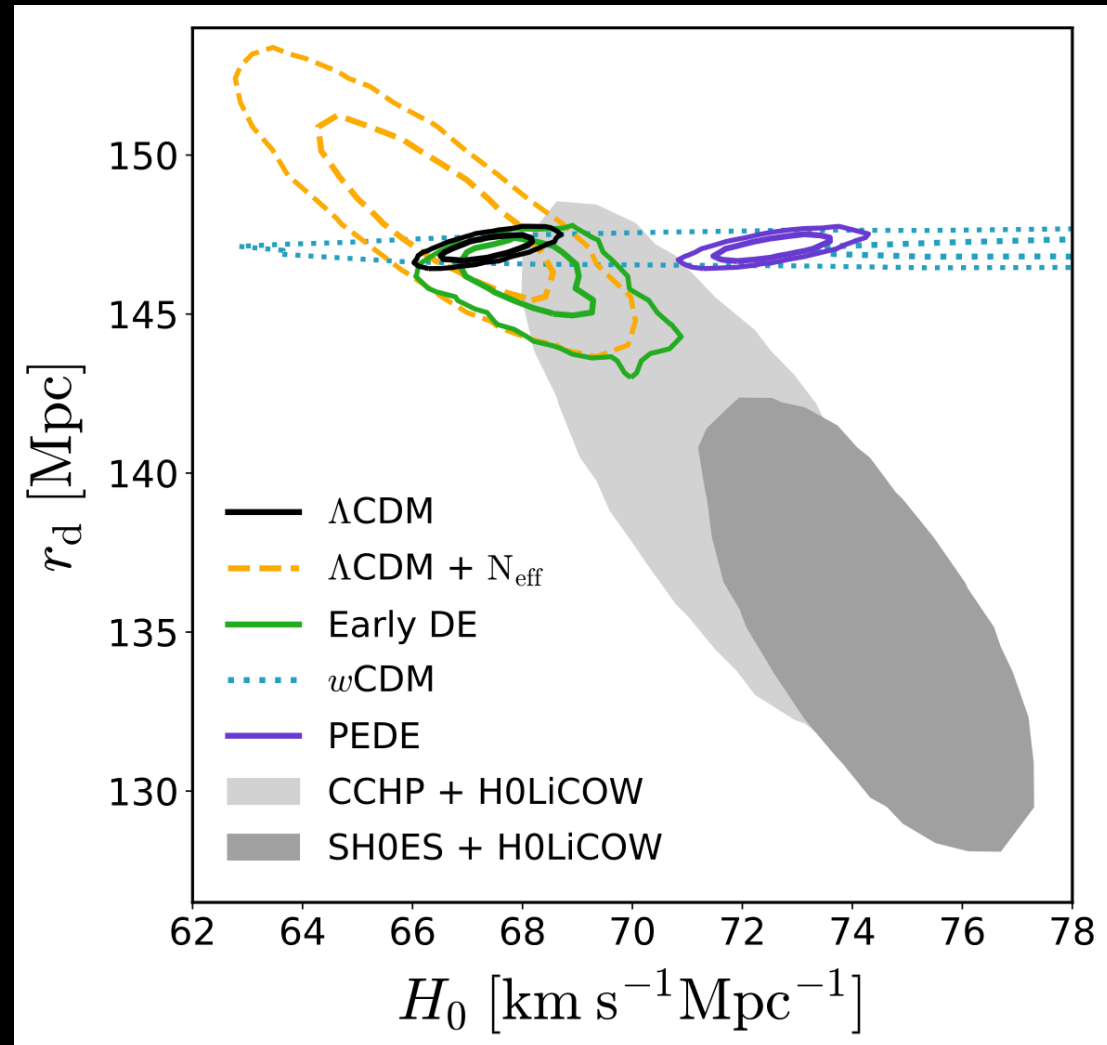


Knox and Millea, *Phys.Rev.D* 101 (2020) 4, 043533

Early vs late time solutions

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

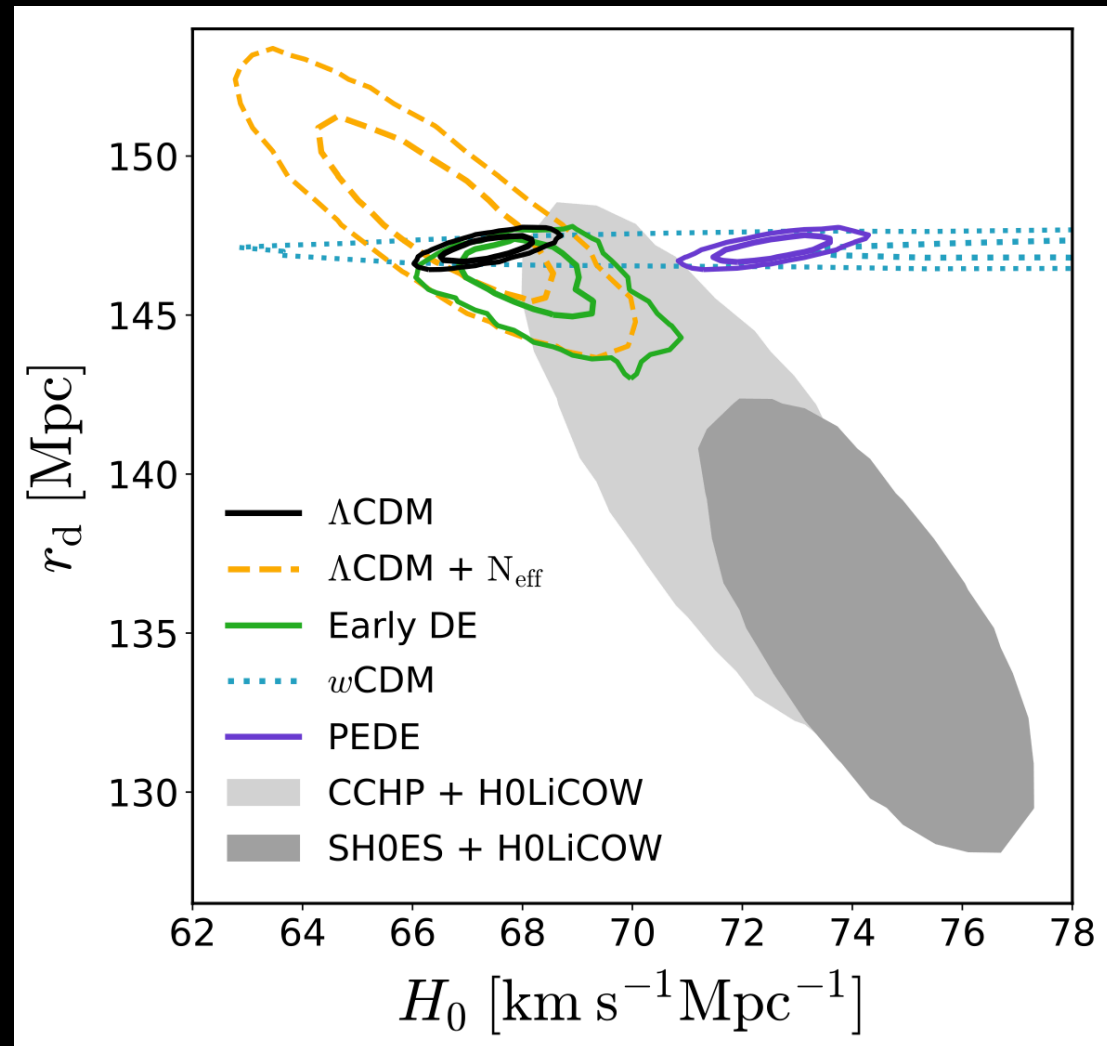
We see that the late time solutions, as w CDM, increase H_0 because they decrease the expansion history at intermediate redshift, but leave r_s unaltered.



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 N_{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.**



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 $H \sim T^2/M_{\text{pl}} \approx m$ just before the recombination, so **the mass of the scalar field should be $m \approx 10^{-27}$ eV,**

similar to an axion particle:

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

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 $n \rightarrow \infty$ like kinetic energy ($\propto a^{-6}$). However, values $n > 5$ are disfavored.

Early Dark Energy

Constraints at 68% cl.

Constraints from <i>Planck</i> 2018 data only: TT+TE+EE		
Parameter	Λ CDM	EDE ($n = 3$)
$\ln(10^{10} A_s)$	3.044 (3.055) \pm 0.016	3.051 (3.056) \pm 0.017
n_s	0.9645 (0.9659) \pm 0.0043	0.9702 (0.9769) ^{+0.0071} _{-0.0069}
$100\theta_s$	1.04185 (1.04200) \pm 0.00029	1.04164 (1.04168) \pm 0.00034
$\Omega_b h^2$	0.02235 (0.02244) \pm 0.00015	0.02250 (0.02250) \pm 0.00020
$\Omega_c h^2$	0.1202 (0.1201) \pm 0.0013	0.1234 (0.1268) ^{+0.0031} _{-0.0030}
τ_{reio}	0.0541 (0.0587) \pm 0.0076	0.0549 (0.0539) \pm 0.0078
$\log_{10}(z_c)$	—	3.66 (3.75) ^{+0.28} _{-0.24}
f_{EDE}	—	< 0.087 (0.068)
θ_i	—	> 0.36 (2.96)
H_0 [km/s/Mpc]	67.29 (67.44) \pm 0.59	68.29 (69.13) ^{+1.02} _{-1.00}
Ω_m	0.3162 (0.3147) \pm 0.0083	0.3145 (0.3138) \pm 0.0086
σ_8	0.8114 (0.8156) \pm 0.0073	0.8198 (0.8280) ^{+0.0109} _{-0.0107}
S_8	0.8331 (0.8355) \pm 0.0159	0.8393 (0.8468) \pm 0.0173
$\log_{10}(f/\text{eV})$	—	26.57 (26.36) ^{+0.39} _{-0.36}
$\log_{10}(m/\text{eV})$	—	-26.94 (-26.90) ^{+0.58} _{-0.53}

Hill et al. *Phys.Rev.D* 102 (2020) 4, 043507

Planck 2018 results shows no evidence for EDE and H_0 is in agreement with the value obtained assuming Λ CDM.

Formally successful models in solving H_0

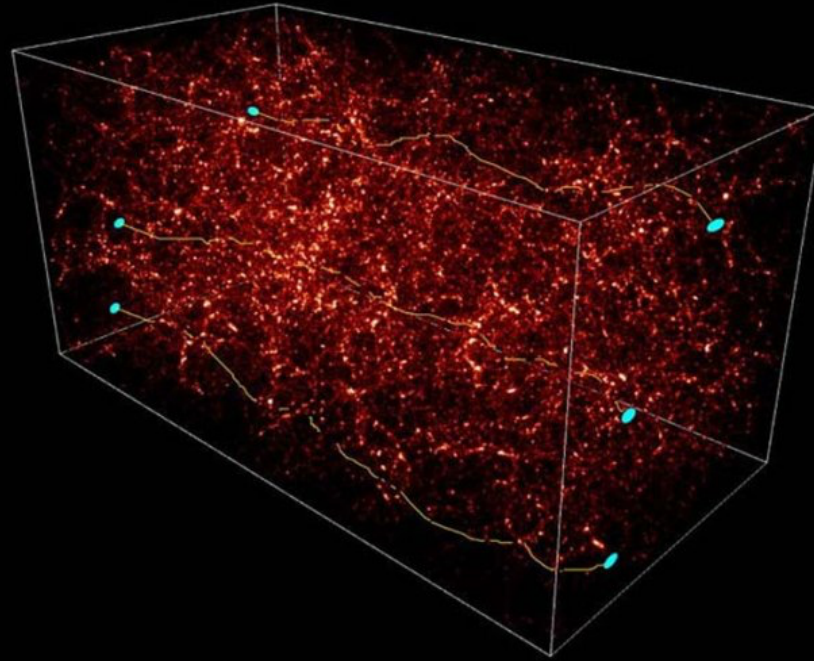
tension $\leq 1\sigma$ “Excellent models”	tension $\leq 2\sigma$ “Good models”	tension $\leq 3\sigma$ “Promising models”
Early Dark Energy [228, 235, 240, 250] Exponential Acoustic Dark Energy [259] Phantom Crossing [315] Late Dark Energy Transition [317] Metastable Dark Energy [314] PEDE [394] Vacuum Metamorphosis [402] Elaborated Vacuum Metamorphosis [401, 402] Sterile Neutrinos [433] Decaying Dark Matter [481] Neutrino-Majoron Interactions [509] IDE [637, 639, 657, 661] DM - Photon Coupling [685] $f(\mathcal{T})$ gravity theory [812] BD- Λ CDM [851] Über-Gravity [59] Galileon Gravity [875] Unimodular Gravity [890] Time Varying Electron Mass [990] Λ CDM [995] Ginzburg-Landau theory [996] Lorentzian Quintessential Inflation [979] Holographic Dark Energy [351]	Early Dark Energy [212, 229, 236, 263] Rock ‘n’ Roll [242] New Early Dark Energy [247] Acoustic Dark Energy [257] Dynamical Dark Energy [309] Running vacuum model [332] Bulk viscous models [340, 341] Holographic Dark Energy [350] Phantom Braneworld DE [378] PEDE [391, 392] Elaborated Vacuum Metamorphosis [401] IDE [659, 670] Interacting Dark Radiation [517] Decaying Dark Matter [471, 474] DM - Photon Coupling [686] Self-interacting sterile neutrinos [711] $f(\mathcal{T})$ gravity theory [817] Über-Gravity [871] VCDM [893] Primordial magnetic fields [992] Early modified gravity [859] Bianchi type I spacetime [999] $f(\mathcal{T})$ [818]	DE in extended parameter spaces [289] Dynamical Dark Energy [281, 309] Holographic Dark Energy [350] Swampland Conjectures [370] MEDE [399] Coupled DM - Dark radiation [534] Decaying Ultralight Scalar [538] BD- Λ CDM [852] Metastable Dark Energy [314] Self-Interacting Neutrinos [700] Dark Neutrino Interactions [716] IDE [634–636, 653, 656, 663, 669] Scalar-tensor gravity [855, 856] Galileon gravity [877, 881] Nonlocal gravity [886] Modified recombination [986] Effective Electron Rest Mass [989] Super Λ CDM [1007] Axi-Higgs [991] Self-Interacting Dark Matter [479] Primordial Black Holes [545]

Table B2. Models solving the H_0 tension with R20 within 1σ , 2σ and 3σ using $Planck$ in combination with additional cosmological probes. Details of the datasets are discussed in the main text.

Combination of datasets

Additional complication:
the early solutions proposed to
alleviate the H_0 tension increase
the S8 tension!

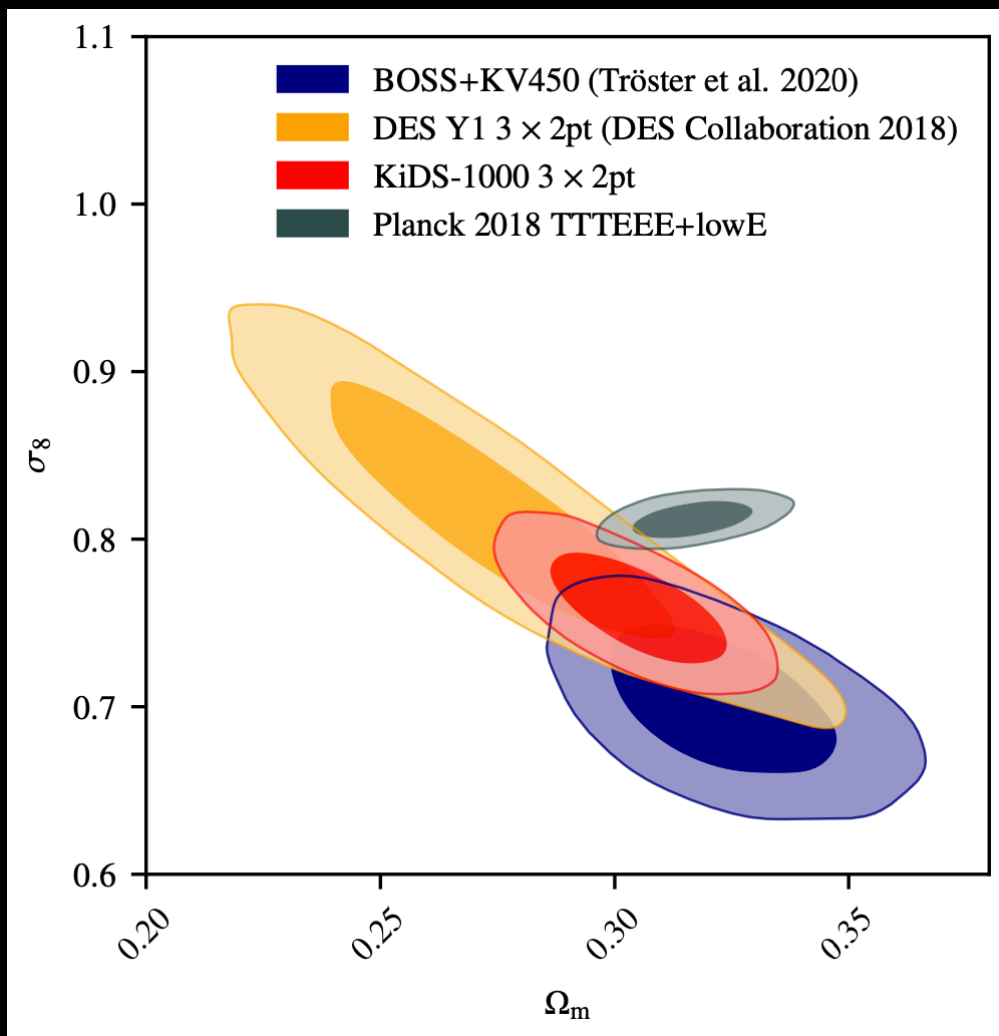
The S8 tension



$$S_8 \equiv \sigma_8 \sqrt{\Omega_m / 0.3}$$

A tension on **S8** is present between the Planck data in the Λ CDM scenario and the cosmic shear data.

The S8 tension



The S8 tension is present at 3.4σ between Planck assuming Λ CDM and KiDS+VIKING-450 and BOSS combined together, or 3.1σ with KiDS-1000.

$$S_8 = 0.834 \pm 0.016$$

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

$$S_8 = 0.728 \pm 0.045$$

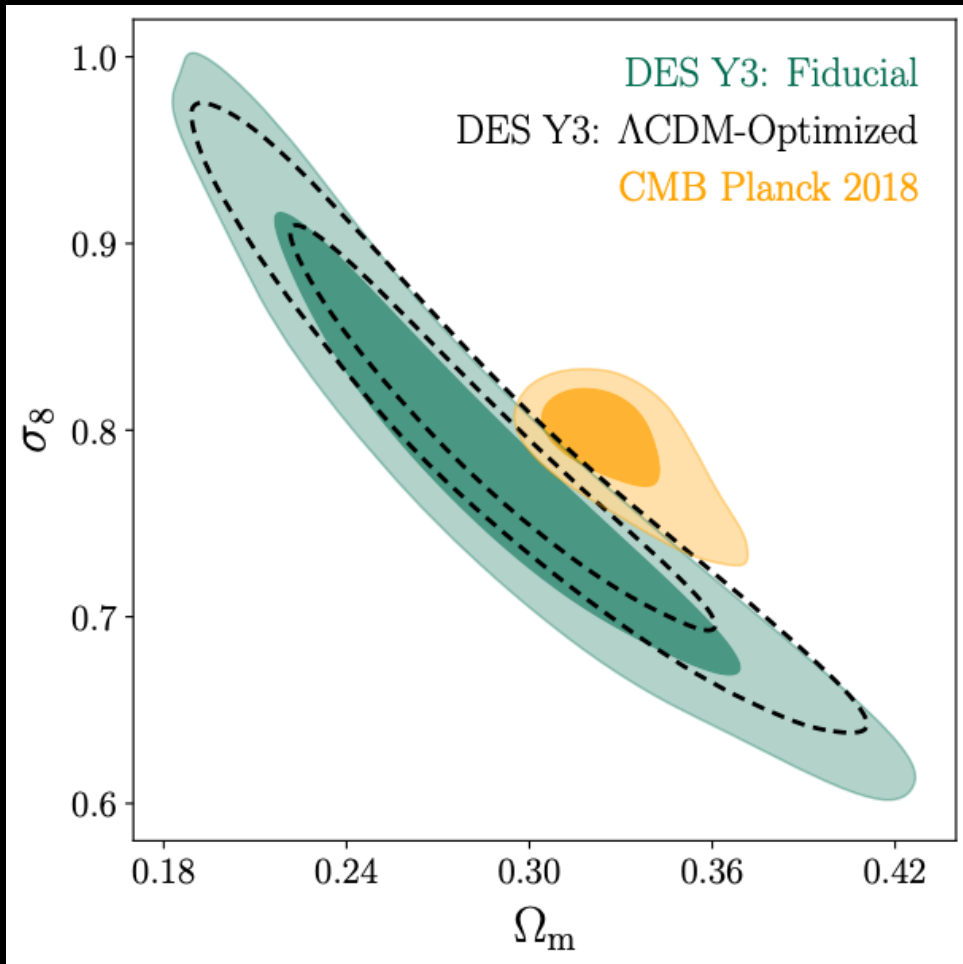
Tröster et al., arXiv:1909.11006 [astro-ph.CO]

$$S_8 = 0.766^{+0.020}_{-0.014}$$

KiDS-1000, Heymans et al., arXiv:2007.15632 [astro-ph.CO]

KiDS-1000, Heymans et al., arXiv:2007.15632 [astro-ph.CO]

The S8 tension



DES-Y3, Amon et al., arXiv:2105.13543 [astro-ph.CO]

The S8 tension is present at 2.5σ between Planck assuming Λ CDM and DES-Y3.

$$S_8 = 0.834 \pm 0.016$$

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

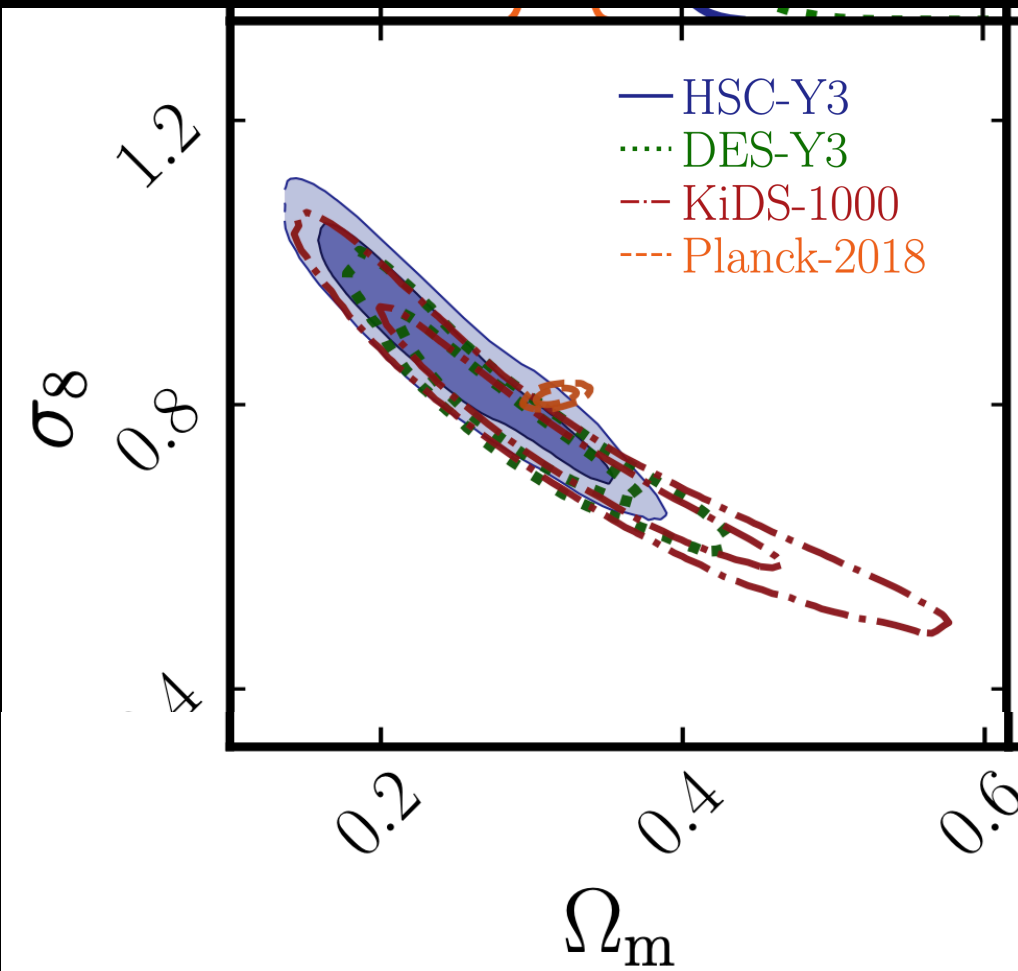
$$S_8 = 0.776^{+0.017}_{-0.017}$$

DES-Y3, Abbott et al., arXiv:2105.13549 [astro-ph.CO]

$$S_8 = 0.759^{+0.025}_{-0.025}$$

DES-Y3 fiducial, Amon et al., arXiv:2105.13543 [astro-ph.CO]

The S8 tension



HSC-Y3, Dalal et al., arXiv:2304.00701 [astro-ph.CO]

The S8 tension is present at about 2σ between Planck assuming Λ CDM and HSC-Y3.

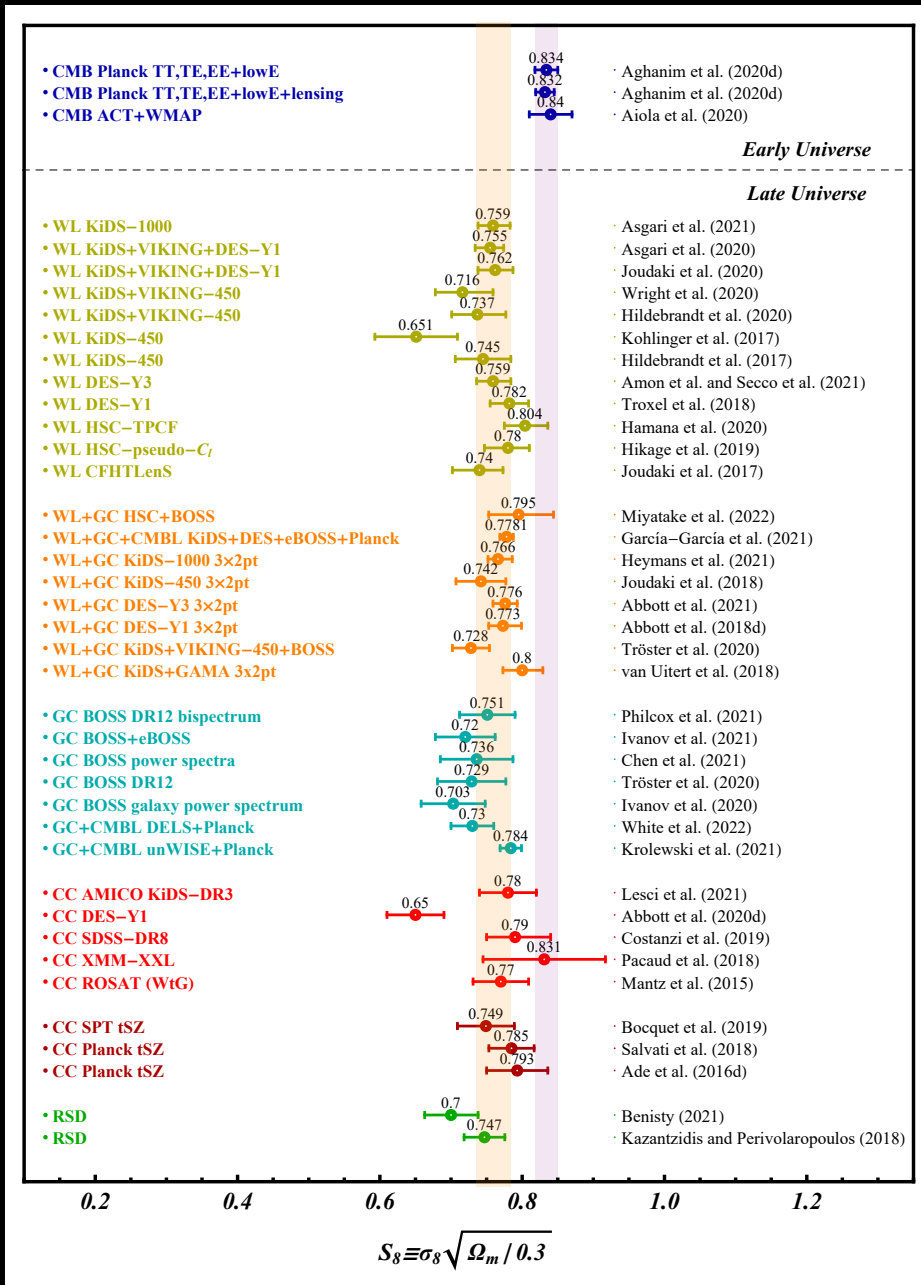
$$S_8 = 0.834 \pm 0.016$$

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

$$S_8 = 0.776^{+0.032}_{-0.033}$$

HSC-Y3, Dalal et al., arXiv:2304.00701 [astro-ph.CO]

The S8 tension

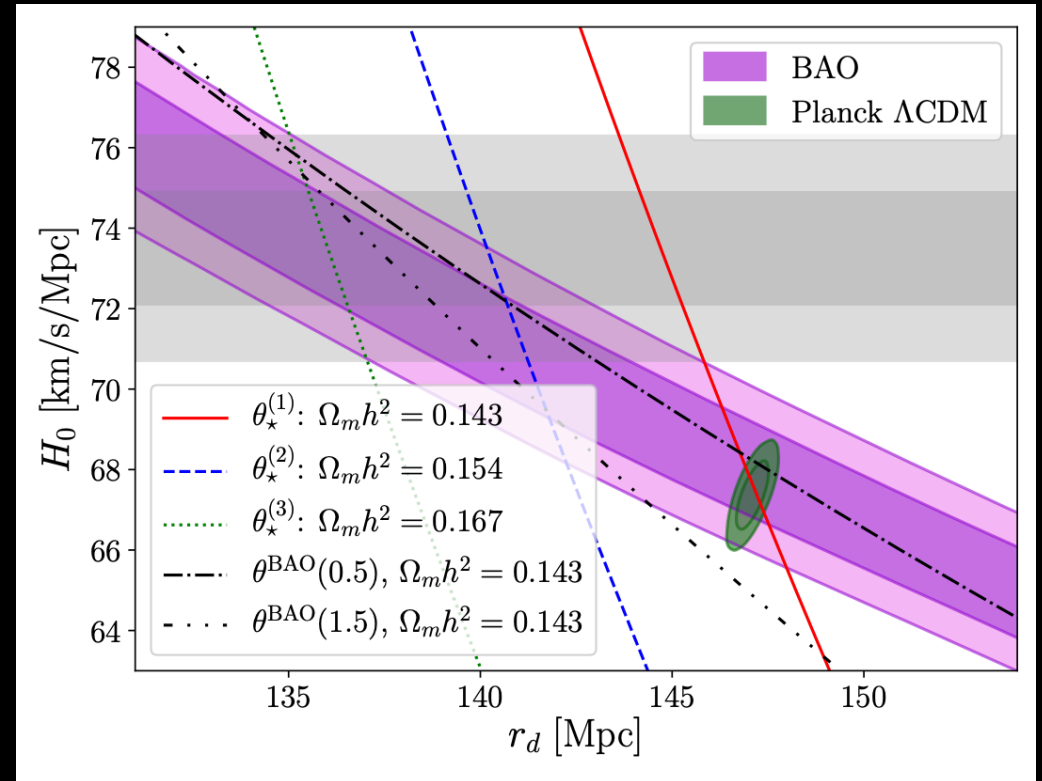


See Di Valentino et al. *Astropart.Phys.* 131 (2021) 102604 and Abdalla et al., arXiv:2203.06142 [astro-ph.CO] for a summary of the possible candidates proposed to solve the S8 tension.

Early solutions to the H0 tension

Actually, a dark energy model that merely changes the value of r_d would not completely resolve the tension, since it will affect the inferred value of Ω_m and transfer the tension to it.

This is a plot illustrating that achieving a full agreement between CMB, BAO and SH0ES through a reduction of r_d requires a higher value of $\Omega_m h^2$.



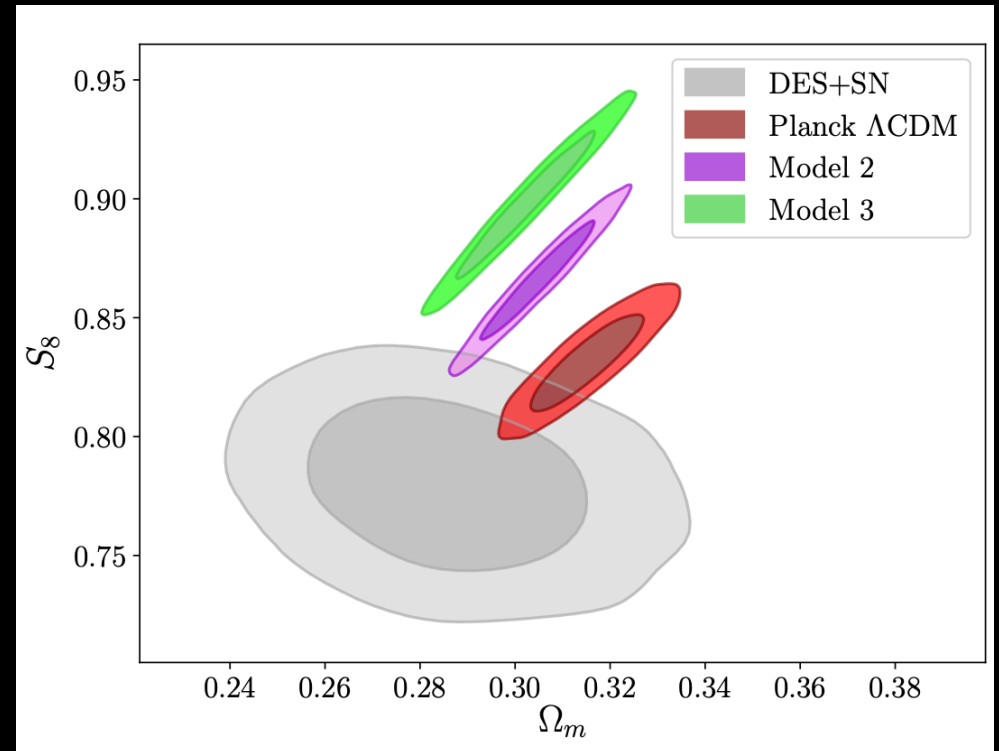
Jedamzik et al., Commun.in Phys. 4 (2021) 123

Early solutions to the H0 tension

Model 2 is defined by the simultaneous fit to BAO and CMB acoustic peaks at $\Omega_m h^2 = 0.155$, while model 3 has $\Omega_m h^2 = 0.167$

The sound horizon problem should be considered not only in the plane H_0 - r_d , but it should be extended to the parameters triplet H_0 - r_d - Ω_m .

The figure shows that when attempting to find a full resolution of the Hubble tension, with CMB, BAO and SH0ES in agreement with each other, one exacerbates the tension with DES, KiDS and HSC.

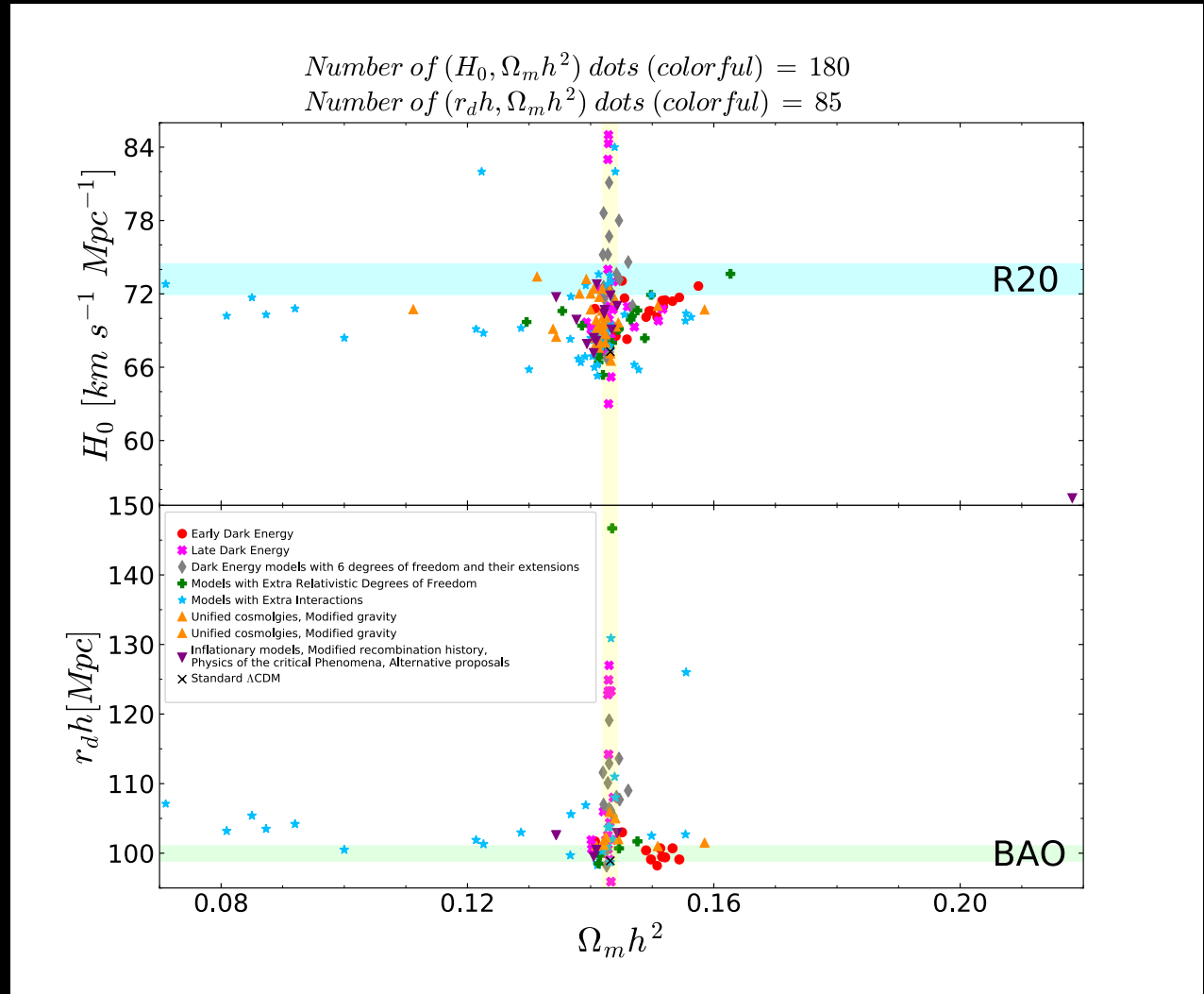


Jedamzik et al., *Commun.in Phys.* 4 (2021) 123

Successful models?

This is the density of the proposed cosmological models: →

At the moment no specific proposal makes a strong case for being highly likely or far better than all others !!!



Di Valentino et al., Class.Quant.Grav. (2021), arXiv:2103.01183 [astro-ph.CO]

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.

The IDE case

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

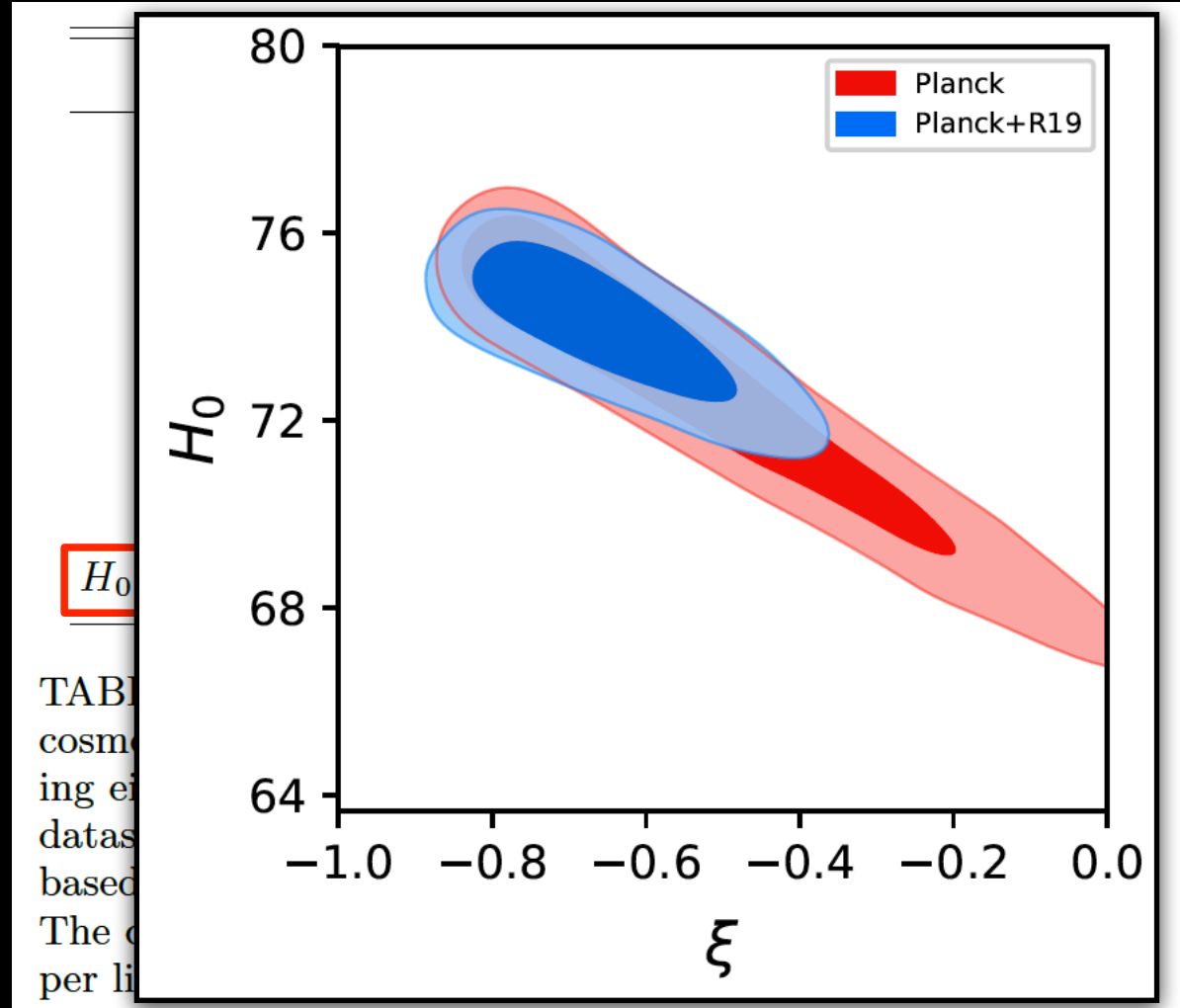
The coupling could affect the value of the present matter energy density Ω_m . Therefore, if within an interacting model Ω_m is smaller (because for negative ξ the dark matter density will decay into the dark energy one), a larger value of H_0 would be required in order to satisfy the peaks structure 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 ± 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.

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.**



The IDE case

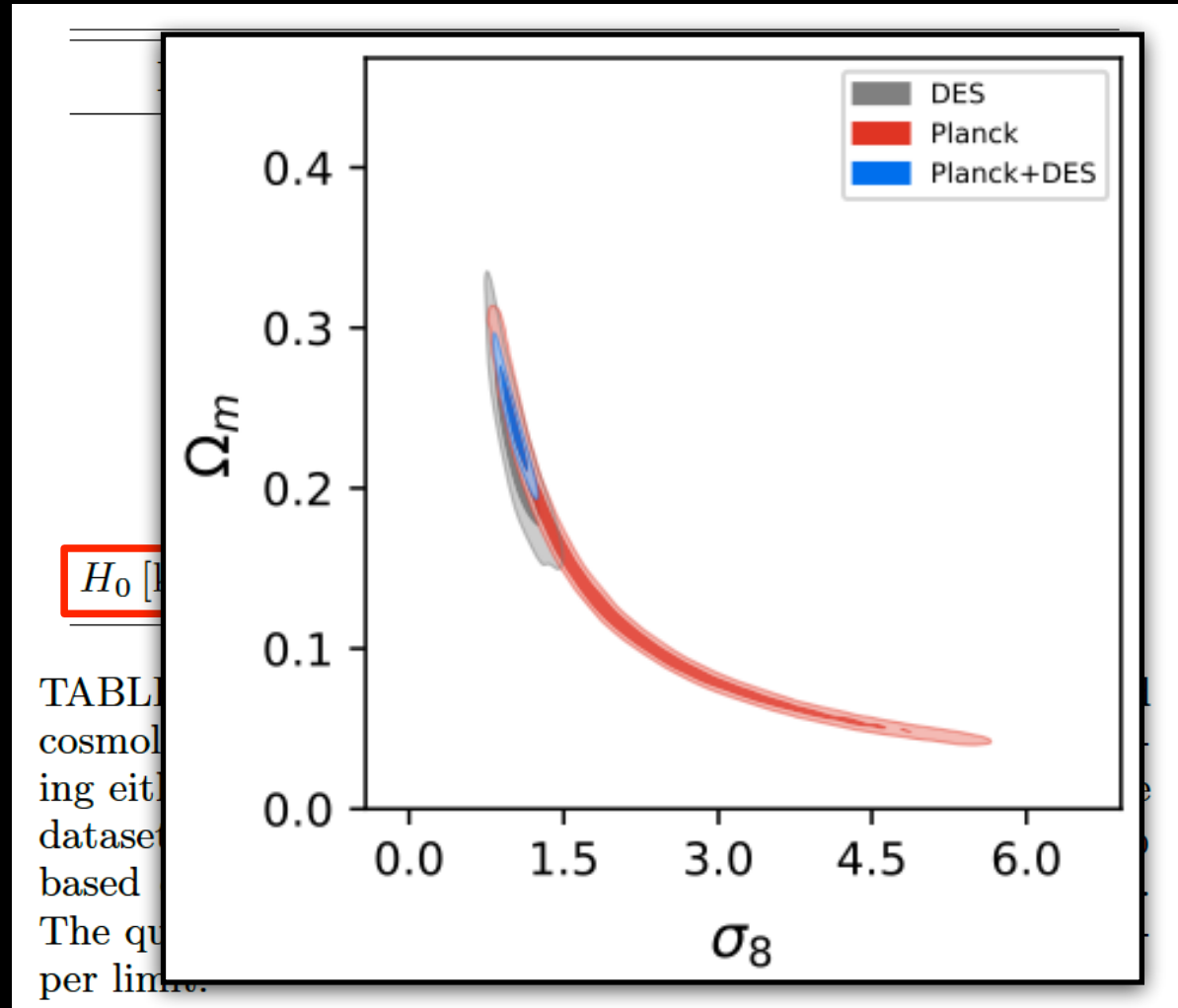
Moreover, we find a shift of the clustering parameter σ_8 towards a higher value, compensated by a lowering of the matter density Ω_m , both with relaxed error bars.

The reason is that once a coupling is switched on and

Ω_m becomes smaller, the clustering parameter σ_8 must be larger to have a proper normalization of the (lensing and clustering) power spectra.

This model can therefore significantly reduce the significance of the S8 tension

(See also Lucca, *Phys.Dark Univ.* 34 (2021) 100899)



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**):

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

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 $|\ln \mathcal{B}| > 1.0$, "moderate" if $|\ln \mathcal{B}| > 2.5$, and "strong" if $|\ln \mathcal{B}| > 5.0$.

The IDE case

Computing the Bayes factor for the IDE model with respect to Λ CDM for the **Planck** dataset we find **$\ln B = 1.2$** , i.e. a **weak evidence** for the IDE model. If we consider **Planck + SH0ES** we find the extremely high value **$\ln B = 10.0$** , indicating a **strong evidence for the IDE model**.

Parameter	<i>Planck</i>	<i>Planck</i> + <i>R19</i>
$\Omega_b h^2$	0.02239 ± 0.00015	0.02239 ± 0.00015
$\Omega_c h^2$	< 0.105	< 0.0615
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$100\theta_s$	$1.0458^{+0.0033}_{-0.0021}$	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.

fake IDE detection

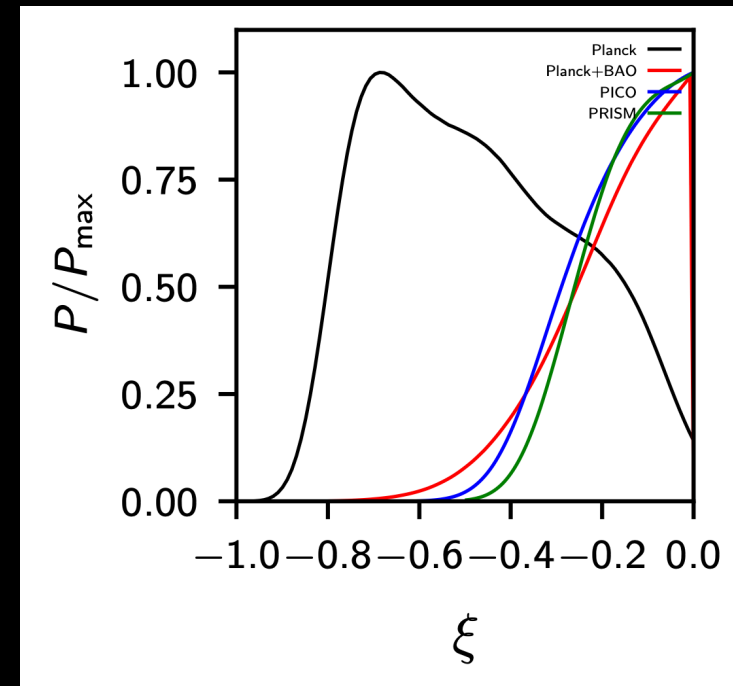
Parameters	Fiducial model	Planck	Planck+BAO	PICO	PRISM
$\Omega_b h^2$	0.02236	0.02238 ± 0.00015	0.02230 ± 0.00014	0.022364 ± 0.000029	0.022361 ± 0.000019
$\Omega_c h^2$	0.1202	$0.056^{+0.025}_{-0.047}$	$0.101^{+0.019}_{-0.006}$	$0.100^{+0.019}_{-0.008}$	$0.103^{+0.016}_{-0.007}$
$100\theta_{MC}$	1.04090	$1.0451^{+0.0021}_{-0.0032}$	$1.0419^{+0.0005}_{-0.0011}$	$1.04206^{+0.0005}_{-0.0011}$	$1.04191^{+0.00042}_{-0.00094}$
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	$-0.48^{+0.16}_{-0.30}$	> -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 $\xi = 0$:

$$-0.85 < \xi < -0.02 \text{ at } 99\% \text{ CL}$$

Mock experiments

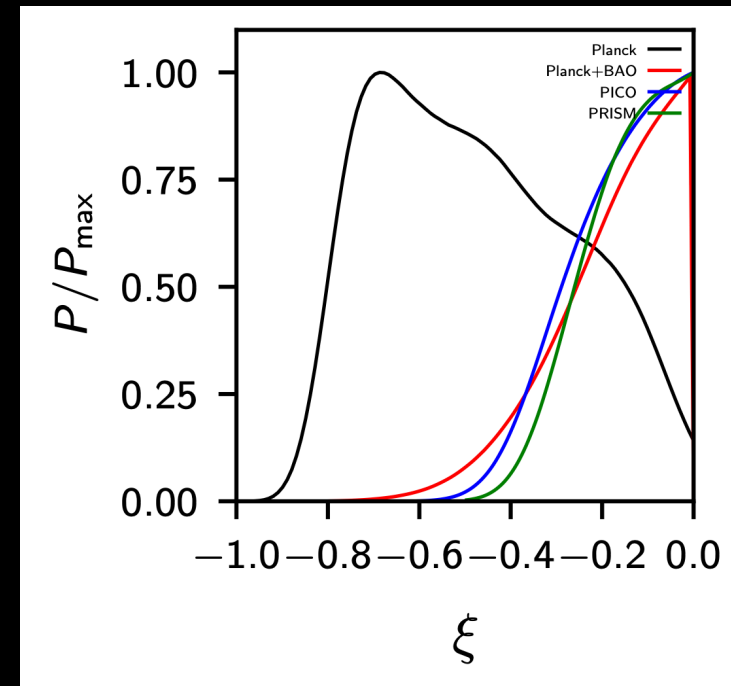


fake IDE detection

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	$-0.48^{+0.16}_{-0.30}$	> -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	$-0.22^{+0.18}_{-0.09} [> -0.48]$	> -0.35	> -0.12
H_0 [km/s/Mpc]	$69.55^{+0.98}_{-1.60}$	$69.04^{+0.84}_{-1.10}$	$68.02^{+0.49}_{-0.60}$
Ω_m	$0.243^{+0.054}_{-0.030}$	$0.261^{+0.038}_{-0.025}$	$0.299^{+0.015}_{-0.007}$

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

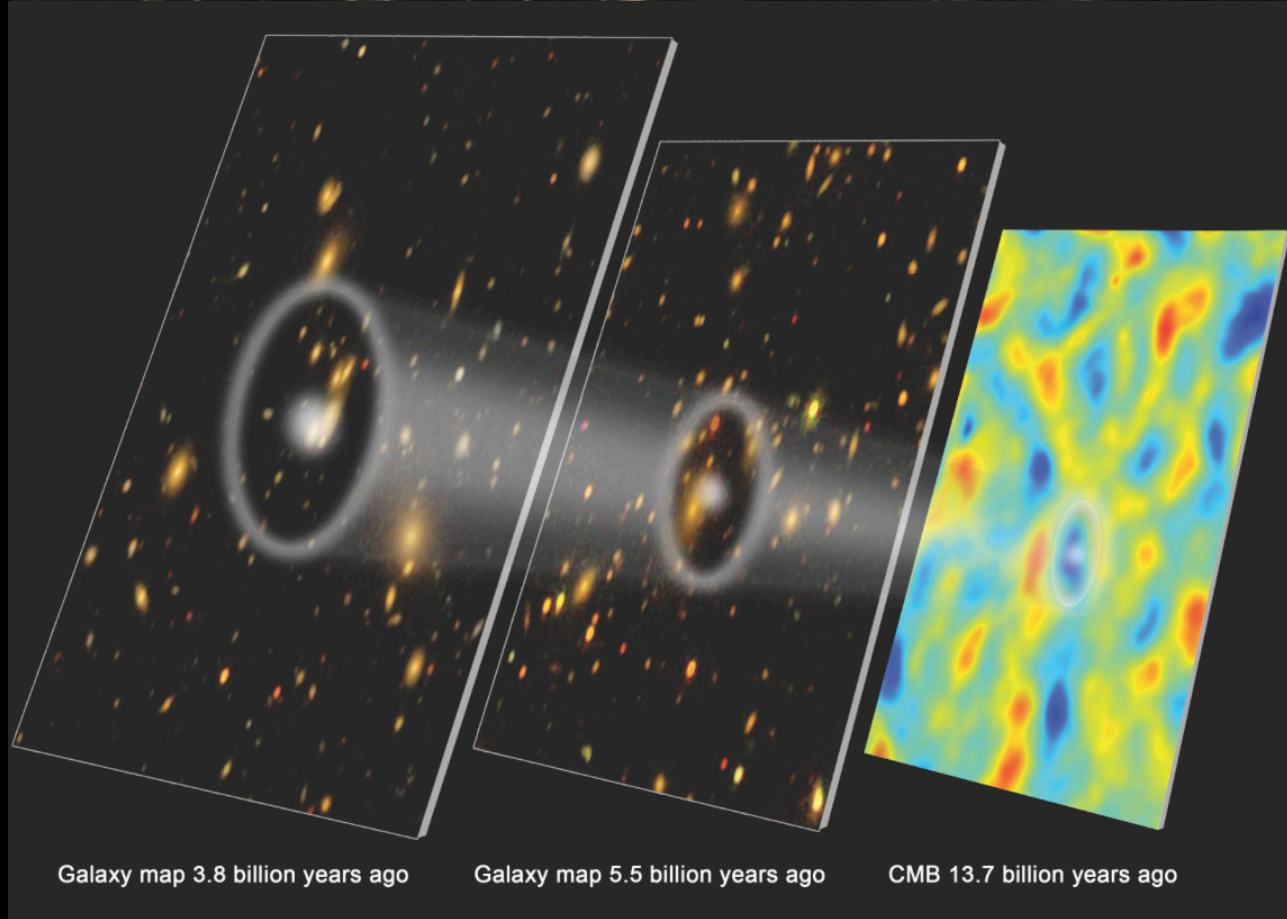
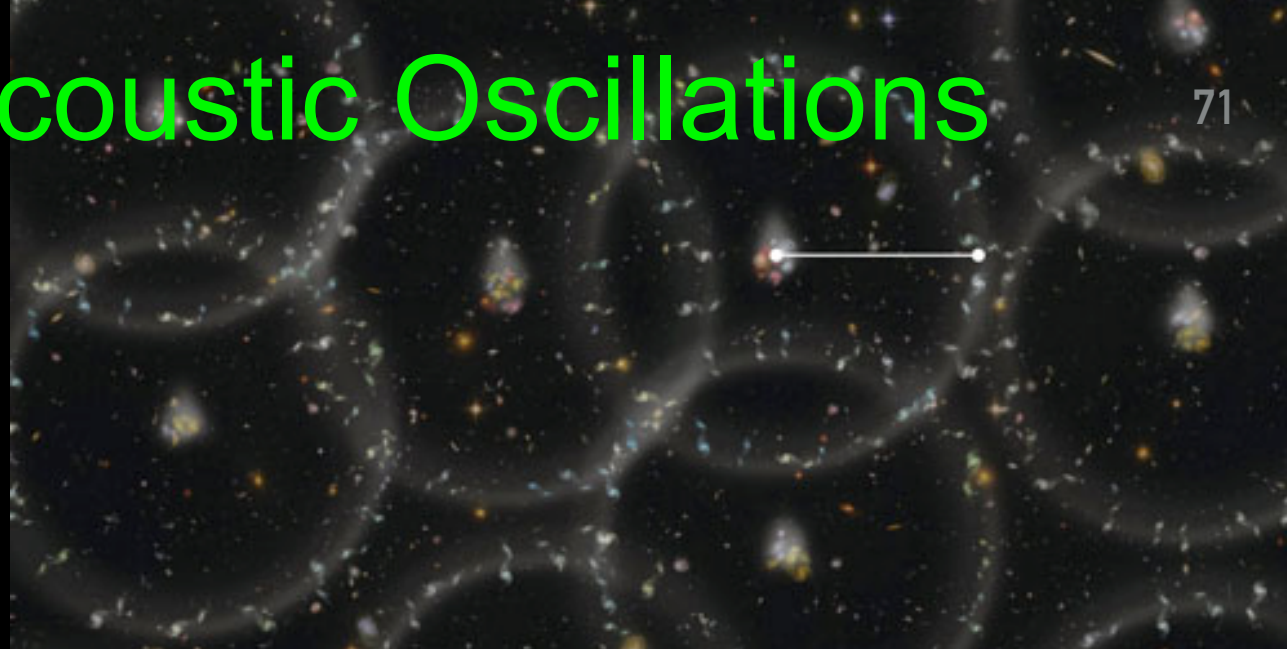
The addition of low-redshift measurements, as BAO data, still hints to the presence of a coupling, albeit at a lower statistical significance. Also for this data sets the Hubble constant value is larger than that obtained in the case of a pure Λ CDM scenario, enough to bring the H_0 tension at 2.1σ with SH0ES.

Baryon Acoustic Oscillations

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BAO is formed in the early universe, when baryons are strongly coupled to photons, and the gravitational collapse due to the CDM is counterbalanced by the radiation pressure. Sound waves that propagate in the early universe imprint a characteristic scale on the CMB. Since the scale of these oscillations can be measured at recombination, BAO is considered a "standard ruler". These fluctuations have evolved and we can observe BAO at low redshifts in the distribution of galaxies.

Since the data reduction process leading to these measurements involves making certain assumptions about the fiducial cosmology, this makes BAO measurements dependent on the cosmological model being used.



Baryon Acoustic Oscillations

In other words, the tension between Planck+BAO and SH0ES could be due to a statistical fluctuation in this case.

Actually, BAO data are extracted under the assumption of Λ CDM, and the modified scenario of interacting dark energy could affect the result.

In fact, the full procedure which leads to the BAO datasets carried out by the different collaborations might be not necessarily valid in extended DE models with important perturbations in the non-linear scales.

BAO datasets (both the pre- and post- reconstruction measurements) might need to be revised in a non-trivial manner when applied to constrain more exotic dark energy cosmologies.

Baryon Acoustic Oscillations

The problem is that for **3D BAO data** one needs to reconstruct the comoving distance and this is done assuming a fiducial model.

We can try to see what happens using **2D BAO measurements**, that are less model dependent because they are obtained working on spherical shells with redshift thickness Δz and only considering their angular distribution.

The IDE case

Parameter	Planck		Planck + BAO		Planck + BAOtr		Planck + BAOtr + H_0	
		+ lensing		+ lensing		+ lensing		+ lensing
H_0 [Km/s/Mpc]	67.32 ± 0.62	67.32 ± 0.53	67.65 ± 0.44	67.60 ± 0.43	69.01 ± 0.51	68.85 ± 0.55	69.88 ± 0.48	69.65 ± 0.44
S_8	0.832 ± 0.016	0.834 ± 0.013	0.825 ± 0.012	0.827 ± 0.011	0.794 ± 0.013	0.802 ± 0.012	0.774 ± 0.013	$0.7871^{+0.0095}_{-0.011}$
r_s [Mpc]	147.06 ± 0.30	147.04 ± 0.27	$147.21^{+0.23}_{-0.26}$	147.13 ± 0.23	147.75 ± 0.26	147.64 ± 0.26	148.06 ± 0.25	147.91 ± 0.24

A comparison between the **3D BAO data**, model dependent and obtained assuming Λ CDM, and the **2D BAO measurements**, less model dependent, shows almost the same results for the Λ CDM scenario.

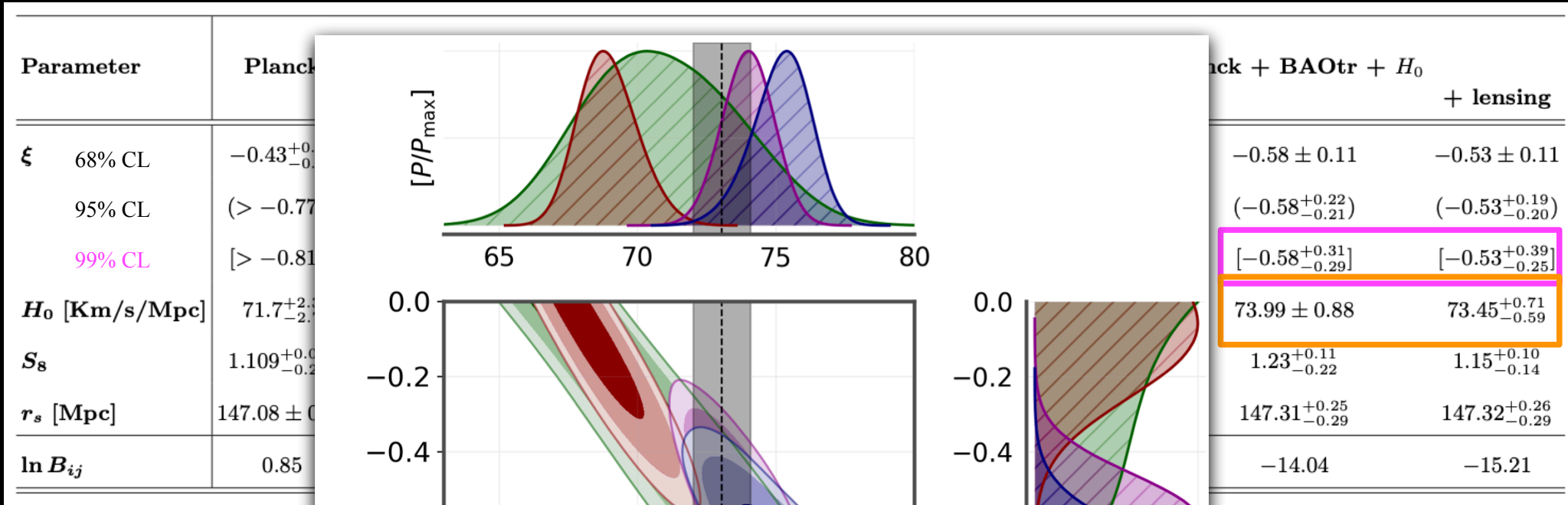
The IDE case

Parameter	Planck		Planck + BAO		Planck + BAOtr		Planck + BAOtr + H_0	
	+ lensing		+ lensing		+ lensing		+ lensing	
ξ 68% CL	$-0.43^{+0.28}_{-0.21}$	$-0.40^{+0.23}_{-0.20}$	> -0.207	> -0.210	$-0.683^{+0.088}_{-0.11}$	$-0.683^{+0.087}_{-0.12}$	-0.58 ± 0.11	-0.53 ± 0.11
95% CL	(> -0.775)	$(-0.40^{+0.40}_{-0.32})$	(> -0.389)	(> -0.411)	$(-0.68^{+0.21}_{-0.19})$	$(-0.68^{+0.23}_{-0.20})$	$(-0.58^{+0.22}_{-0.21})$	$(-0.53^{+0.19}_{-0.20})$
99% CL	$[> -0.819]$	$[> -0.743]$	$[> -0.486]$	$[> -0.527]$	$[-0.68^{+0.29}_{-0.23}]$	$[-0.68^{+0.37}_{-0.27}]$	$[-0.58^{+0.31}_{-0.29}]$	$[-0.53^{+0.39}_{-0.25}]$
H_0 [Km/s/Mpc]	$71.7^{+2.3}_{-2.7}$	71.6 ± 2.1	$68.93^{+0.79}_{-1.2}$	$69.08^{+0.74}_{-1.3}$	$75.2^{+1.2}_{-0.75}$	$75.3^{+1.3}_{-0.75}$	73.99 ± 0.88	$73.45^{+0.71}_{-0.59}$
S_8	$1.109^{+0.063}_{-0.28}$	$1.053^{+0.079}_{-0.21}$	$0.891^{+0.025}_{-0.062}$	$0.893^{+0.021}_{-0.065}$	$1.49^{+0.24}_{-0.29}$	1.49 ± 0.26	$1.23^{+0.11}_{-0.22}$	$1.15^{+0.10}_{-0.14}$
r_s [Mpc]	147.08 ± 0.30	147.12 ± 0.27	147.03 ± 0.25	147.05 ± 0.25	147.32 ± 0.27	147.35 ± 0.29	$147.31^{+0.25}_{-0.29}$	$147.32^{+0.26}_{-0.29}$
$\ln B_{ij}$	0.85	-0.17	1.60	0.60	-9.22	-11.68	-14.04	-15.21

A comparison between the **3D BAO data**, model dependent and obtained assuming Λ CDM, and the **2D BAO measurements**, less model dependent, shows completely different results for the IDE model. There is a strong evidence for the coupling at more than 99% CL, solving at the same time the H_0 tension with SH0ES.

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The IDE case



There is a strong evidence for the coupling at more than 99% CL, solving at the same time the H_0 tension with SH0ES.

The IDE case

Table II. Constraints at 68% CL on the parameters of the Λ CDM model.

Parameter	CMB	CMB+BAO-3D	CMB+BAO-2D (ON)	CMB+BAO-2D (M&M)
$10^2 \times \Omega_b h^2$	2.236 ± 0.015	2.245 ± 0.013	2.263 ± 0.014	2.246 ± 0.014
$\Omega_c h^2$	0.1202 ± 0.0014	0.11911 ± 0.00096	0.1165 ± 0.0011	0.11877 ± 0.00097
H_0	67.32 ± 0.62	67.84 ± 0.43	69.01 ± 0.51	67.96 ± 0.44
τ_{reio}	0.0536 ± 0.0081	0.0590 ± 0.0070	0.0606 ± 0.0081	0.0567 ± 0.0080
$\log(10^{10} A_s)$	3.043 ± 0.016	3.053 ± 0.015	3.049 ± 0.017	3.047 ± 0.016
n_s	0.9646 ± 0.0045	0.9677 ± 0.0037	0.9742 ± 0.0038	0.9688 ± 0.0037

A comparison between the **3D BAO data** and the **2D BAO measurements** [Menote & Marra arXiv:2112.10000](#), from the same BOSS DR12 and eBOSS DR16, gives exactly the same results for the Λ CDM scenario.

The IDE case

Table I. Constraints at 68% (95%) CL on the parameters of the IDE model.

Parameter	CMB	CMB+BAO-3D	CMB+BAO-2D (ON)	CMB+BAO-2D (M&M)
$10^2 \times \Omega_b h^2$	2.239 ± 0.015	2.236 ± 0.013	2.248 ± 0.014	2.237 ± 0.014
$\Omega_c h^2$	$0.067^{+0.042}_{-0.031} (< 0.115)$	$0.101^{+0.016}_{-0.012}$	$0.022^{+0.014}_{-0.019}$	$0.089^{+0.019}_{-0.016}$
H_0	71.6 ± 2.1	$68.92^{+0.96}_{-1.2}$	$75.2^{+1.1}_{-0.96}$	69.9 ± 1.1
τ_{reio}	0.0534 ± 0.0079	0.0544 ± 0.0079	0.0556 ± 0.0082	0.0537 ± 0.0078
$\log(10^{10} A_s)$	3.042 ± 0.016	3.045 ± 0.016	3.044 ± 0.017	3.044 ± 0.016
n_s	0.9655 ± 0.0045	0.9650 ± 0.0037	0.9695 ± 0.0040	0.9657 ± 0.0039
ξ	$-0.40^{+0.23}_{-0.20} (> -0.775)$	$> -0.207 (> -0.389)$	$-0.683^{+0.088}_{-0.11}$	$-0.26^{+0.18}_{-0.12} (> -0.505)$

A comparison between the **3D BAO data** and the **2D BAO measurements** [Menote & Marra arXiv:2112.10000](#), from the same BOSS DR12 and eBOSS DR16, gives different H_0 values for the IDE scenario.

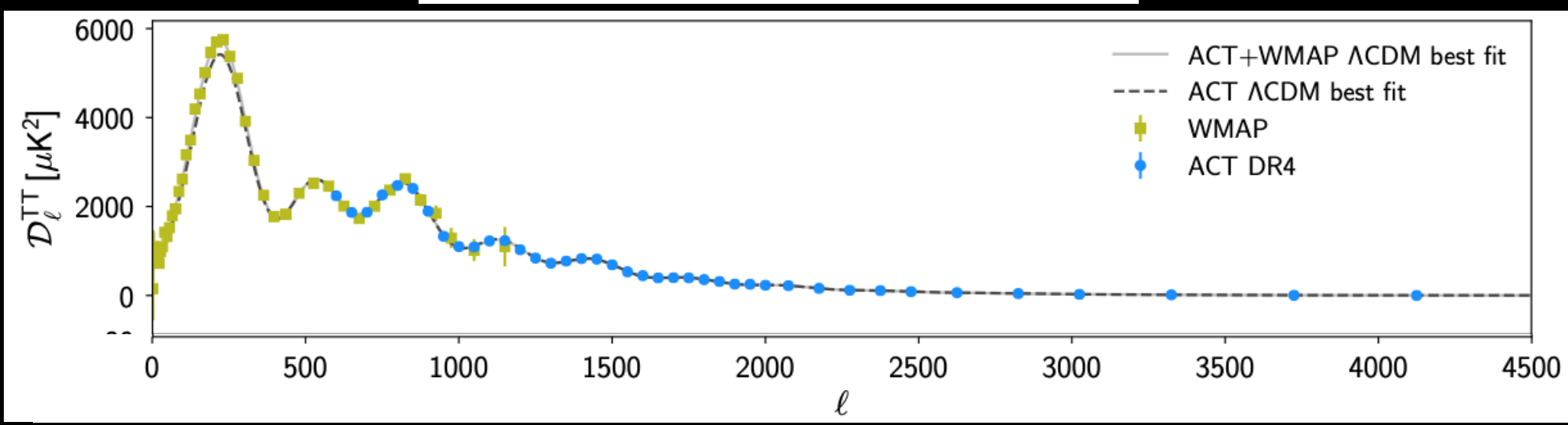
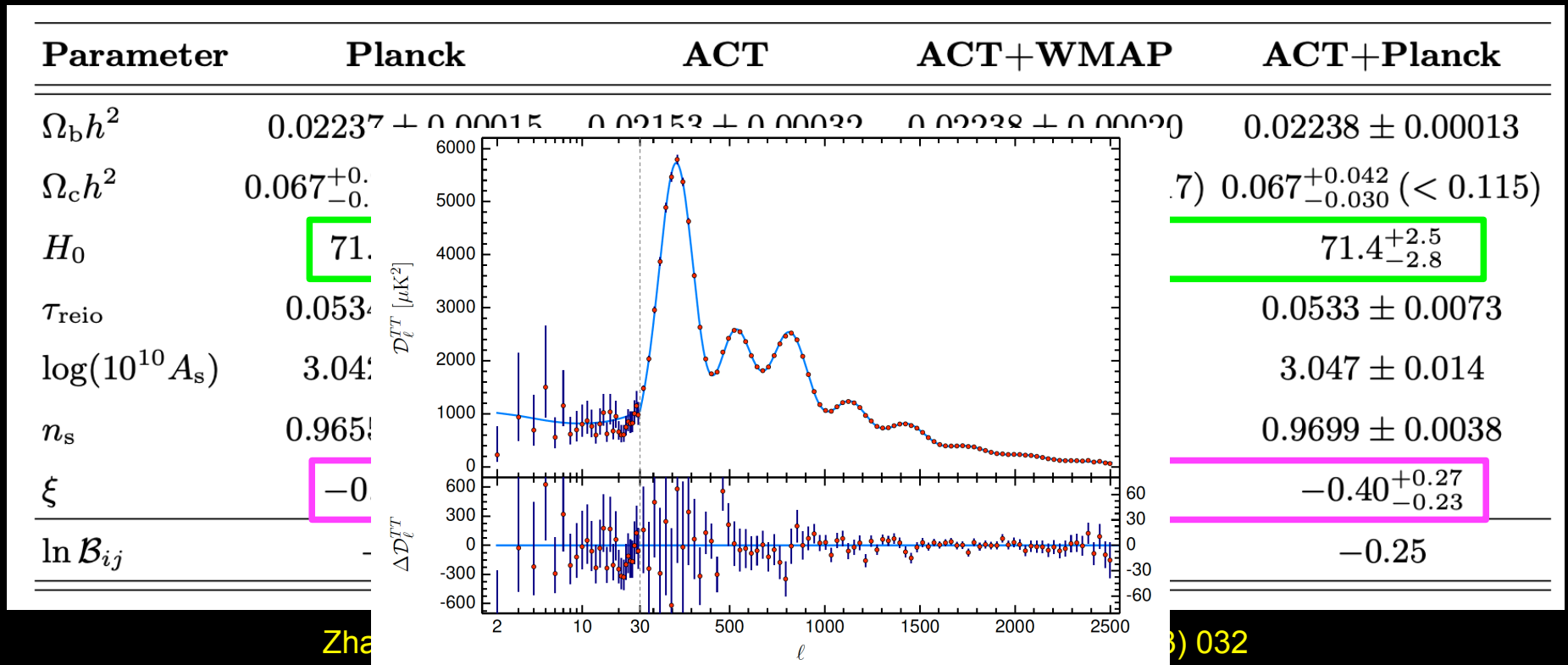
IDE from ACT

Parameter	Planck	ACT	ACT+WMAP	ACT+Planck
$\Omega_b h^2$	0.02237 ± 0.00015	0.02153 ± 0.00032	0.02238 ± 0.00020	0.02238 ± 0.00013
$\Omega_c h^2$	$0.067^{+0.042}_{-0.031} (< 0.115)$	$< 0.0754 (< 0.111)$	$0.070^{+0.046}_{-0.021} (< 0.117)$	$0.067^{+0.042}_{-0.030} (< 0.115)$
H_0	71.6 ± 2.1	$72.6^{+3.4}_{-2.6}$	$71.3^{+2.6}_{-3.2}$	$71.4^{+2.5}_{-2.8}$
τ_{reio}	0.0534 ± 0.0079	0.063 ± 0.015	0.061 ± 0.014	0.0533 ± 0.0073
$\log(10^{10} A_s)$	3.042 ± 0.016	3.046 ± 0.030	3.064 ± 0.028	3.047 ± 0.014
n_s	0.9655 ± 0.0045	1.010 ± 0.016	$0.9741^{+0.0066}_{-0.0064}$	0.9699 ± 0.0038
ξ	$-0.40^{+0.23}_{-0.20}$	$-0.46^{+0.20}_{-0.28}$	$-0.38^{+0.35}_{-0.14}$	$-0.40^{+0.27}_{-0.23}$
$\ln \mathcal{B}_{ij}$	-0.17	-0.07	0.06	-0.25

Zhai, Giarè, van de Bruck, Di Valentino, et al, *JCAP* 07 (2023) 032

Let's now consider different combinations of CMB datasets.

IDE from ACT



IDE from ACT

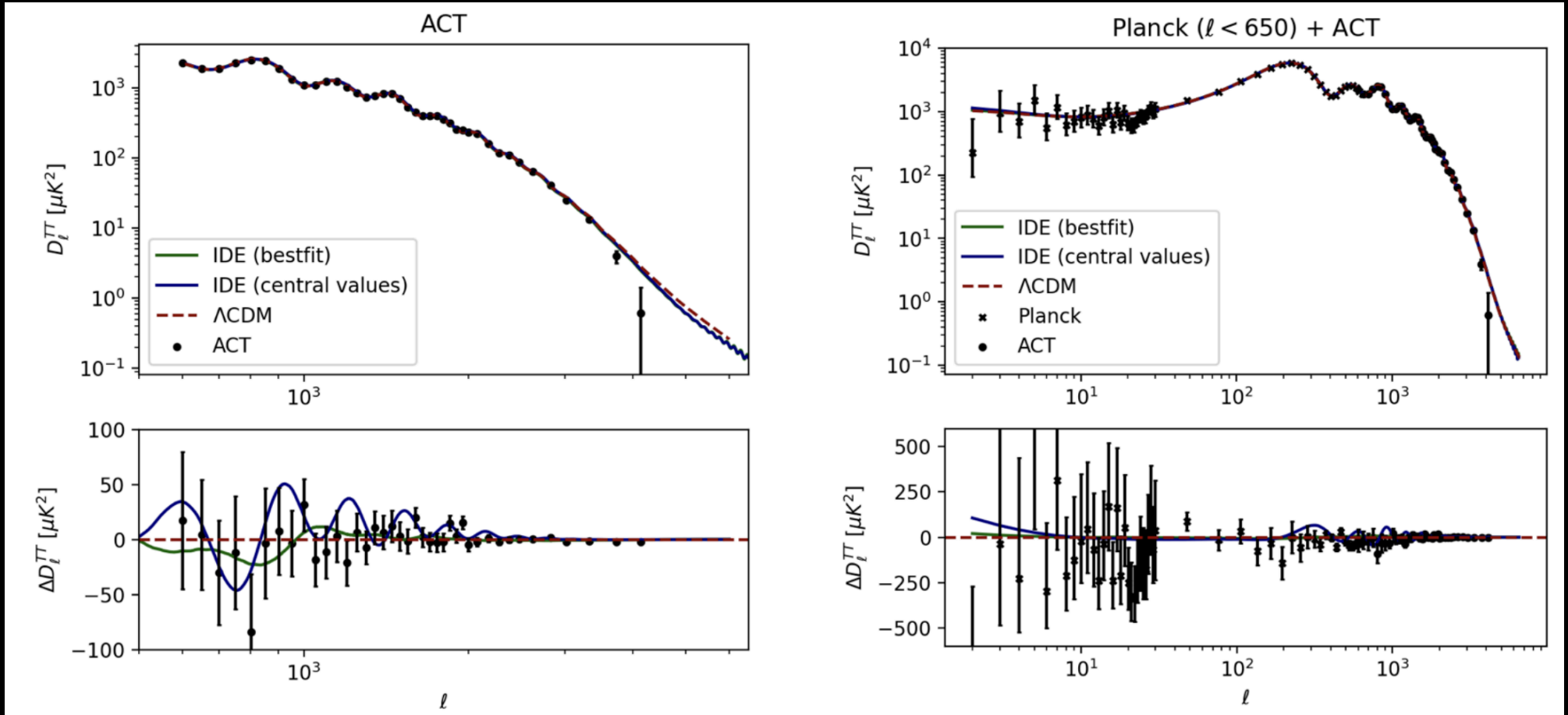
Parameter	Planck	ACT	ACT+WMAP	ACT+Planck
$\Omega_b h^2$	0.02237 ± 0.00015	0.02153 ± 0.00032	0.02238 ± 0.00020	0.02238 ± 0.00013
$\Omega_c h^2$	$0.067^{+0.042}_{-0.031} (< 0.115)$	$< 0.0754 (< 0.111)$	$0.070^{+0.046}_{-0.021} (< 0.117)$	$0.067^{+0.042}_{-0.030} (< 0.115)$
H_0	71.6 ± 2.1	$72.6^{+3.4}_{-2.6}$	$71.3^{+2.6}_{-3.2}$	$71.4^{+2.5}_{-2.8}$
τ_{reio}	0.0534 ± 0.0079	0.063 ± 0.015	0.061 ± 0.014	0.0533 ± 0.0073
$\log(10^{10} A_s)$	3.042 ± 0.016	3.046 ± 0.030	3.064 ± 0.028	3.047 ± 0.014
n_s	0.9655 ± 0.0045	1.010 ± 0.016	$0.9741^{+0.0066}_{-0.0064}$	0.9699 ± 0.0038
ξ	$-0.40^{+0.23}_{-0.20}$	$-0.46^{+0.20}_{-0.28}$	$-0.38^{+0.35}_{-0.14}$	$-0.40^{+0.27}_{-0.23}$
$\ln \mathcal{B}_{ij}$	-0.17	-0.07	0.06	-0.25

Zhai, Giarè, van de Bruck, Di Valentino, et al, *JCAP* 07 (2023) 032

If we consider different combinations of CMB datasets, they provide similar results, favoring IDE with a 95% CL significance in the majority of the cases.

Remarkably, such a preference remains consistent when cross-checked through independent probes, while always yielding a value of the expansion rate H_0 consistent with the local distance ladder measurements.

IDE from ACT



Zhai, Giarè, van de Bruck, Di Valentino, et al, *JCAP* 07 (2023) 032

It is easy to observe that the preference for $\xi < 0$ is primarily driven by the high multipole ACT CMB data that have a reduced amplitude. These data are also responsible for the improvement of the fit in the context of IDE models compared to the minimal ΛCDM , indicating that it is a genuine effect rather than one caused by parameter degeneracies.

Let's see another example
at late time...

Omnipotent DE

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

Adil, Akarsu, Di Valentino et al., [arXiv:2306.08046](https://arxiv.org/abs/2306.08046)

We named “**Omnipotent DE**” a class of phenomenologically DE models that are capable of incorporating all six combinations of negative and positive DE density ($\rho_{DE} < 0$ and $\rho_{DE} > 0$) with different equation of states $w_{DE} < -1$, $w_{DE} = -1$, and $w_{DE} > -1$ into a single expansion scenario for at least one point in its parameter space.

Phantom Crossing

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:

$$\begin{aligned}H^2(a)/H_0^2 &= \Omega_{m0}a^{-3} + \Omega_{k0}a^{-2} + \Omega_{\gamma0}a^{-4} \\ &+ \left(\frac{1 - \Omega_{m0} - \Omega_{k0} - \Omega_{\gamma0}}{1 + \alpha(1 - a_m)^2 + \beta(1 - a_m)^3} \right) \\ &\quad [1 + \alpha(a - a_m)^2 + \beta(a - a_m)^3],\end{aligned}$$

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.

Phantom Crossing

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 .

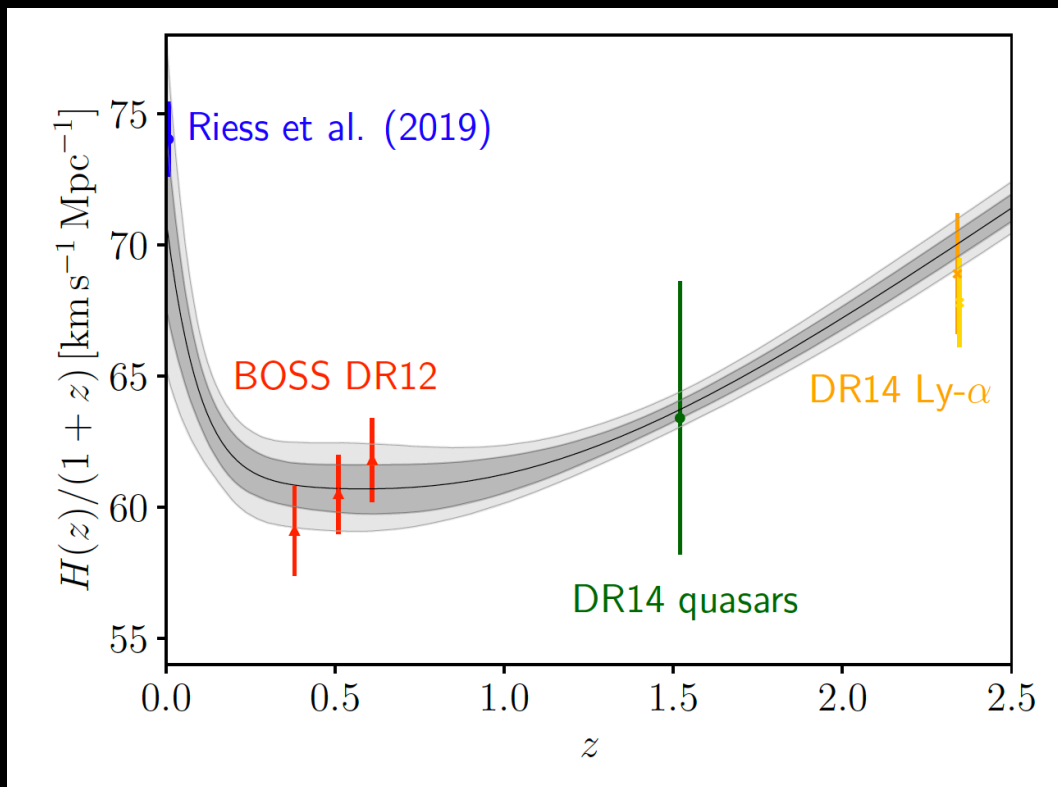
Moreover this model also helps to alleviate the H_0 tension between low and high redshift observations below 2σ , even for the full datasets combination.

Phantom Crossing

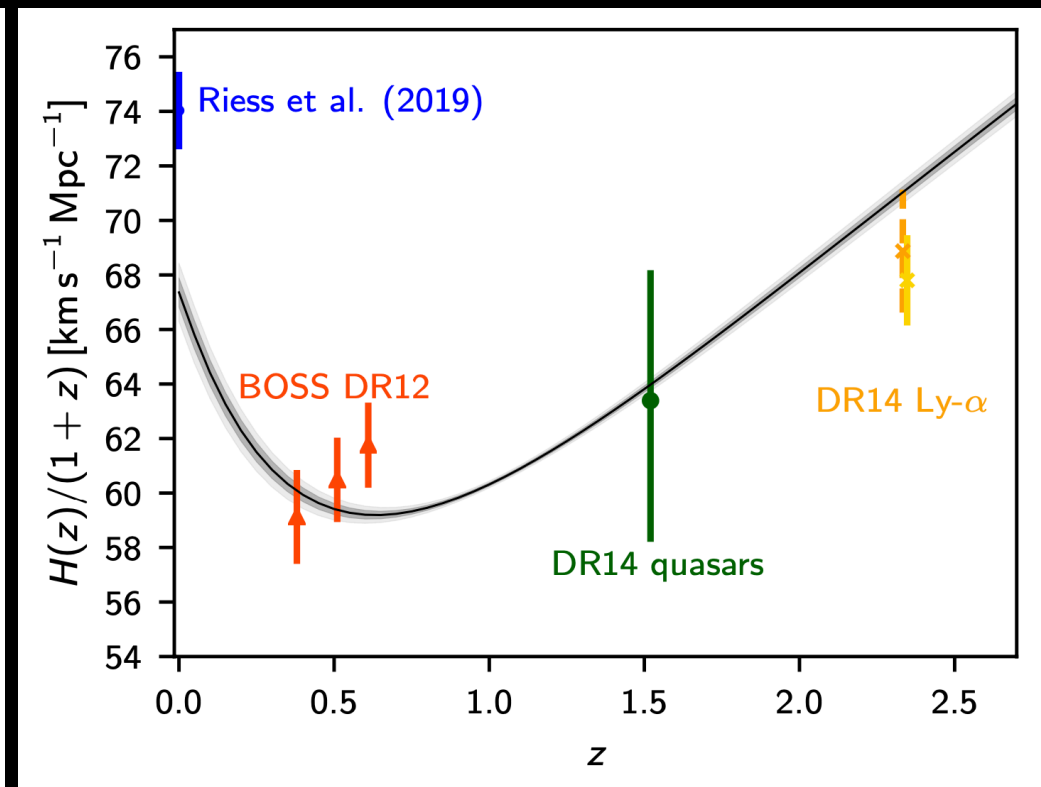
Parameters	Planck +BAO	Planck +PantheonPlus	Planck +PantheonPlus&SH0ES	Planck+BAO +PantheonPlus&SH0ES
$\Omega_c h^2$	0.1196 ± 0.0011	0.1193 ± 0.0013	0.1176 ± 0.0011	0.1198 ± 0.0011
$10^2 \Omega_b h^2$	2.241 ± 0.014	2.243 ± 0.015	2.257 ± 0.014	2.243 ± 0.014
$100\theta_{MC}$	1.04191 ± 0.00029	1.04193 ± 0.00029	1.04207 ± 0.00029	1.04191 ± 0.00029
τ	0.0517 ± 0.0076	0.0516 ± 0.0077	$0.0490^{+0.0081}_{-0.0071}$	0.0502 ± 0.0076
n_s	0.9662 ± 0.0038	0.9669 ± 0.0043	0.9714 ± 0.0041	0.9659 ± 0.0038
$\ln(10^{10} A_s)$	3.038 ± 0.015	3.037 ± 0.015	$3.027^{+0.016}_{-0.014}$	3.035 ± 0.015
a_m	$0.841^{+0.053}_{-0.062}$	$0.952^{+0.042}_{-0.016}$	$0.957^{+0.016}_{-0.023}$	$0.922^{+0.041}_{-0.035}$
α	$7.2^{+4.8}_{-3.9}$	$3.4^{+1.5}_{-2.5}$	$7.0^{+1.6}_{-2.0}$	< 2.77
β	> 11.1	$7.3^{+3.0}_{-6.0}$	$16.5^{+3.4}_{-4.3}$	$6.5^{+1.9}_{-3.4}$
H_0 [km/s/Mpc]	$72.1^{+3.2}_{-4.5}$	$68.9^{+1.4}_{-2.0}$	73.49 ± 0.98	70.05 ± 0.64

The same results are confirmed for the new updated datasets BAO DR16 and Pantheon+, **redeeming the possibility of a late time solution, if the DE is not monotonic and can be negative.**

Phantom Crossing



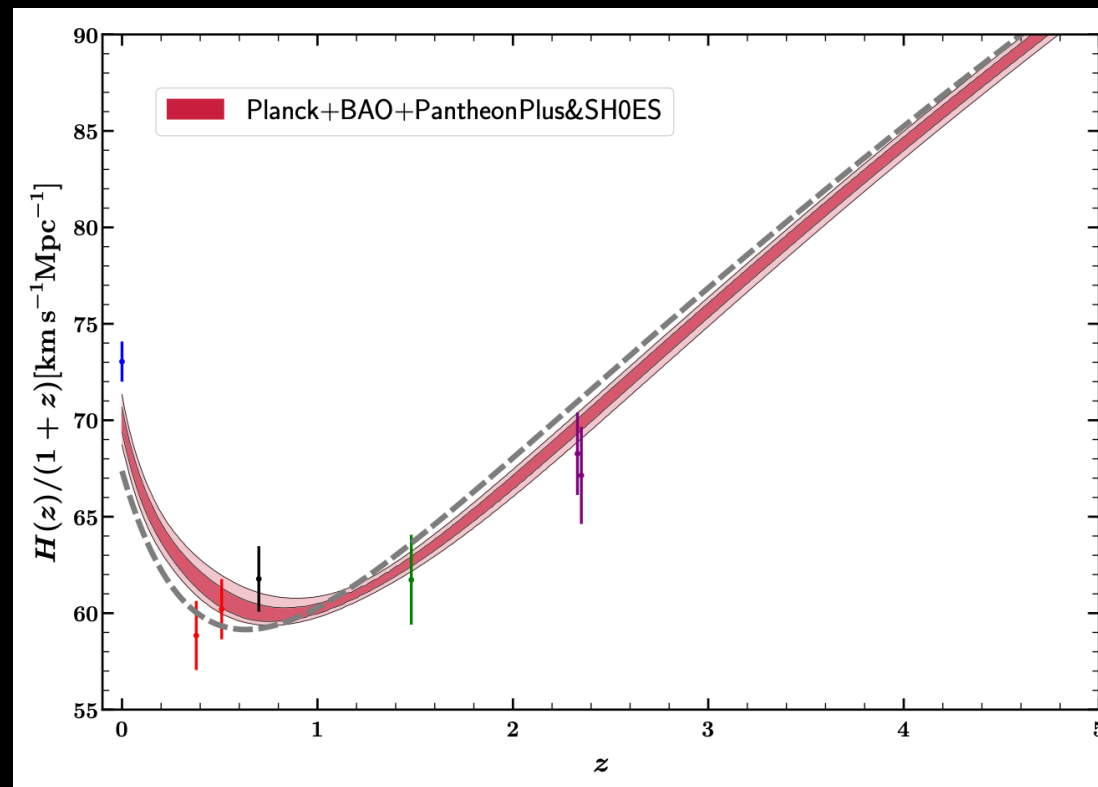
Di Valentino et al., *Entropy* 23 (2021) 4, 404



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

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

Phantom Crossing



Adil, Akarsu, Di Valentino et al., *arXiv:2306.08046*

And the same it is true for the most updated full dataset combination Planck+BAO+PantheonPlus&SH0ES.

Phantom Crossing

	Phantom-crossing Dark Energy (PDE)		
Parameter	Base + LSS	Base + LSS + S_8	Base + LSS + S_8 + H_0
a_m	$0.774^{+0.037}_{-0.020}$	$0.774^{+0.038}_{-0.020}$	$0.773^{+0.044}_{-0.025}$
α	$8.2^{+2.6}_{-3.7}$	$8.0^{+2.5}_{-3.6}$	$6.5^{+1.6}_{-2.8}$
β	$14.2^{+6.7}_{-8.7}$	$14.1^{+6.8}_{-8.4}$	$10.2^{+4.5}_{-6.9}$
$100 \omega_b$	2.246 ± 0.019	2.245 ± 0.018	2.246 ± 0.018
$10 \omega_{cdm}$	1.165 ± 0.015	1.166 ± 0.011	1.163 ± 0.010
H_0	$75.70^{+2.05}_{-2.32}$	$75.60^{+1.93}_{-2.12}$	73.92 ± 1.09
τ	0.057 ± 0.005	0.057 ± 0.005	0.057 ± 0.005
$\ln(10^{10} A_s)$	3.038 ± 0.012	3.038 ± 0.011	3.037 ± 0.011
n_s	0.974 ± 0.006	0.974 ± 0.005	0.975 ± 0.005
r_{drag}	$147. \pm 0.38$	147.91 ± 0.31	147.97 ± 0.30
Ω_m	0.244 ± 0.015	0.245 ± 0.013	0.255 ± 0.007
σ_8	0.854 ± 0.022	0.855 ± 0.021	0.839 ± 0.013
S_8	0.770 ± 0.017	0.771 ± 0.010	0.774 ± 0.010

Chudaykin et al., [arXiv:2203.03666](https://arxiv.org/abs/2203.03666) [astro-ph.CO]

Base (SPT3G + Planck TT + Planck lensing) + LSS data prefer a phantom crossing at more than 4σ , and without including any priors is in agreement with H_0 and S_8 .

Let's see another example
of negative DE...

Sign-switching cosmological constant

The Λ_s CDM model is inspired by the recent conjecture that the universe went through a spontaneous AdS-dS transition characterized by a sign-switching cosmological constant:

$$\Lambda \rightarrow \Lambda_s \equiv \Lambda_{s0} \operatorname{sgn}[z_{\dagger} - z],$$

Akarsu, E Di Valentino et al., *arXiv:2307.10899*

Data set	Planck	Planck+BAOtr	Planck+BAOtr +PP	Planck+BAOtr +PP&SH0ES	Planck+BAOtr +PP&SH0ES+KiDS-1000
Model	Λ_s CDM Λ CDM	Λ_s CDM Λ CDM	Λ_s CDM Λ CDM	Λ_s CDM Λ CDM	Λ_s CDM Λ CDM
z_{\dagger}	unconstrained	$1.70^{+0.09}_{-0.19}(1.65)$	$1.87^{+0.13}_{-0.21}(1.75)$	$1.70^{+0.10}_{-0.13}(1.67)$	$1.72^{+0.09}_{-0.12}(1.70)$
M_B [mag]	--	--	$-19.317^{+0.021}_{-0.025}(-19.311)$ $-19.407 \pm 0.013(-19.411)$	$-19.290 \pm 0.017(-19.278)$ $-19.379 \pm 0.012(-19.373)$	$-19.282 \pm 0.017(-19.280)$ $-19.372 \pm 0.011(-19.369)$
H_0 [km/s/Mpc]	$70.77^{+0.79}_{-2.70}(71.22)$ $67.39 \pm 0.55(67.28)$	$73.30^{+1.20}_{-1.00}(73.59)$ $68.84 \pm 0.48(68.61)$	$71.72^{+0.73}_{-0.92}(71.97)$ $68.55 \pm 0.44(68.54)$	$72.82 \pm 0.65(73.20)$ $69.57 \pm 0.42(69.73)$	$73.16 \pm 0.64(73.36)$ $69.83 \pm 0.37(69.96)$
Ω_m	$0.2860^{+0.0230}_{-0.0099}(0.2796)$ $0.3151 \pm 0.0075(0.3163)$	$0.2643^{+0.0072}_{-0.0090}(0.2618)$ $0.2958 \pm 0.0061(0.2984)$	$0.2768^{+0.0072}_{-0.0063}(0.2759)$ $0.2995 \pm 0.0056(0.2992)$	$0.2683 \pm 0.0052(0.2646)$ $0.2869 \pm 0.0051(0.2849)$	$0.2646 \pm 0.0052(0.2622)$ $0.2837 \pm 0.0045(0.2816)$
S_8	$0.801^{+0.026}_{-0.016}(0.791)$ $0.832 \pm 0.013(0.835)$	$0.777 \pm 0.011(0.772)$ $0.802 \pm 0.011(0.804)$	$0.791 \pm 0.011(0.794)$ $0.808 \pm 0.010(0.804)$	$0.783 \pm 0.010(0.777)$ $0.788 \pm 0.010(0.784)$	$0.774 \pm 0.009(0.773)$ $0.781 \pm 0.008(0.782)$
χ^2_{\min}	2778.06 2780.52	2793.38 2820.30	4219.68 4235.18	4097.32 4138.26	4185.34 4226.50
$\ln \mathcal{B}_{ij}$	-1.28	-12.65	-7.52	-19.47	-19.77

Sign-switching cosmological constant

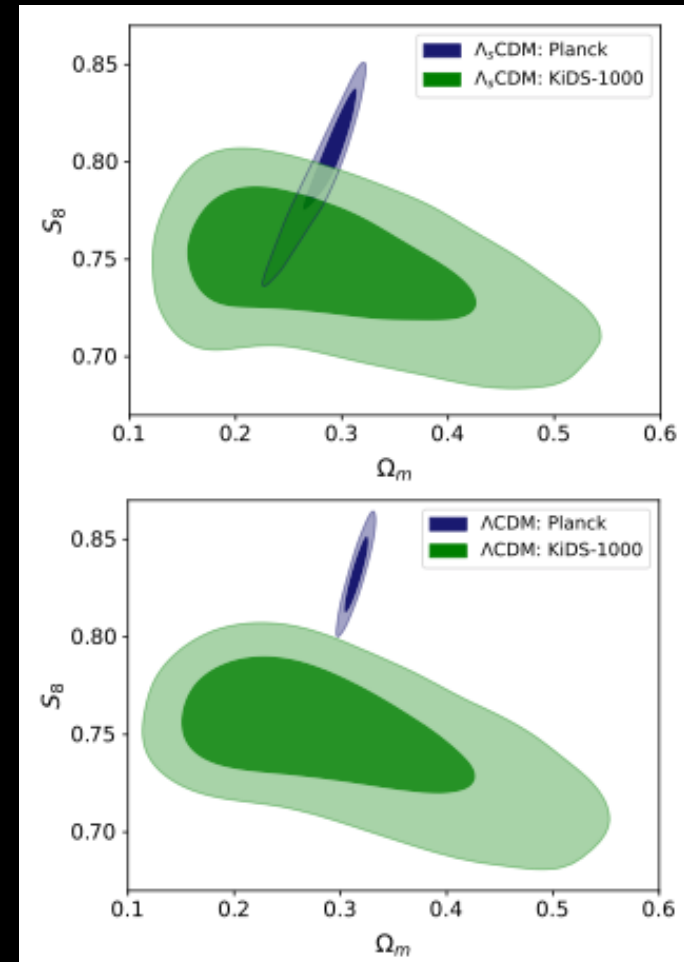
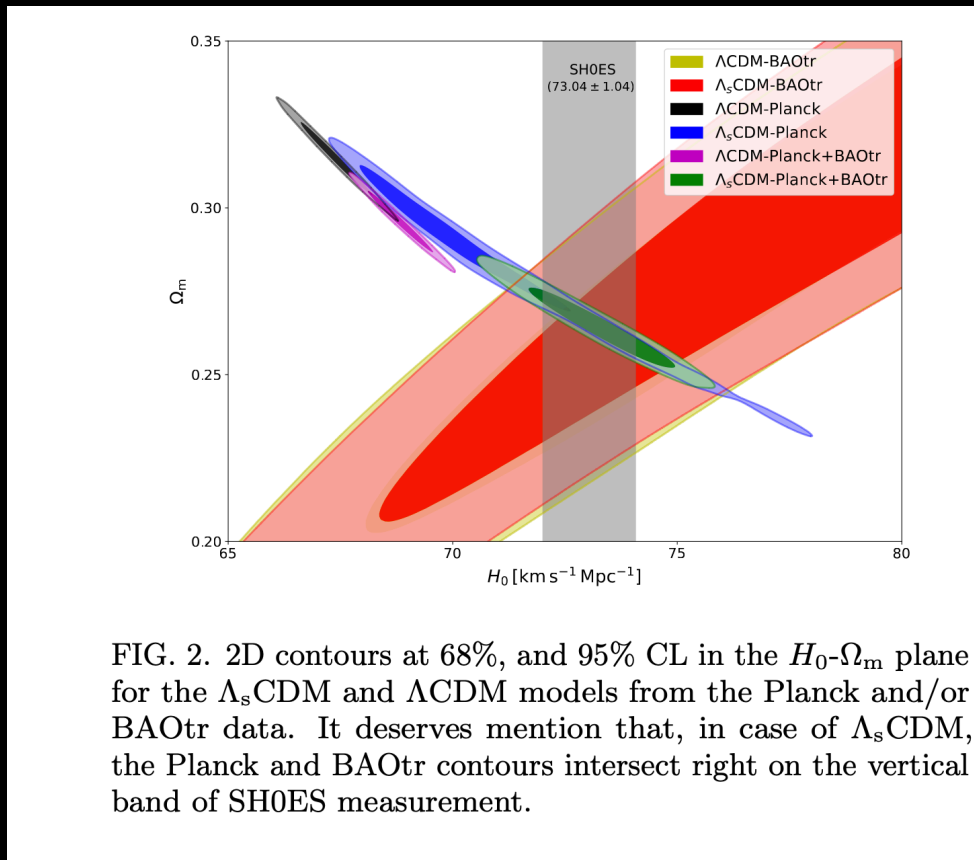
We see that there is no H_0 tension in the present analyses of Λ_s CDM with all data combinations including the BAOtr data, and this is very strongly favored over Λ CDM in terms of Bayesian evidence. The favoured transition redshift is $z_t \sim 1.7$.

Akarsu, E Di Valentino et al., *arXiv:2307.10899*

Data set	Planck	Planck+BAOtr	Planck+BAOtr +PP	Planck+BAOtr +PP&SH0ES	Planck+BAOtr +PP&SH0ES+KiDS-1000
Model	Λ_s CDM Λ CDM	Λ_s CDM Λ CDM	Λ_s CDM Λ CDM	Λ_s CDM Λ CDM	Λ_s CDM Λ CDM
z_t	unconstrained	$1.70^{+0.09}_{-0.19}(1.65)$	$1.87^{+0.13}_{-0.21}(1.75)$	$1.70^{+0.10}_{-0.13}(1.67)$	$1.72^{+0.09}_{-0.12}(1.70)$
M_B [mag]	--	--	$-19.317^{+0.021}_{-0.025}(-19.311)$	$-19.290 \pm 0.017(-19.278)$	$-19.282 \pm 0.017(-19.280)$
	--	--	$-19.407 \pm 0.013(-19.411)$	$-19.379 \pm 0.012(-19.373)$	$-19.372 \pm 0.011(-19.369)$
H_0 [km/s/Mpc]	$70.77^{+0.79}_{-2.70}(71.22)$ $67.39 \pm 0.55(67.28)$	$73.30^{+1.20}_{-1.00}(73.59)$ $68.84 \pm 0.48(68.61)$	$71.72^{+0.73}_{-0.92}(71.97)$ $68.55 \pm 0.44(68.54)$	$72.82 \pm 0.65(73.20)$ $69.57 \pm 0.42(69.73)$	$73.16 \pm 0.64(73.36)$ $69.83 \pm 0.37(69.96)$
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$\ln \mathcal{B}_{ij}$	-1.28	-12.65	-7.52	-19.47	-19.77

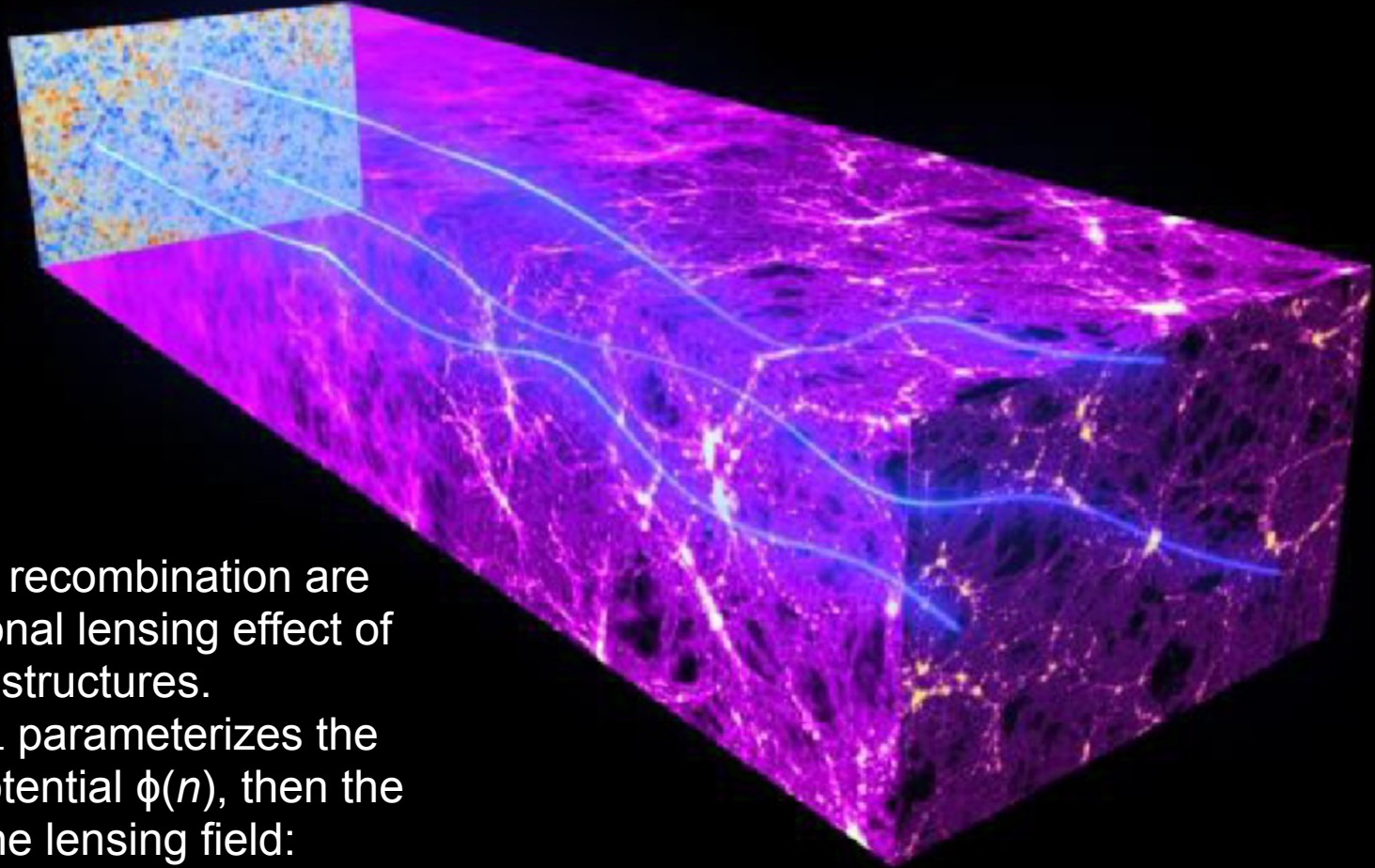
Sign- switching cosmological constant

We see that there is no H_0 tension in the present analyses of Λ_s CDM with all data combinations including the BAOtr data.
Also the S8 tension is completely solved.



...but the excess of lensing in
Planck could explain S8...

A_L internal anomaly



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:

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

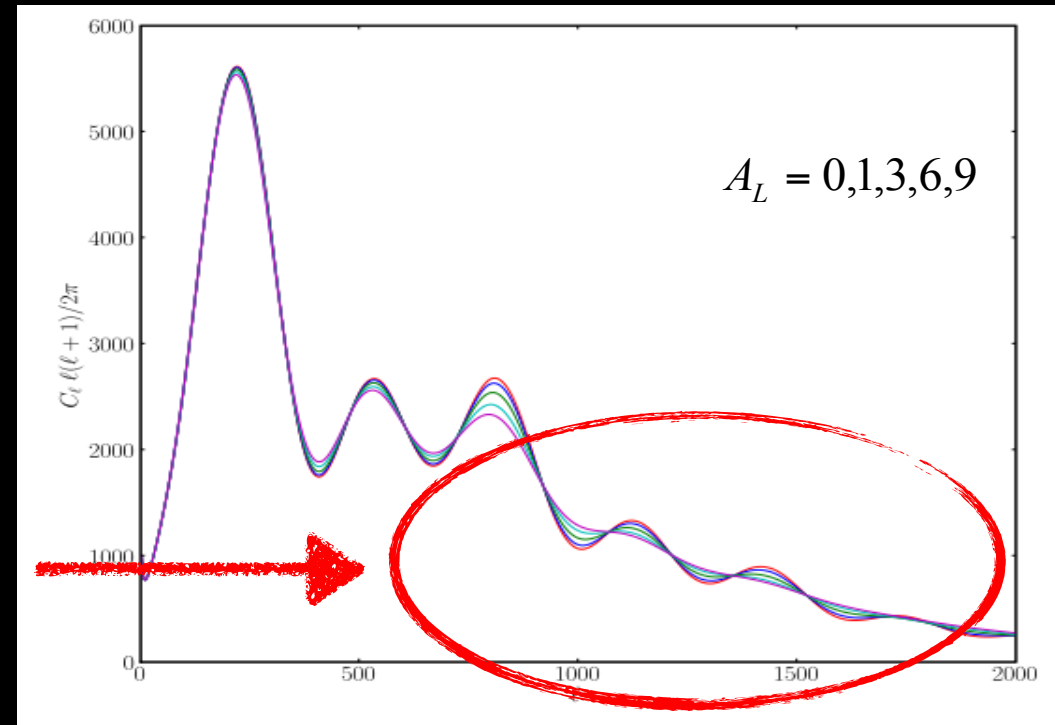
The gravitational lensing deflects the photon path by a quantity defined by the gradient of the lensing potential $\phi(n)$, integrated along the line of sight n , remapping the temperature field.

A_L internal anomaly

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

A_L : a failed consistency check

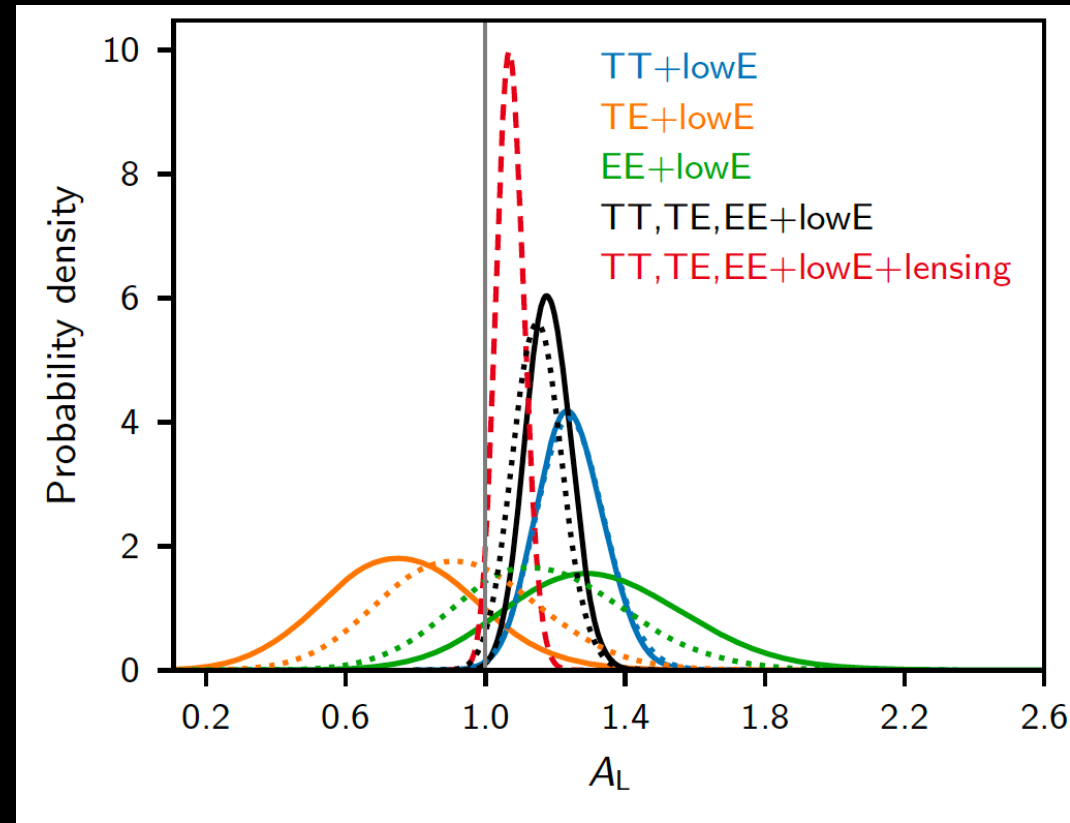
The Planck lensing-reconstruction power spectrum is consistent with the amplitude expected for Λ CDM models that fit the CMB spectra, so the Planck lensing measurement is compatible with $A_L = 1$.

However, the distributions of A_L inferred from the CMB power spectra alone indicate a preference for $A_L > 1$.

The joint combined likelihood shifts the value preferred by the TT data downwards towards $A_L = 1$, but the error also shrinks, increasing the significance of $A_L > 1$ to 2.8σ .

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

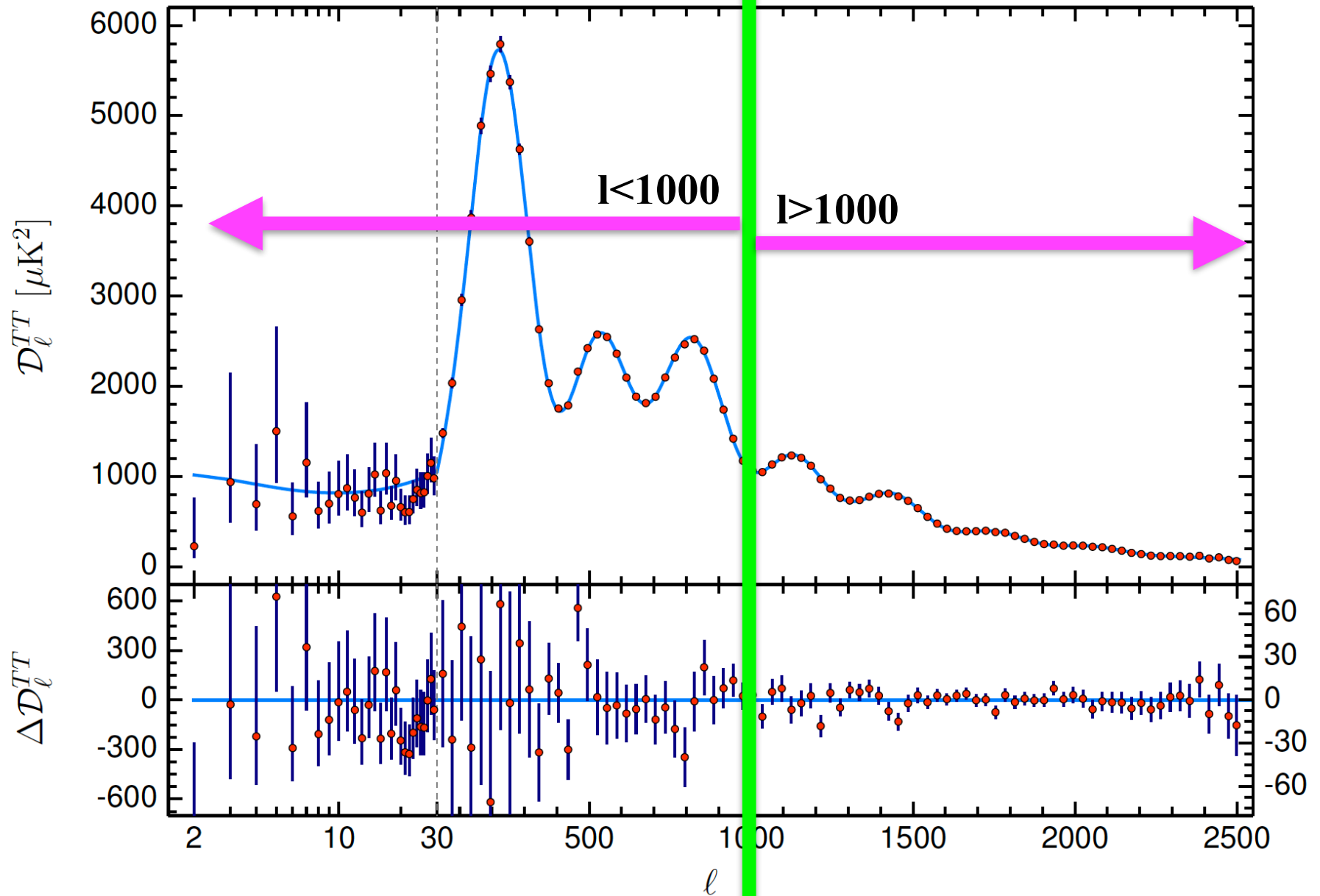
Planck 2018, Astron.Astrophys. 641 (2020) A6



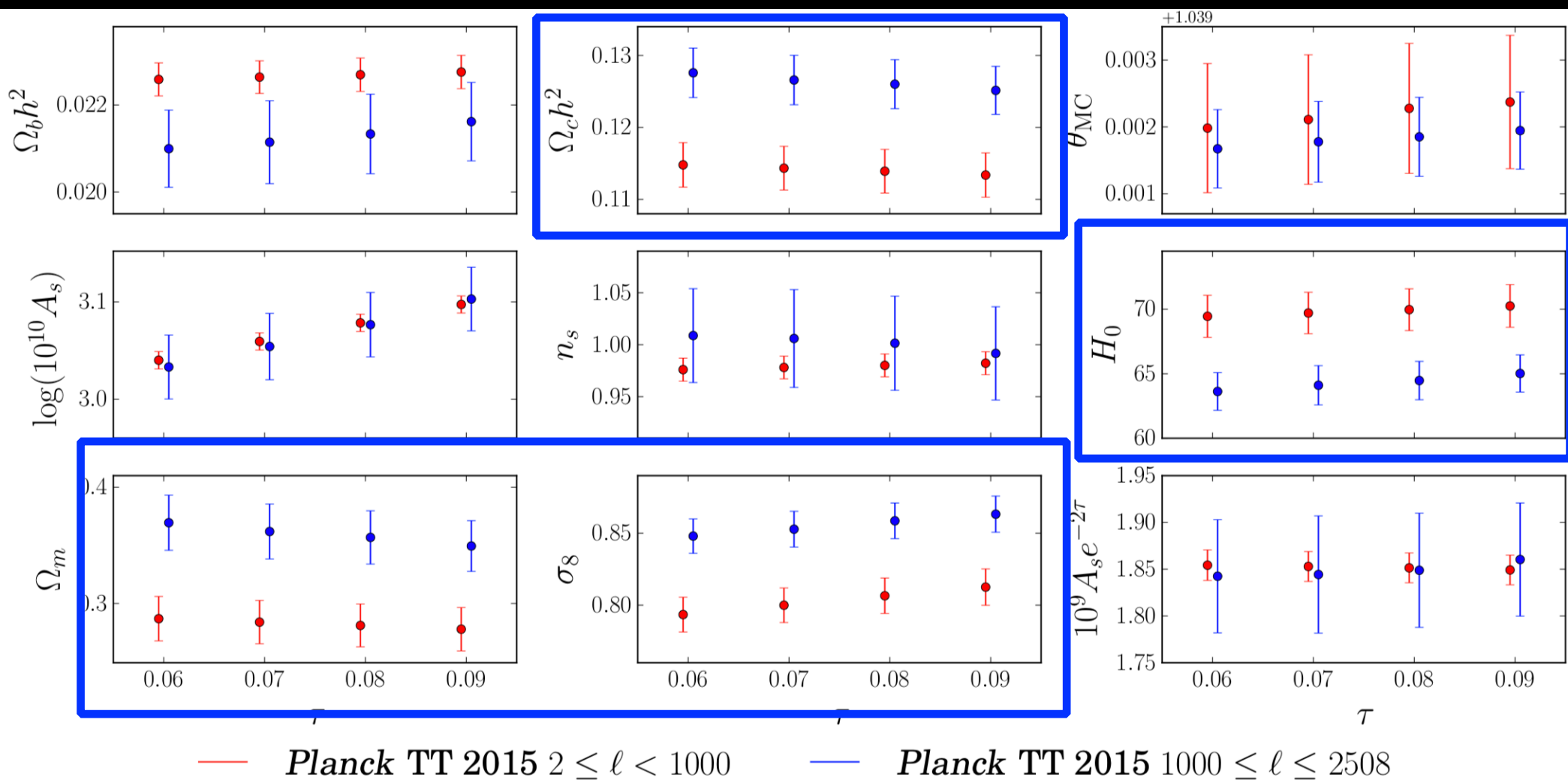
$$A_L = 1.243 \pm 0.096 \quad (68\%, \text{ Planck TT+lowE}),$$

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

A_L can explain internal tension

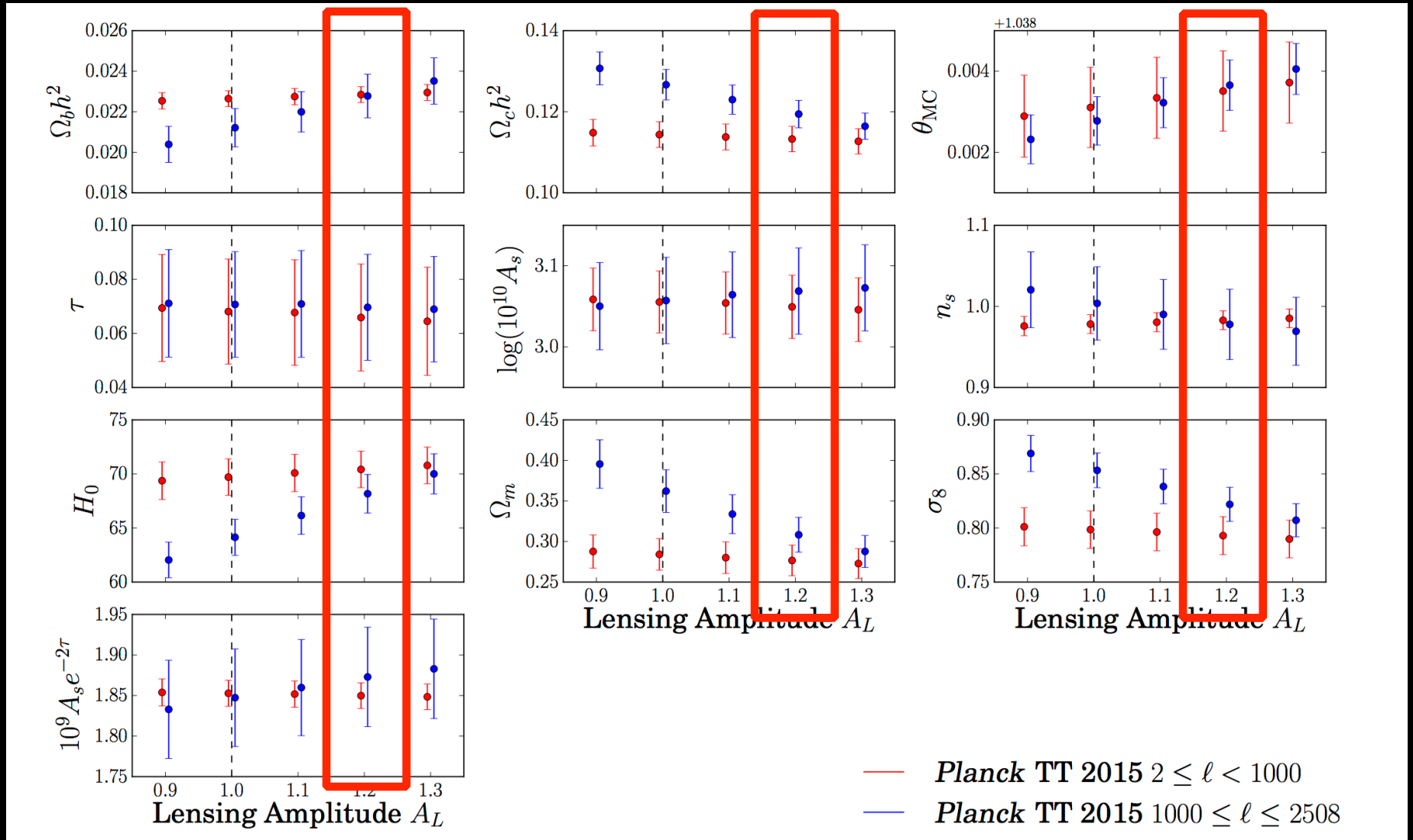


A_L can explain internal tension



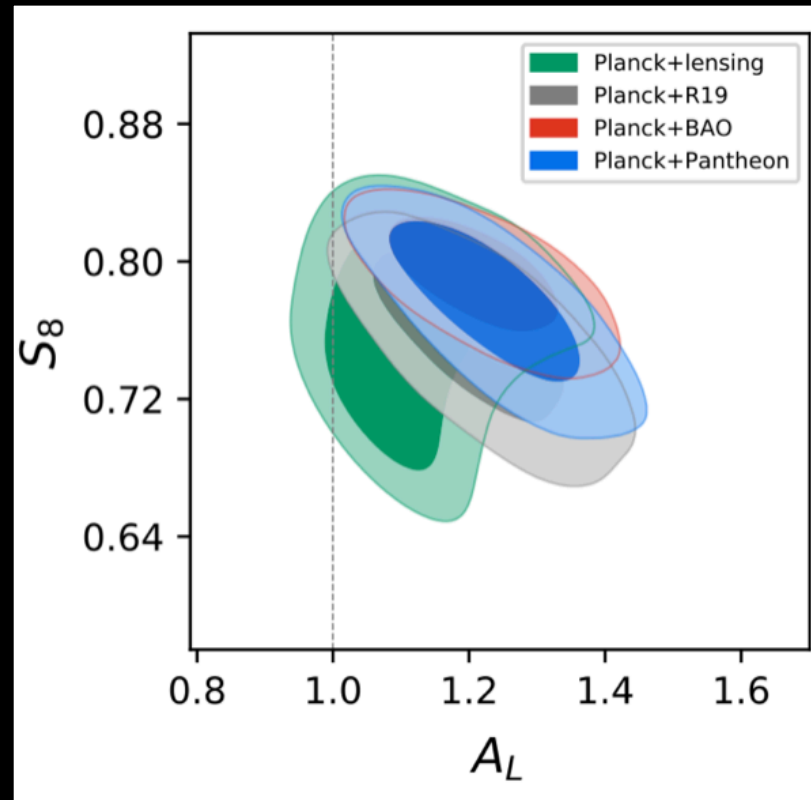
Marginalized 68.3% confidence Λ CDM parameter constraints from fits to the $l < 1000$ and $l \geq 1000$ *Planck* TT 2015 spectra. Tension at more than 2σ level appears in $\Omega_c h^2$ and derived parameters, including H_0 , Ω_m , and σ_8 .

A_L can explain internal tension



Increasing A_L smooths out the high order acoustic peaks, improving the agreement between the two multipole ranges.

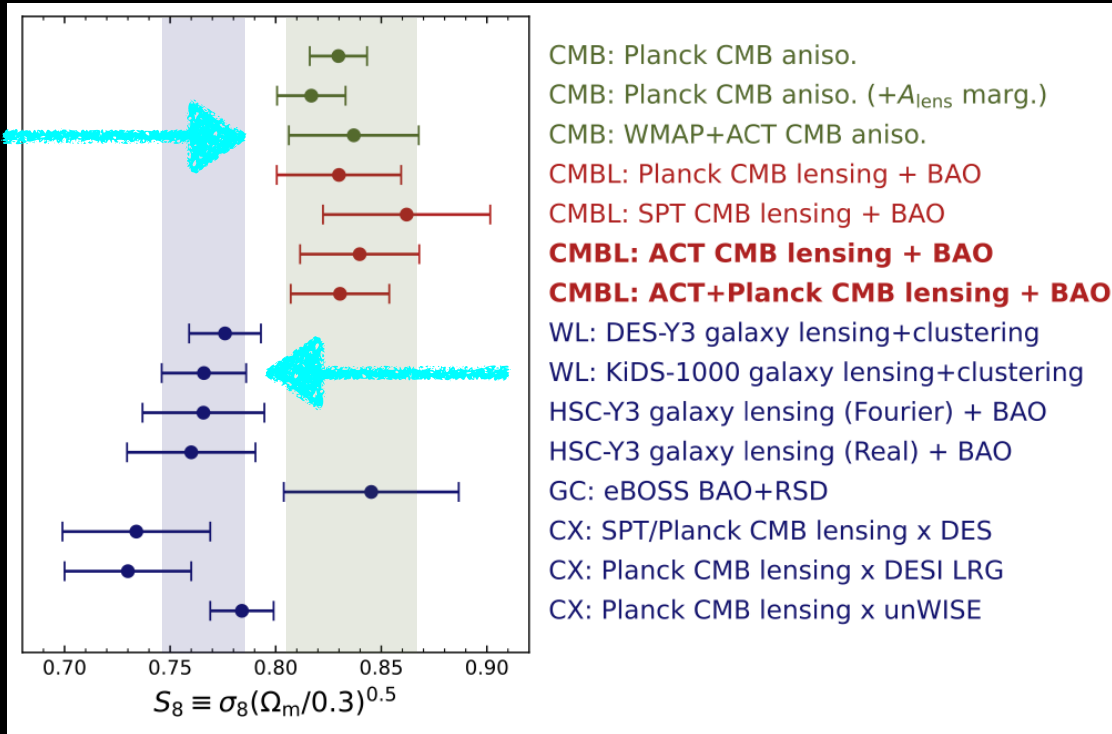
A_L can explain the S_8 tension



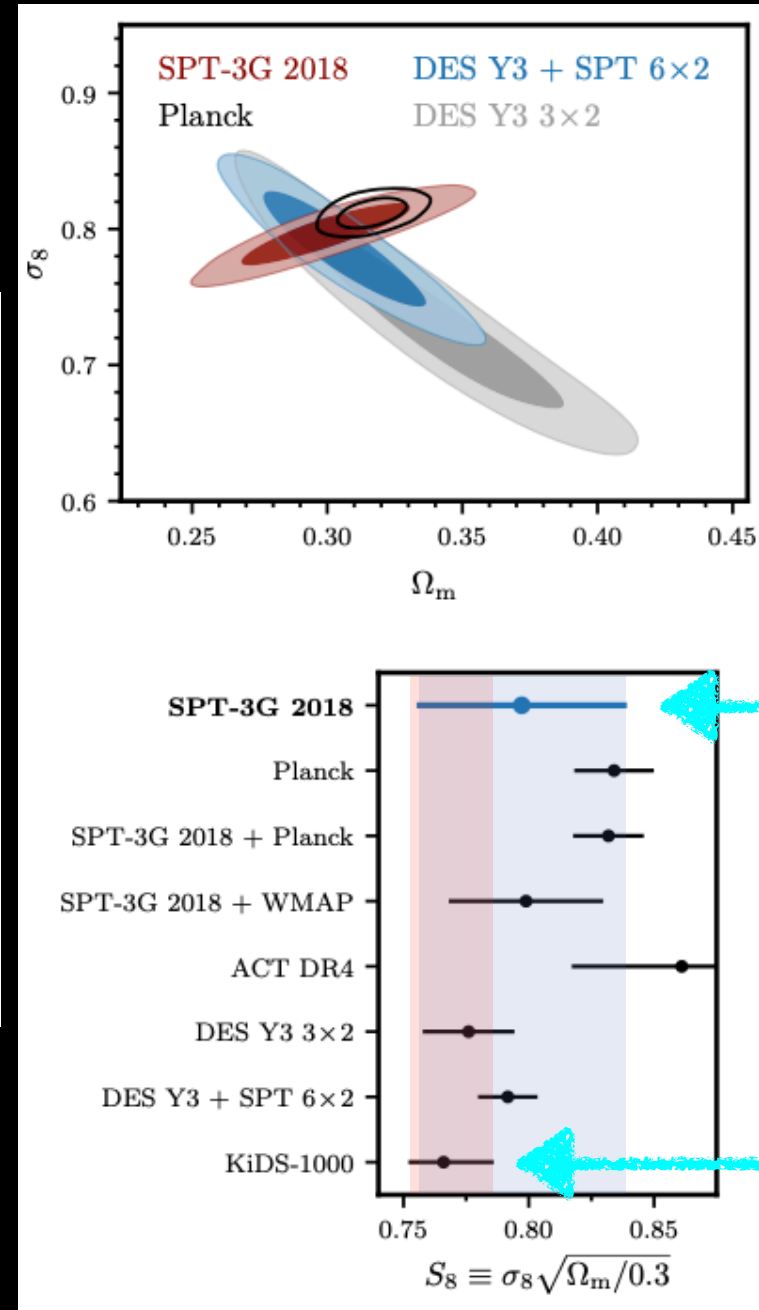
Di Valentino, Melchiorri and Silk, JCAP 2001 (2020) no.01, 013

A_L that is larger than the expected value at about 3 standard deviations even when combining the Planck data with BAO and supernovae type Ia external datasets.

Alternative CMB are not in significant tension

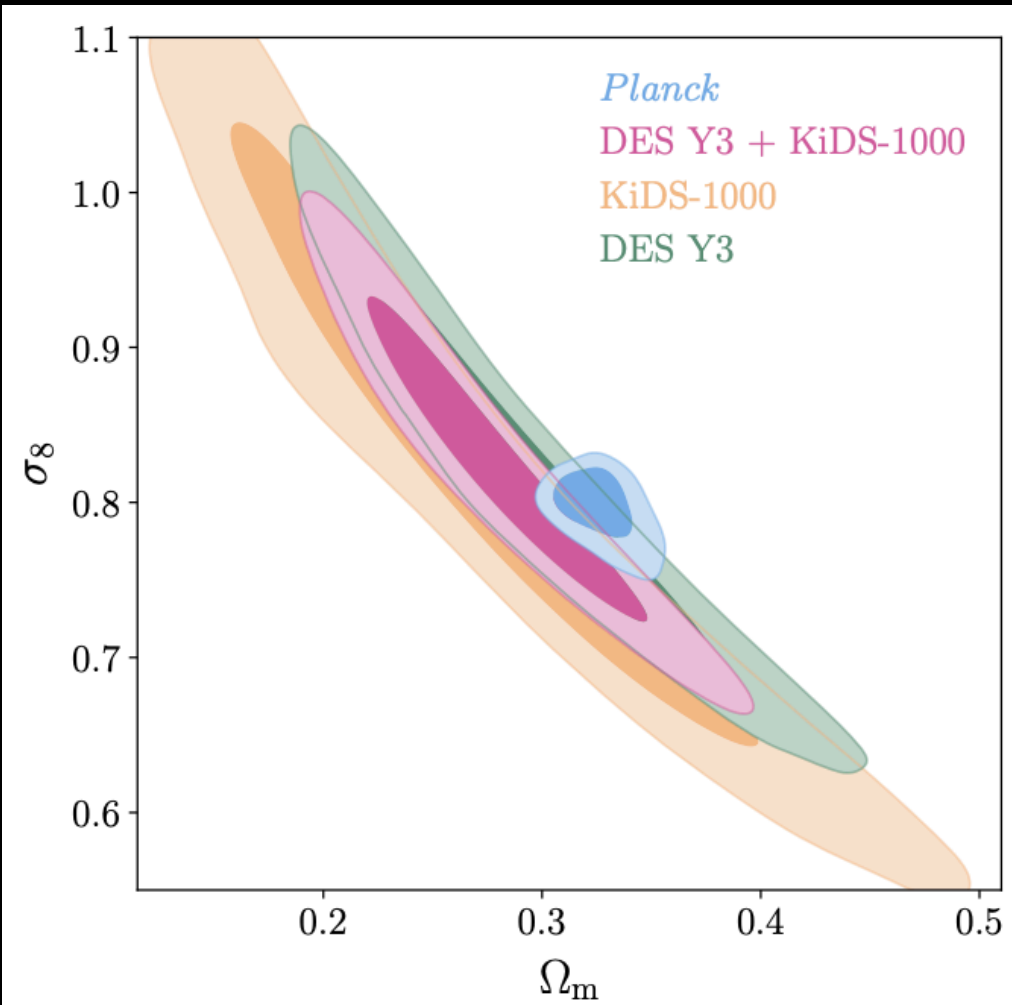


ACT collaboration, arXiv:2304.05203



SPT-3G collaboration, arXiv:2212.05642

DES Y3 + KiDS-1000



There is no more S_8 tension, showing now **an agreement at about 1.7σ** between Planck assuming Λ CDM and this combined analysis.

$$S_8 = 0.790^{+0.018}_{-0.014}$$

DES Y3 + KiDS-1000 collaborations, arXiv:2305.17173 [astro-ph.CO]

DES Y3 + KiDS-1000 collaborations, arXiv:2305.17173 [astro-ph.CO]

But...

assuming General Relativity,
is there a **physical explanation**
for A_L ?

Planck 2018 results. VI. Cosmological parameters

Planck Collaboration: N. Aghanim⁵⁴, Y. Akrami^{15,57,59}, M. Ashdown^{65,5}, J. Aumont⁹⁵, C. Baccigalupi⁷⁸, M. Ballardini^{21,41}, A. J. Banday^{95,8}, R. B. Barreiro⁶¹, N. Bartolo^{29,62}, S. Basak⁸⁵, R. Battye⁶⁴, K. Benabed^{55,90}, J.-P. Bernard^{95,8}, M. Bersanelli^{32,45}, P. Bielewicz^{75,78}, J. J. Bock^{63,10}, J. R. Bond⁷, J. Borrill^{12,93}, F. R. Bouchet^{55,90}, F. Boulanger^{89,54,55}, M. Bowring²⁶, G. Brinza^{44,30,47}, R. C. Butler⁸⁷, J.-F. Cardoso^{55,90}, J. Carron²³, A. Challinor^{58,65,11}, H. C. Chiang⁶⁰, F. Cuttaia⁴¹, P. de Bernardis³¹, G. de Zotti⁴², J. Delabrouille⁶⁰, A. Ducout⁶⁶, X. Dupac³⁵, S. Dusini⁶², G. Efstathiou⁶⁵, J. Ferguson¹¹, R. Fernandez-Cobos⁶¹, F. Finelli^{41,47}, F. Forastieri⁶⁰, S. Galli^{55,90,1}, K. Gangui², R. T. Génova-Santos^{60,16}, M. Gerbino⁶⁰, A. Gruppuso^{41,47}, J. E. Gudmundsson^{94,25}, J. Hamann⁸⁶, Y. Han^{77,80,74}, Z. Huang⁸³, A. H. Jaffe⁵³, W. C. Jones²⁵, A. Karakci⁵⁹, I. Kneib⁶⁰, N. Krachmalnicoff⁷⁸, M. Kunz^{14,54,3}, H. Kurki-Suonio^{24,40}, M. Le Jeune², P. Lemos^{58,65}, J. Lesgourgues⁵⁶, F. Levri⁶⁰, M. López-Cañiego³⁵, P. M. Lubin²⁸, Y.-Z. Ma^{77,80,74}, J. M. M. M. M. A. Marcos-Caballero⁶¹, M. Maris⁴³, P. G. Martin⁷, M. Marín ⁶⁰, P. R. Meinhold²⁸, A. Melchiorri^{21,50}, A. Mennella^{32,45}, D. Molinari^{30,41,48}, L. Montier^{95,8}, G. Morgante⁴¹, A. Mouton⁶⁰, B. Partridge³⁹, G. Patanchon², H. V. Peiris²², F. Perrotta⁶⁰, J. P. Rachen¹⁸, M. Reinecke⁷², M. Remazeilles⁶⁴, A. R. Ruiz-Granados^{60,16}, L. Salvati⁵⁴, M. Sandri⁴¹, M. Savelain⁶⁰, R. Sunyaev^{72,91}, A.-S. Suur-Uski^{24,40}, J. A. Tauber³⁶, D. L. Valenziano⁴¹, J. Valiviita^{24,40}, B. Van Tent⁶⁹, L. Vibert ⁶⁰, S. D. M. White⁶⁰

(Affiliation)

We present cosmological parameter results from the final full-sky release of the Planck satellite mission, based on 15 months of observations. The data are consistent with the standard Λ CDM model, but show a clear preference for a non-zero curvature of the universe. We present cosmological parameter results from the final full-sky isotropies, combining information from the temperature and polarization measurements of large-scale polarization allow the significant gains in the precision of other correlated parameters. In many parameters, with residual modelling uncertainties estimated using a spatially-flat 6-parameter Λ CDM cosmology having a power spectrum from polarization, temperature, and lensing, separately and in combination. The best-fit cosmological parameters are: matter density $\Omega_b h^2 = 0.0224 \pm 0.0001$, scalar spectral index $n_s = 0.9649 \pm 0.0049$, tensor-to-scalar ratio $r = 0.066 \pm 0.019$, Hubble constant $H_0 = (67.4 \pm 0.5) \text{ km s}^{-1} \text{ Mpc}^{-1}$; matter density $\Omega_m = 0.315 \pm 0.007$, dark energy density $\Omega_\Lambda = 0.685 \pm 0.007$. We find no compelling evidence for extensions to the base- Λ CDM model (considering single-parameter extensions) we constrain the effective number of degrees of freedom N_{eff} to be consistent with the Standard Model prediction $N_{\text{eff}} = 3.046$, and find that this is preferred over the base- Λ CDM model, but this is not supported by BAO data. The joint constraint with BAO measurements on N_{eff} with Type Ia supernovae (SNe), the dark-energy equation of state w is consistent with a constant. We find no evidence for deviations from a purely adiabatic initial state. Using the tensor-to-scalar ratio r from the Keck Array data, we place a limit on the tensor-to-scalar ratio $r < 0.036$ at 95% confidence. The agreement with BAO, SNe, and some galaxy lensing observations including galaxy clustering (which prefers lower fluctuation amplitude) and measurements of the Hubble constant (which prefer a high value) are consistent with the Λ CDM data.

Key words. Cosmology: observations – Cosmology: theory – Cosmic background radiation – cosmological parameters

$$\Omega_K = -0.044^{+0.018}_{-0.015} \quad (68\%, \text{Planck TT,TE,EE+lowE}), \quad (46b)$$

a detection of curvature at about 3.4σ

an apparent detection of curvature at well over 2σ . The 99% probability region for the TT,TE,EE+lowE result is $-0.095 < \Omega_K < -0.007$, with only about 1/10000 samples at $\Omega_K \geq 0$. This is not entirely a volume effect, since the best-fit χ^2 changes by $\Delta\chi^2_{\text{eff}} = -11$ compared to base Λ CDM when adding the one additional curvature parameter. The reasons for the pull towards

*Corresponding author: G. Efstathiou, gpe@ast.cam.ac.uk

†Corresponding author: S. Galli, gallis@iap.fr

‡Corresponding author: A. Lewis, antony@cosmologist.info

Curvature of the universe

*Corresponding author: G. Efstathiou, gpe@ast.cam.ac.uk

†Corresponding author: S. Galli, gallis@iap.fr

‡Corresponding author: A. Lewis, antony@cosmologist.info

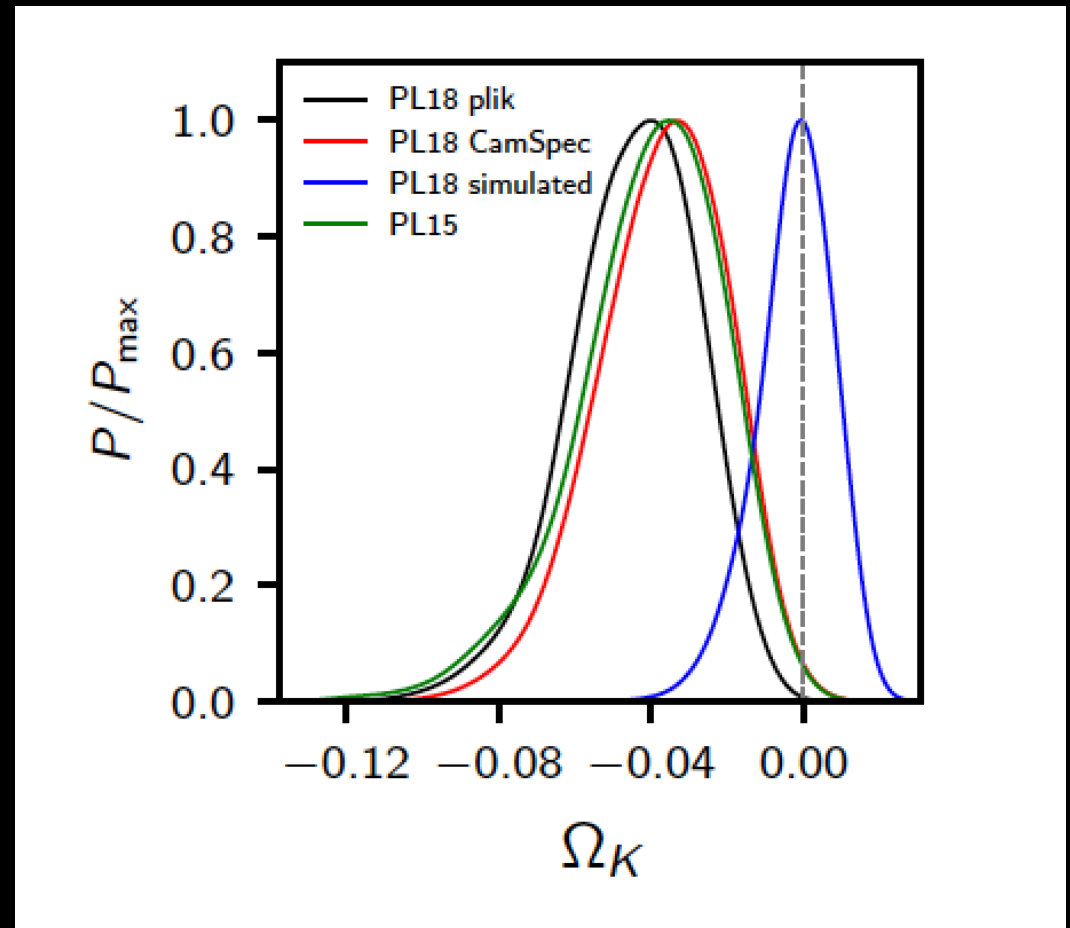
Curvature of the universe

Can Planck provide an **unbiased and reliable estimate** of the curvature of the Universe?

This may not be the case since a "geometrical degeneracy" is present with Ω_m .

When precise CMB measurements at arc-minute angular scales are included, since **gravitational lensing** depends on the matter density, its detection **breaks the geometrical degeneracy**. The Planck experiment with its improved angular resolution offers the unique opportunity of a precise measurement of curvature from a single CMB experiment.

We simulated Planck, finding that such experiment could constrain curvature with a 2% uncertainty, without any significant bias towards closed models.



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

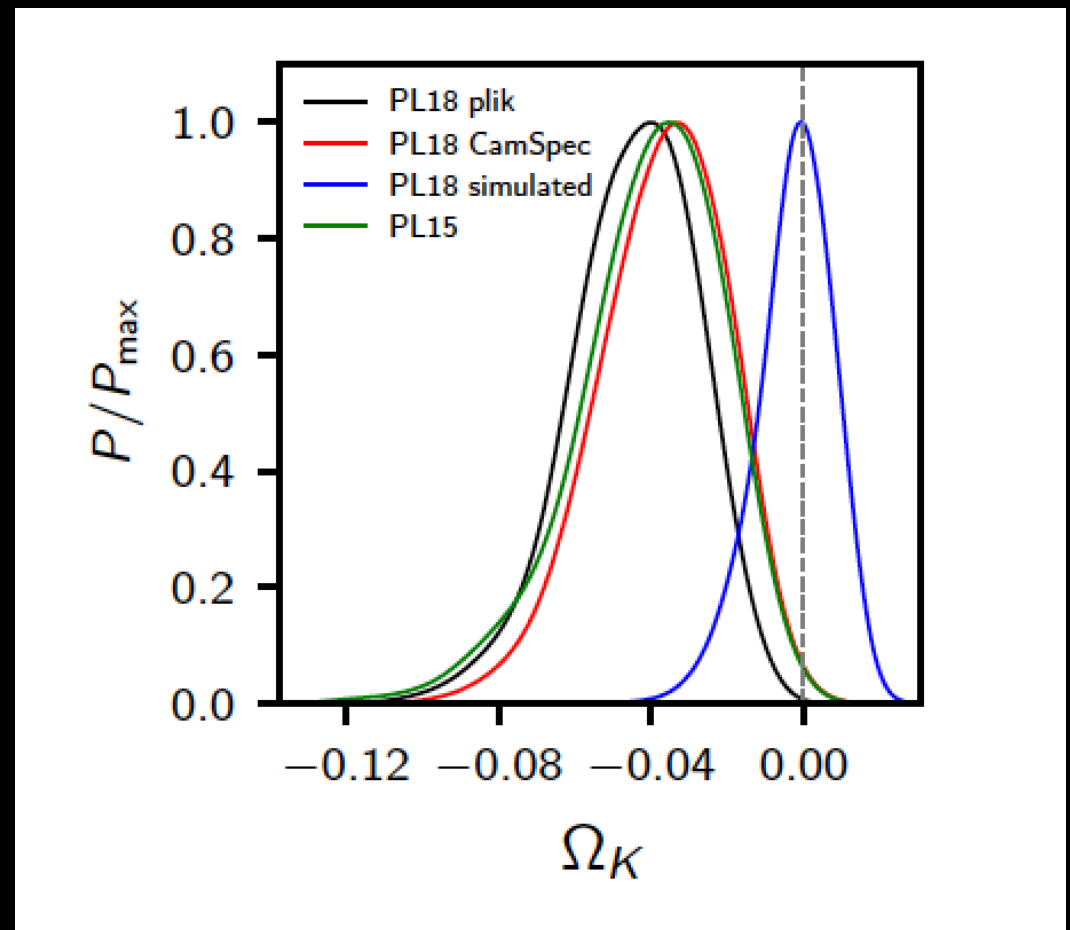
Curvature of the universe

Planck favours a closed Universe ($\Omega_K < 0$) with 99.985% probability.

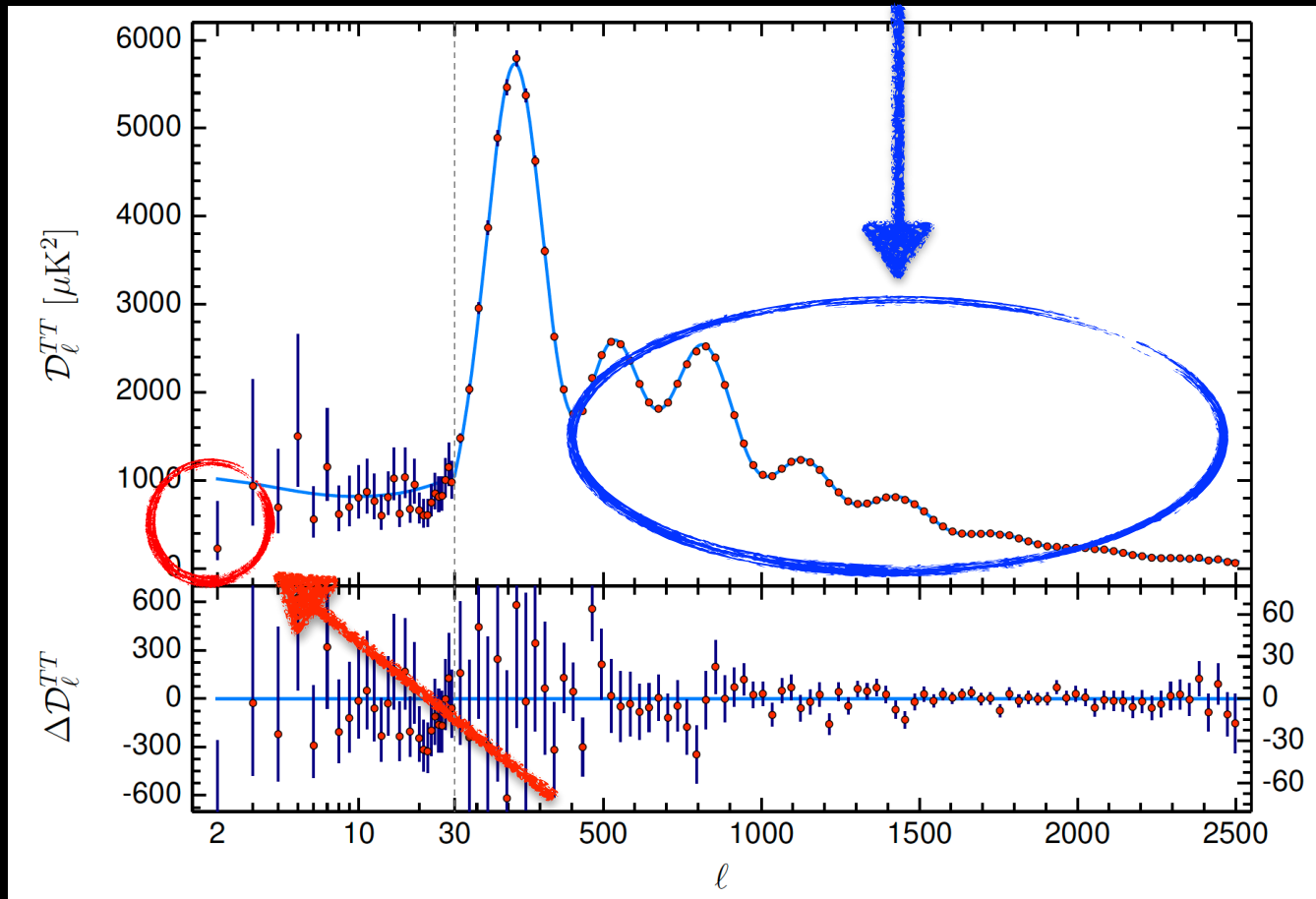
A closed Universe with $\Omega_K = -0.0438$ provides a better fit to PL18 with respect to a flat model.

This is not entirely a volume effect, since the best-fit $\Delta\chi^2$ changes by -11 compared to base Λ CDM when adding the one additional curvature parameter.

The improvement is due also to the fact that closed models could also lead to a large-scale cut-off in the primordial density fluctuations in agreement with the observed low CMB anisotropy quadrupole.



Low CMB anisotropy quadrupole



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

A model with $\Omega_k < 0$ is slightly preferred with respect to a flat model with $AL > 1$, because closed models better fit not only the damping tail, but also the low-multipole data, especially the quadrupole.

Astrophysics

[Submitted on 5 Mar 2003 (v1), last revised 30 Jul 2003 (this version, v2)]

Is the Low CMB Quadrupole a Signature of Spatial Curvature?

G. Efstathiou (University of Cambridge)

The temperature anisotropy power spectrum measured with the Wilkinson Microwave Anisotropy Probe (WMAP) at high multipoles is in spectacular agreement with an inflationary Lambda-dominated cold dark matter cosmology. However, the low order multipoles (especially the quadrupole) have lower amplitudes than expected from this cosmology, indicating a need for new physics. Here we speculate that the low quadrupole amplitude is associated with spatial curvature. We show that positively curved models are consistent with the WMAP data and that the quadrupole amplitude can be reproduced if the primordial spectrum truncates on scales comparable to the curvature scale.

Comments: 4 pages, Latex, 2 figs, revised version accepted by MNRAS

Subjects: Astrophysics (astro-ph)

Journal reference: Mon.Not.Roy.Astron.Soc. 343 (2003) L95

DOI: [10.1046/j.1365-8711.2003.06940.x](https://doi.org/10.1046/j.1365-8711.2003.06940.x)Cite as: [arXiv:astro-ph/0303127](https://arxiv.org/abs/astro-ph/0303127)(or [arXiv:astro-ph/0303127v2](https://arxiv.org/abs/astro-ph/0303127v2) for this version)

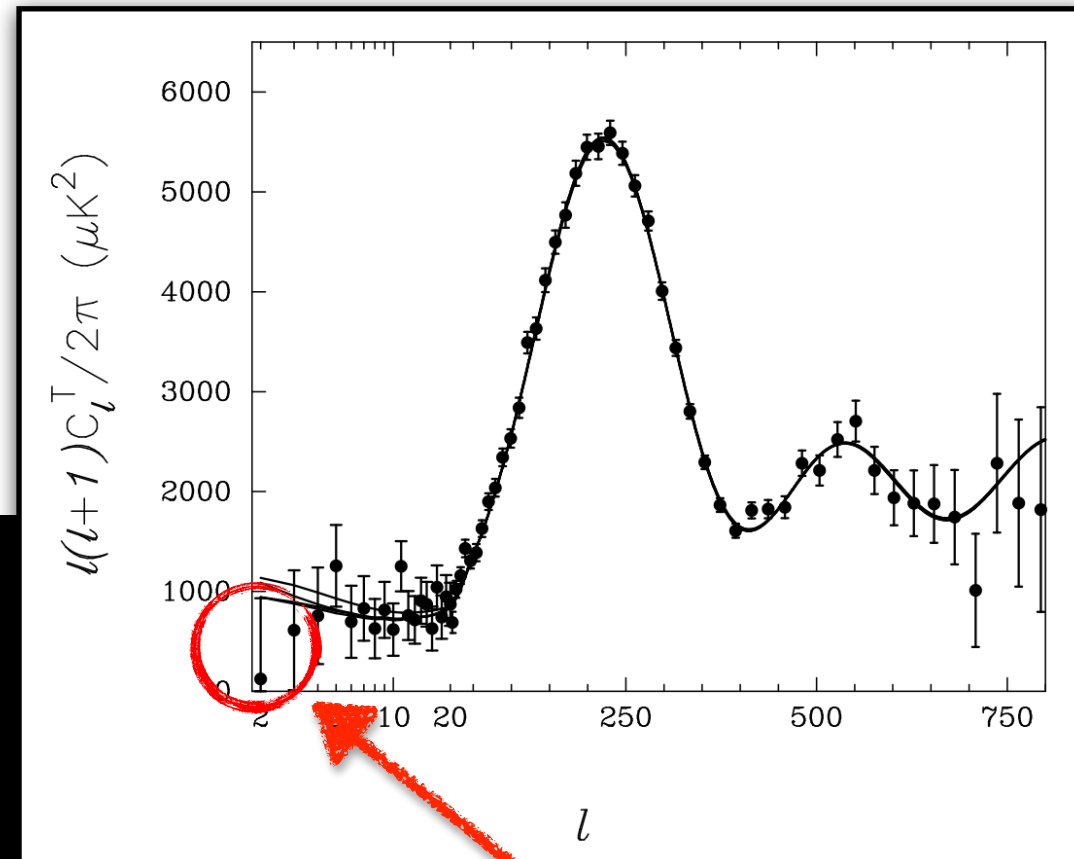
Submission history

From: George Efstathiou [[view email](#)]

[v1] Wed, 5 Mar 2003 23:30:33 UTC (21 KB)

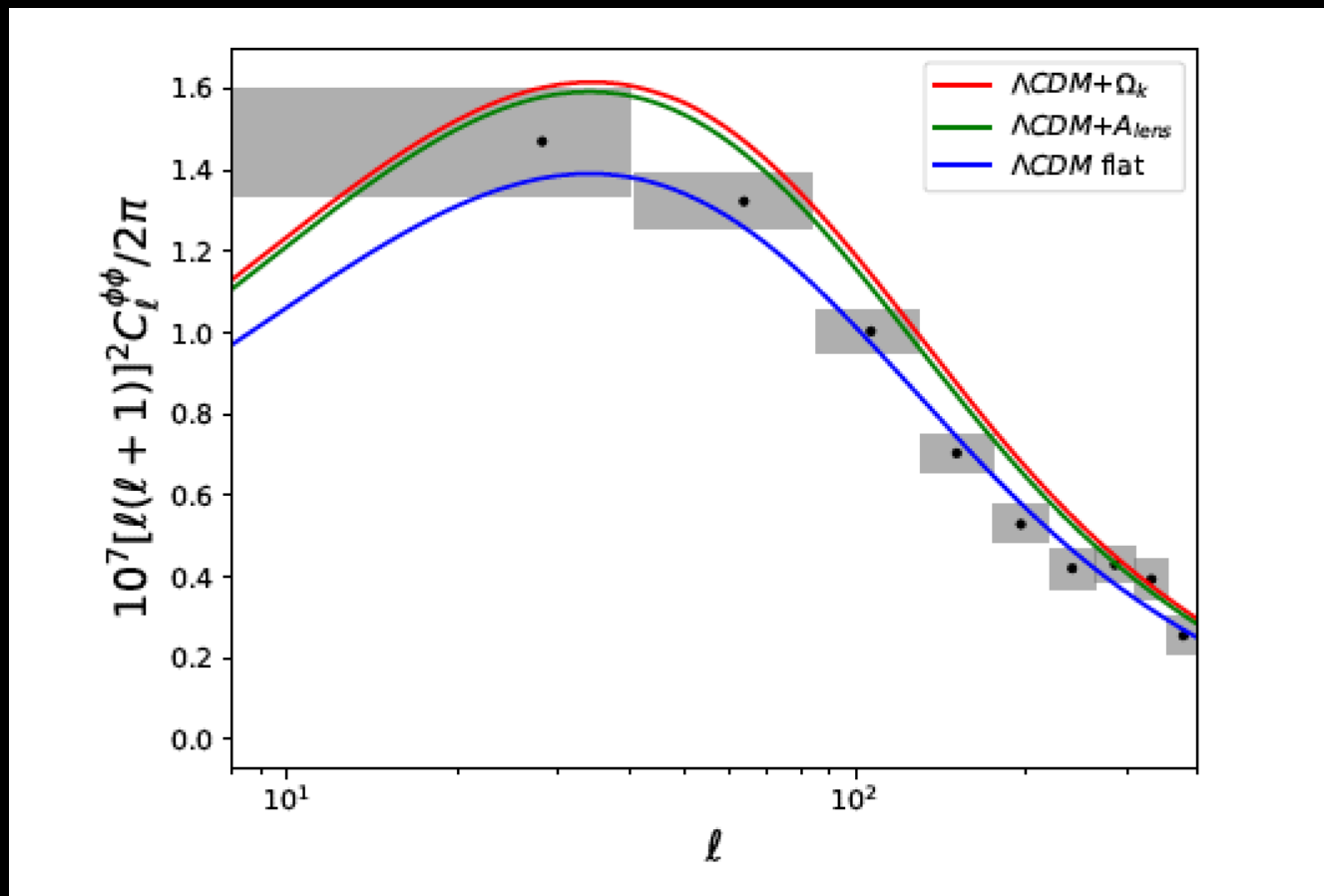
[v2] Wed, 30 Jul 2003 10:16:45 UTC (22 KB)

A lower quadrupole than predicted by the Λ CDM was already present in WMAP, and a closed universe to explain this effect was already taken into account.

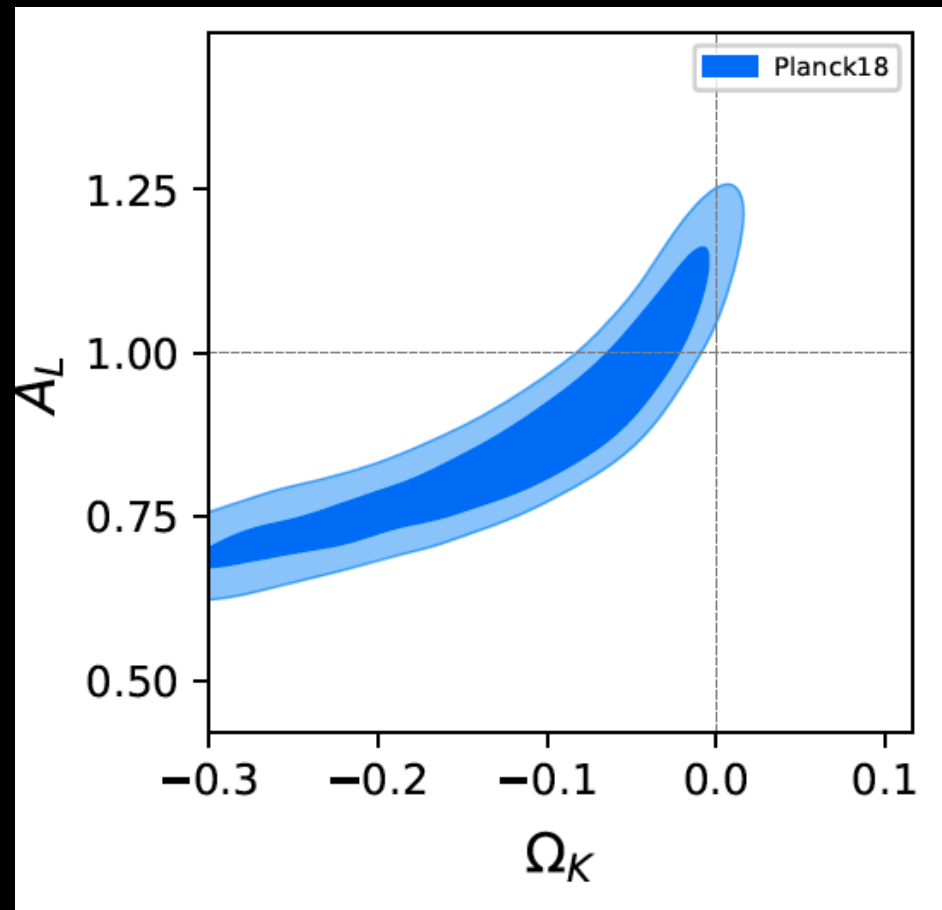


What about CMB lensing?

Closed models predict substantially higher lensing amplitudes than in Λ CDM, because the dark matter content can be greater, leading to a larger lensing signal. The reasons for the pull towards negative values of Ω_K are essentially the same as those that lead to the preference for $A_L > 1$.



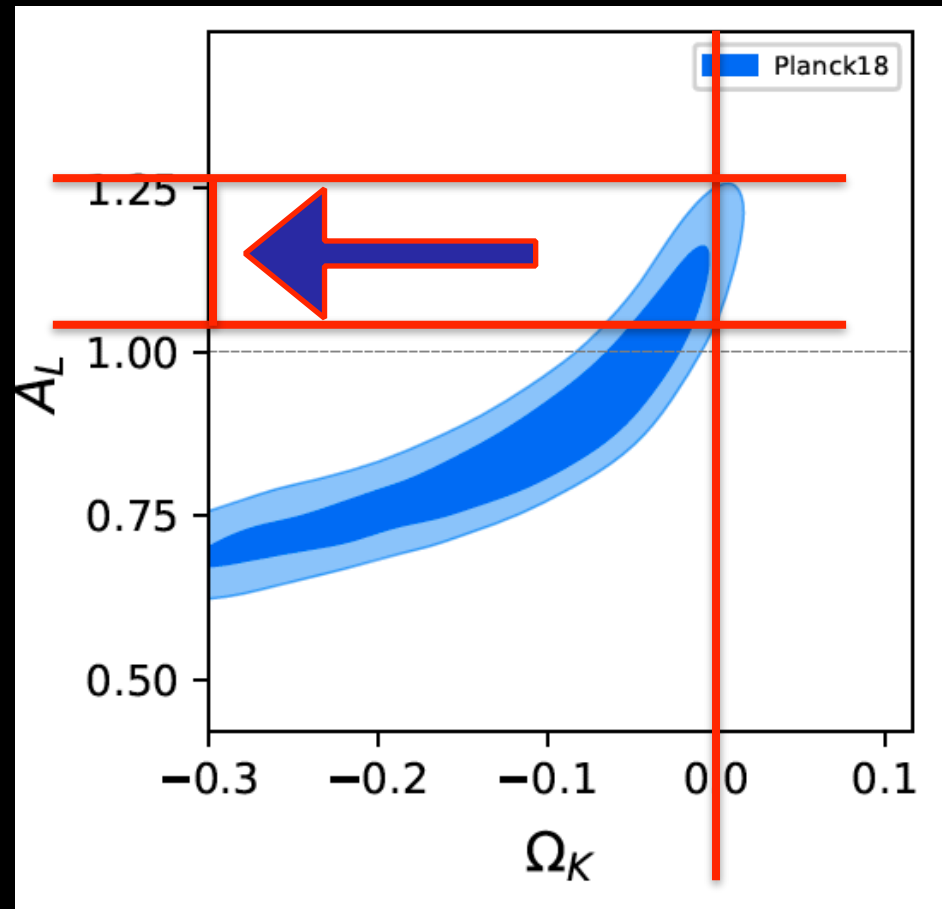
A closed universe (Friedmann 1922) can explain A_L !



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

A degeneracy between curvature and the A_L parameter is clearly present. A closed universe can provide a robust physical explanation to the enhancement of the lensing amplitude. In fact, the curvature of the Universe is not new physics beyond the standard model, but it is predicted by the General Relativity, and depends on the energy content of the Universe.

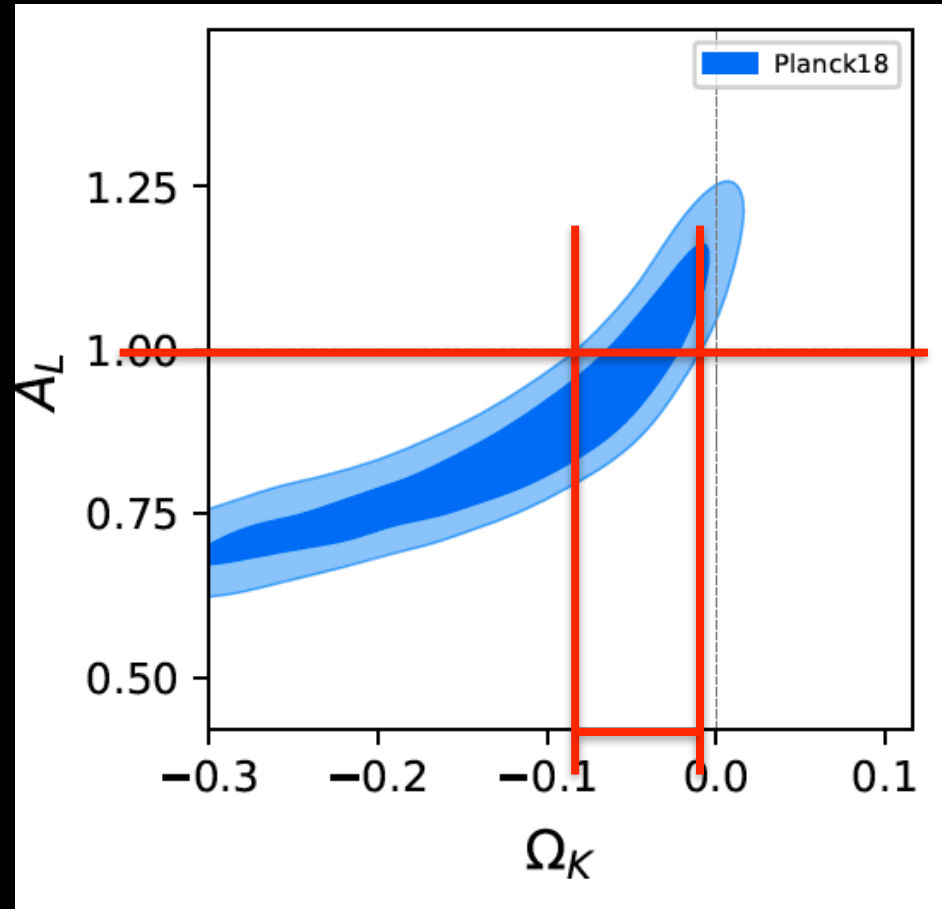
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A degeneracy between curvature and the A_L parameter is clearly present. **A closed universe can provide a robust physical explanation** to the enhancement of the lensing amplitude. In fact, the curvature of the Universe **is not new physics** beyond the standard model, but it is predicted by the General Relativity, and depends on the energy content of the Universe.

The evolution over time of the geometry of the universe is described by
Einstein's equations:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^2}T_{\mu\nu} + \Lambda g_{\mu\nu}$$

which relate the purely geometric properties of space-time, with the distribution of energy of the universe. For this it is sufficient to know the energy content of the Universe to determine its geometry and vice-versa.

Adopting a 4-dimensional coordinate system for the space-time and the Cosmological Principle, i.e. a universe homogeneous and isotropic at large scales, the resulting metric is the **Friedmann-Lemaitre-Robertson-Walker (FLRW)**, that describes the distance between two events in space-time.

$$ds^2 = c^2 dt^2 - a^2(t) \left[\frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + \sin^2\theta d\varphi^2) \right]$$

The evolution over time of the geometry of the universe is described by Einstein's equations:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^2}T_{\mu\nu} + \Lambda g_{\mu\nu}$$

which relate the purely geometric properties of space-time, with the distribution of energy of the universe. For this it is sufficient to know the energy content of the Universe to determine its geometry and vice-versa.

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The curvature parameter k can be positive, null or negative, depending on the value of the curvature of the universe: positive, flat or negative.

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^2}T_{\mu\nu} + \Lambda g_{\mu\nu}$$

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Combining together the **FLRW metric** and **Einstein's equations** we obtain the **Friedmann equations** that describe the **expansion history of the universe**:

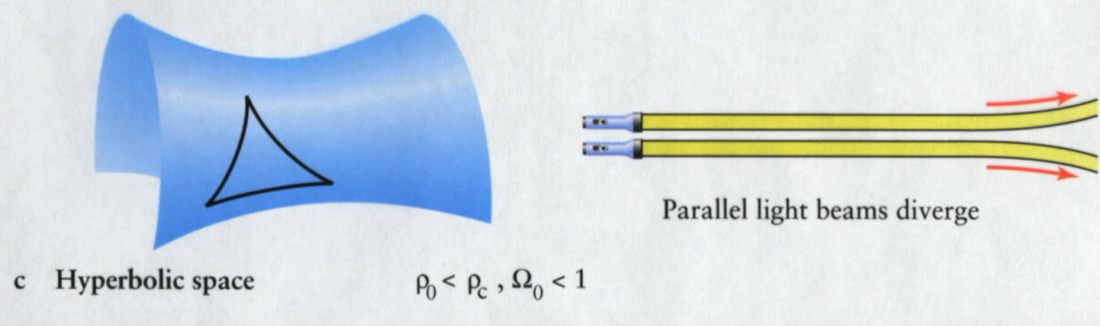
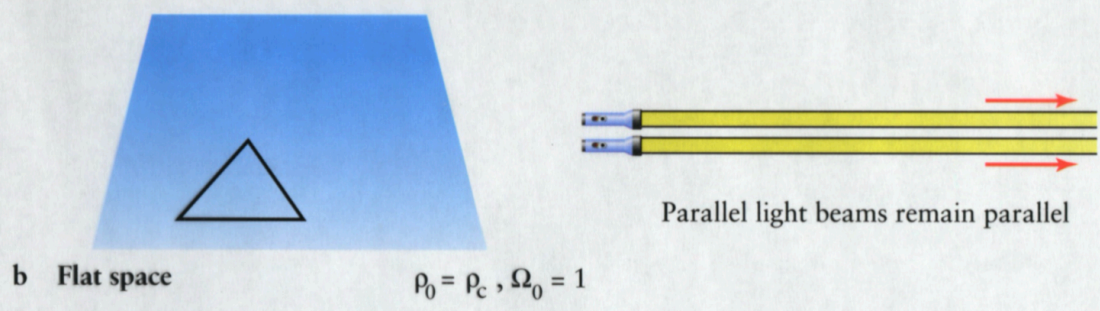
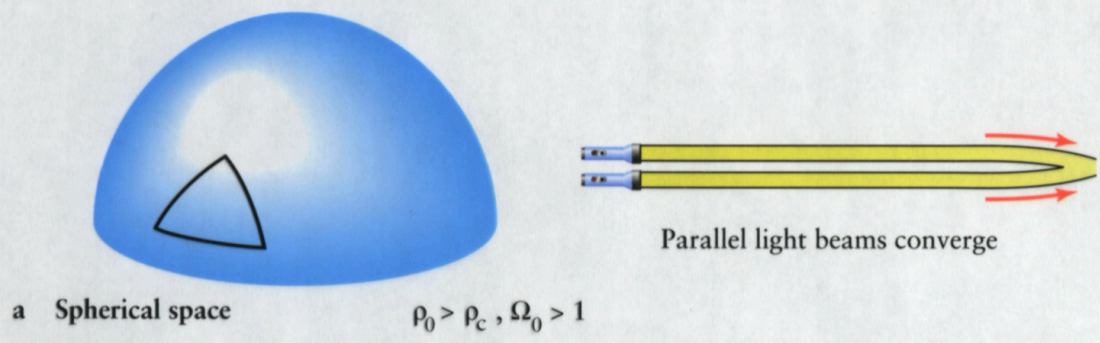
1st

$$H^2 = \left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$

2nd

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$

which relate the purely geometric properties of space-time, with the distribution of energy of the universe. For this it is sufficient to know the energy content of the Universe to determine its geometry and vice-versa.



If we divide the **1st Friedmann equation**, for the critical density (density of a flat universe), we obtain today:

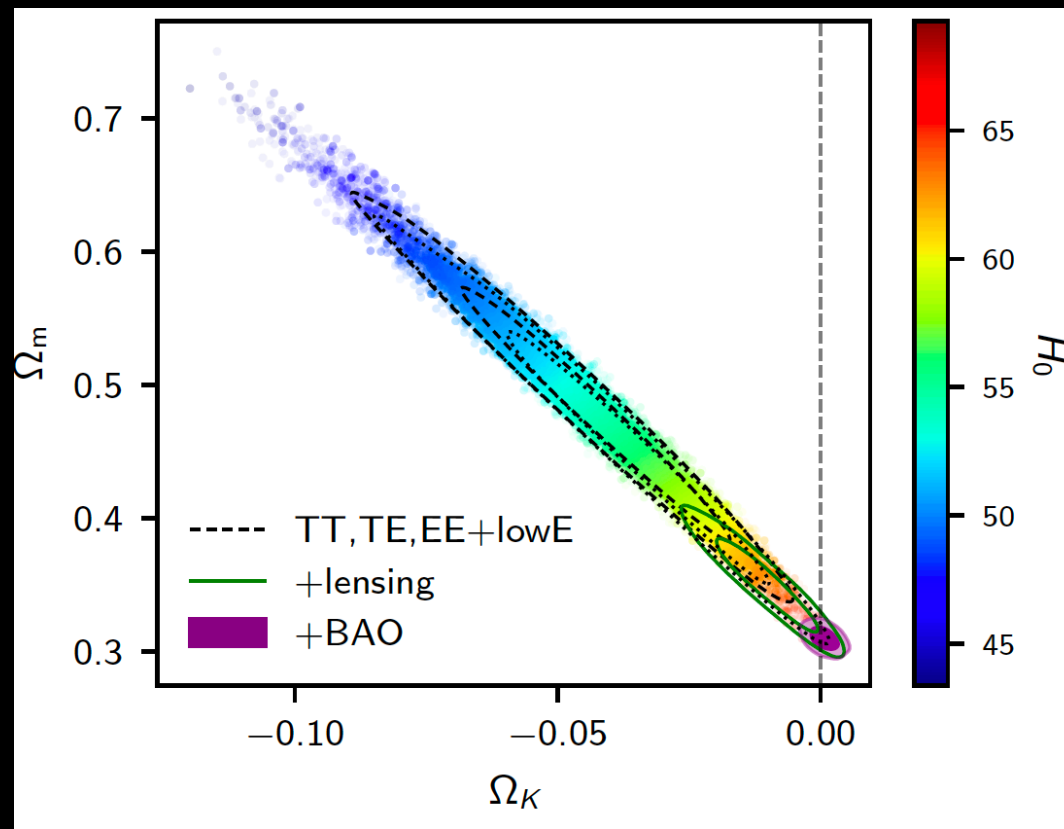
$$\Omega = \sum_i \Omega_i = \Omega_m + \Omega_\Lambda + \Omega_r = 1 - \Omega_k$$

From this equation it is possible to estimate the curvature of the universe, independently measuring the various contributions to the total density parameter Ω .

Figure: <http://w3.phys.nthu.edu.tw>

{	$\Omega > 1 \quad \Omega_k < 0$	$k > 0$: closed Universe
	$\Omega = 1 \quad \Omega_k = 0$	$k = 0$: flat Universe
	$\Omega < 1 \quad \Omega_k > 0$	$k < 0$: open Universe

What about Planck+BAO?



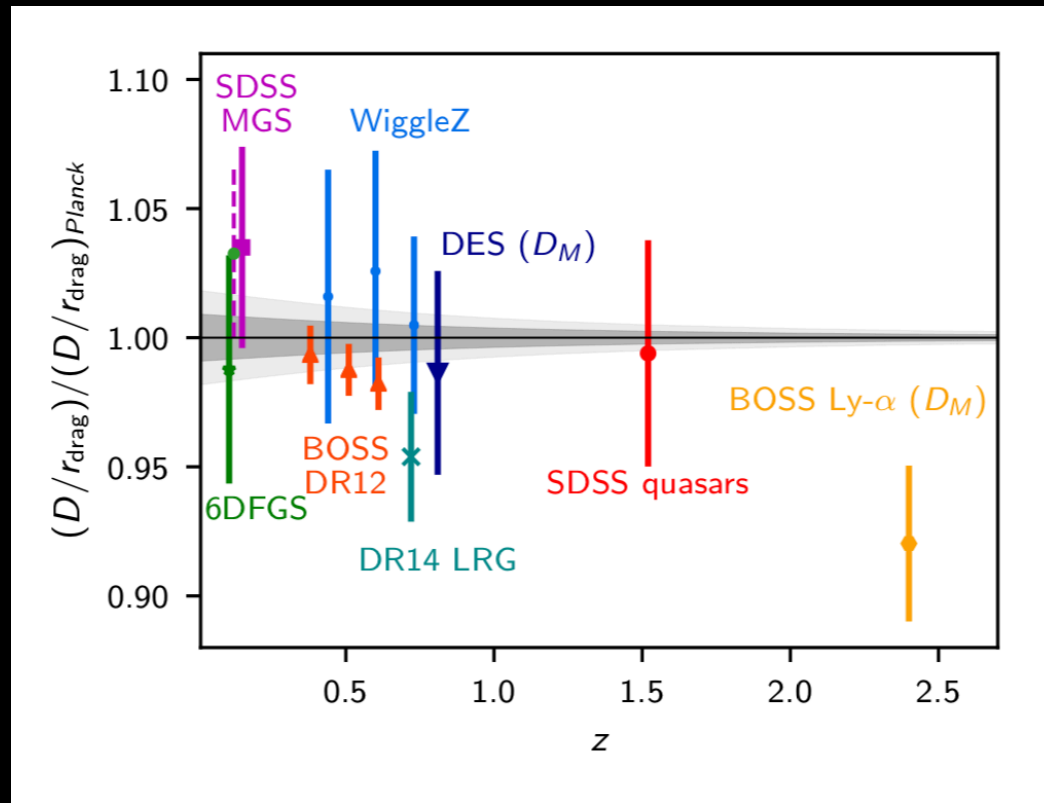
Planck 2018, Astron.Astrophys. 641 (2020) A6

Adding BAO data, a joint constraint is very consistent with a flat universe.

$$\Omega_K = 0.0007 \pm 0.0019 \quad (68\%, \text{TT, TE, EE+lowE} \\ \text{+lensing+BAO}).$$

Given the significant change in the conclusions from Planck alone, it is reasonable to **investigate whether they are actually consistent**. In fact, a basic assumption for combining complementary datasets is that these ones must be consistent, i.e. **they must plausibly arise from the same cosmological model**.

BAO tension



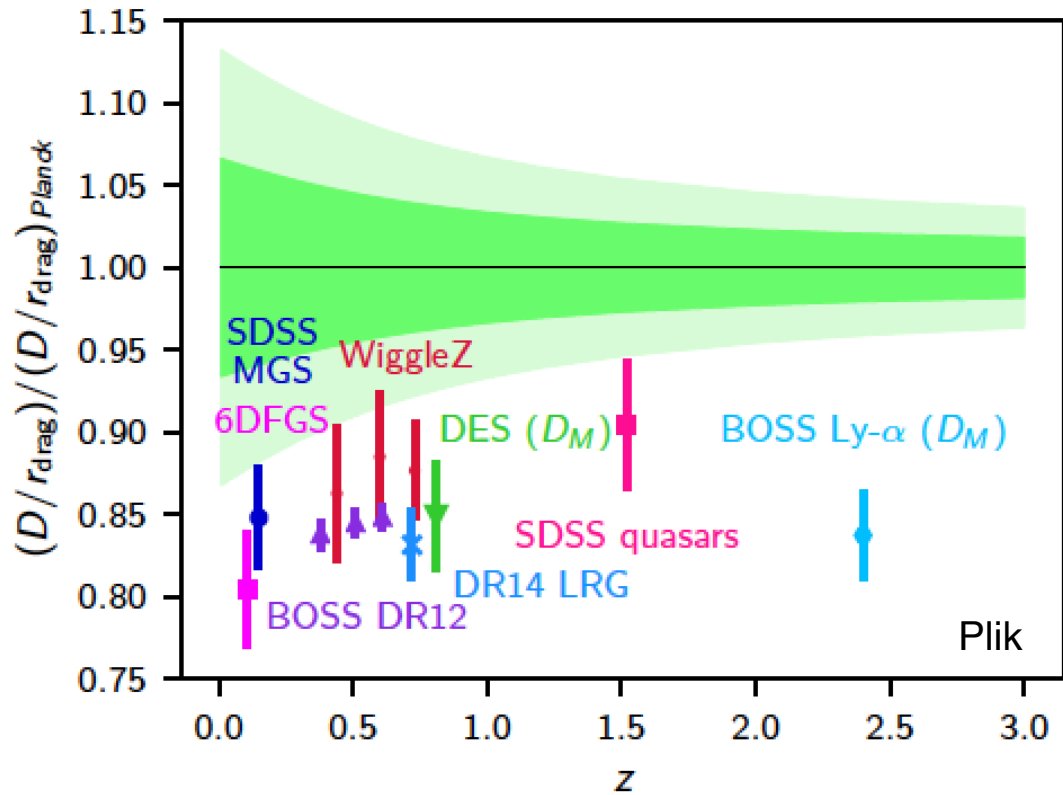
Planck 2018, Astron.Astrophys. 641 (2020) A6

This is a **plot of the acoustic-scale distance ratio**, $D_V(z)/r_{\text{drag}}$, as a function of redshift, taken from several recent BAO surveys, and divided by the mean acoustic-scale ratio obtained by Planck adopting a model. r_{drag} is the comoving size of the sound horizon at the baryon drag epoch, and D_V , the dilation scale, is a combination of the Hubble parameter $H(z)$ and the comoving angular diameter distance $D_M(z)$.

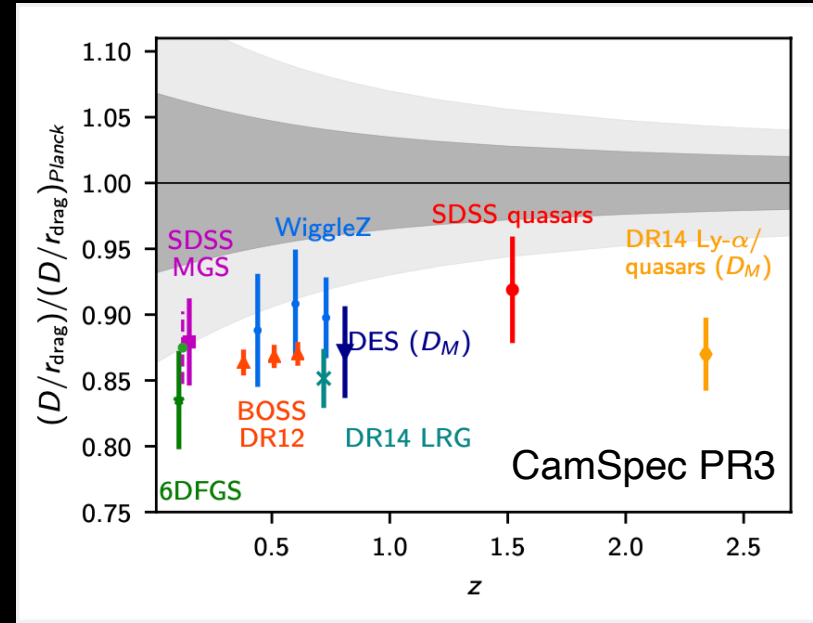
121

In a Λ CDM model the BAO data agree really well with the Planck measurements...

BAO tension



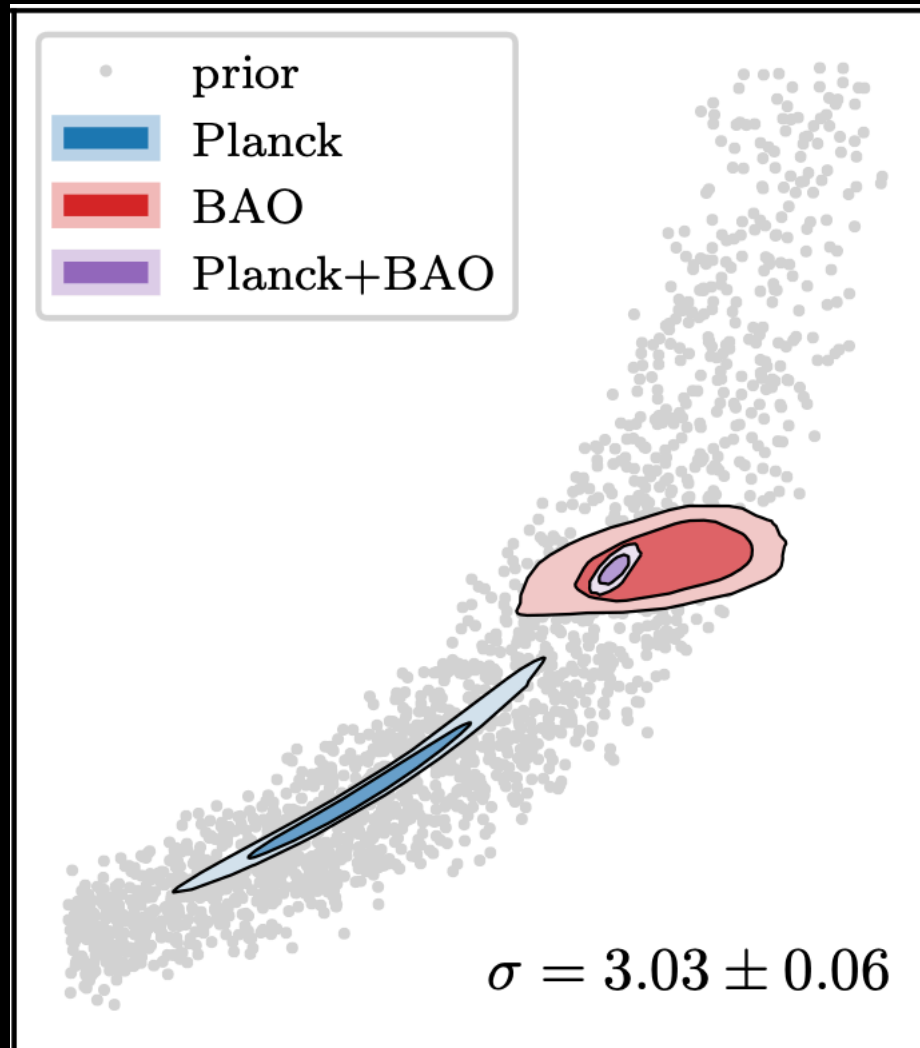
Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203



Di Valentino et al., in preparation

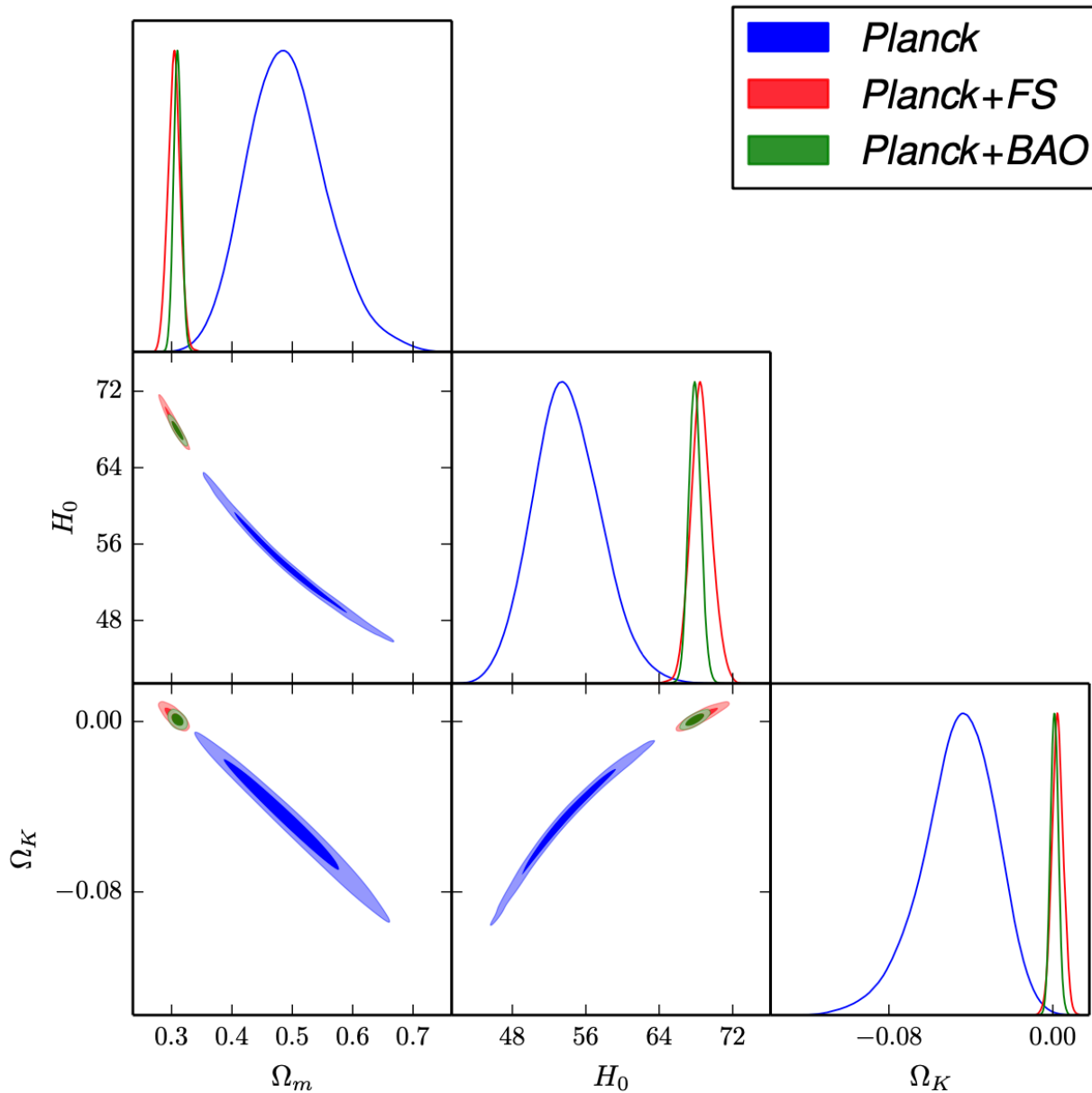
... but when we let curvature to vary
there is a striking disagreement between Planck spectra and BAO measurements!

BAO tension



In agreement with
Handley, Phys.Rev.D 103 (2021) 4, L041301

What about Planck+FS?



The strong disagreement between Planck and BAO is evident in this triangular plot, as well as that with the full-shape (FS) galaxy power spectrum measurements from the BOSS DR12 CMASS sample, at an effective redshift $z_{\text{eff}} = 0.57$.

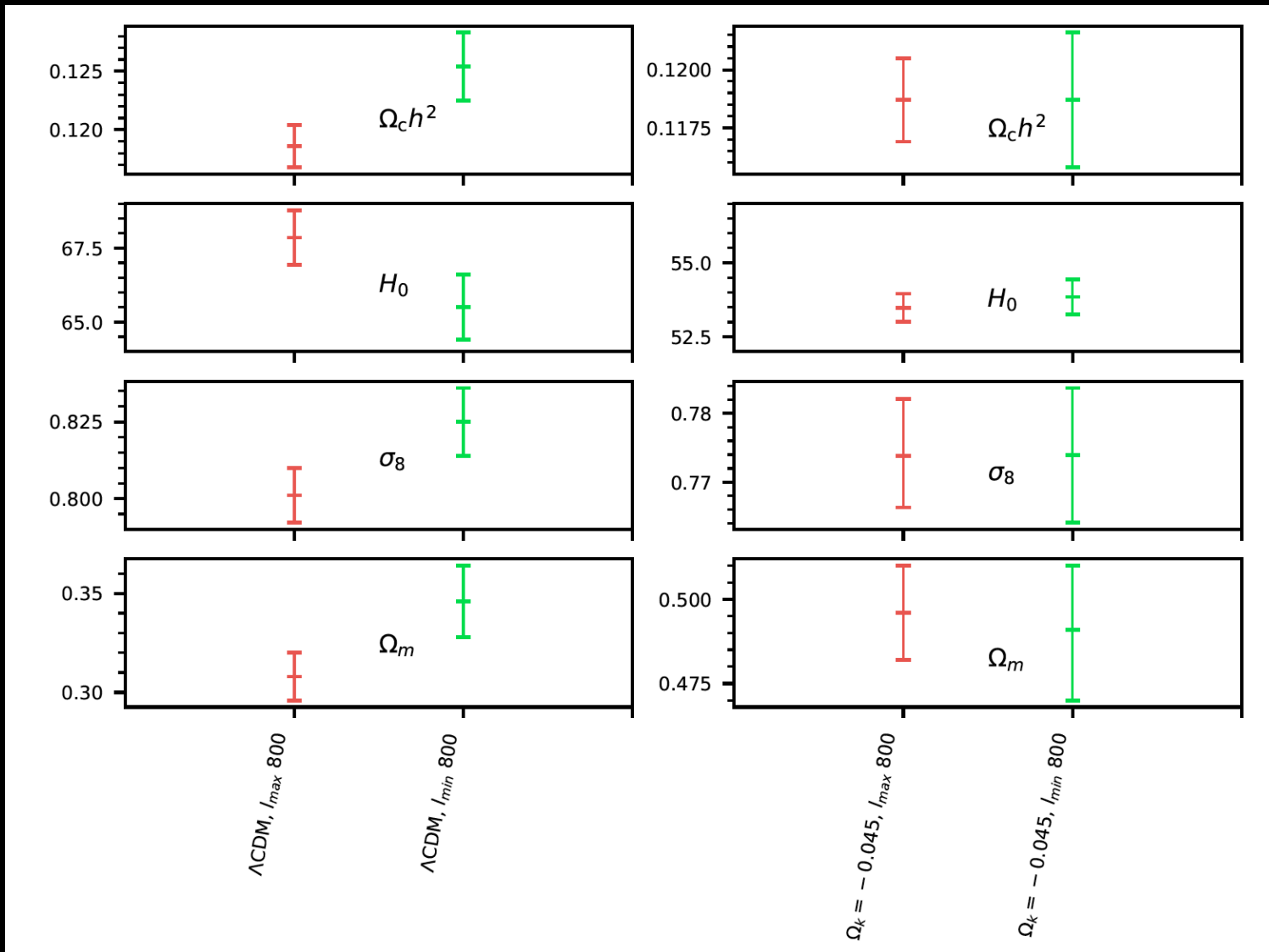
Λ CDM+ Ω_k : a 7 parameter standard model

As it has been convincingly pointed out in [Anselmi et al., arXiv:2207.06547](#),
in absence of any theoretical arguments,
we cannot use observations that suggest small Ω_k to enforce $\Omega_k=0$.

The common practice of assuming $\Omega_k=0$ places
the onus on proponents of “curved Λ CDM”
to provide sufficient evidence that $\Omega_k \neq 0$,
and this is required as an additional parameter.

Given the current tensions in cosmological parameters and
CMB anomalies this choice is at least open to debate.
So it would be preferable to have the standard cosmological
phenomenological model with at least 7 parameters.

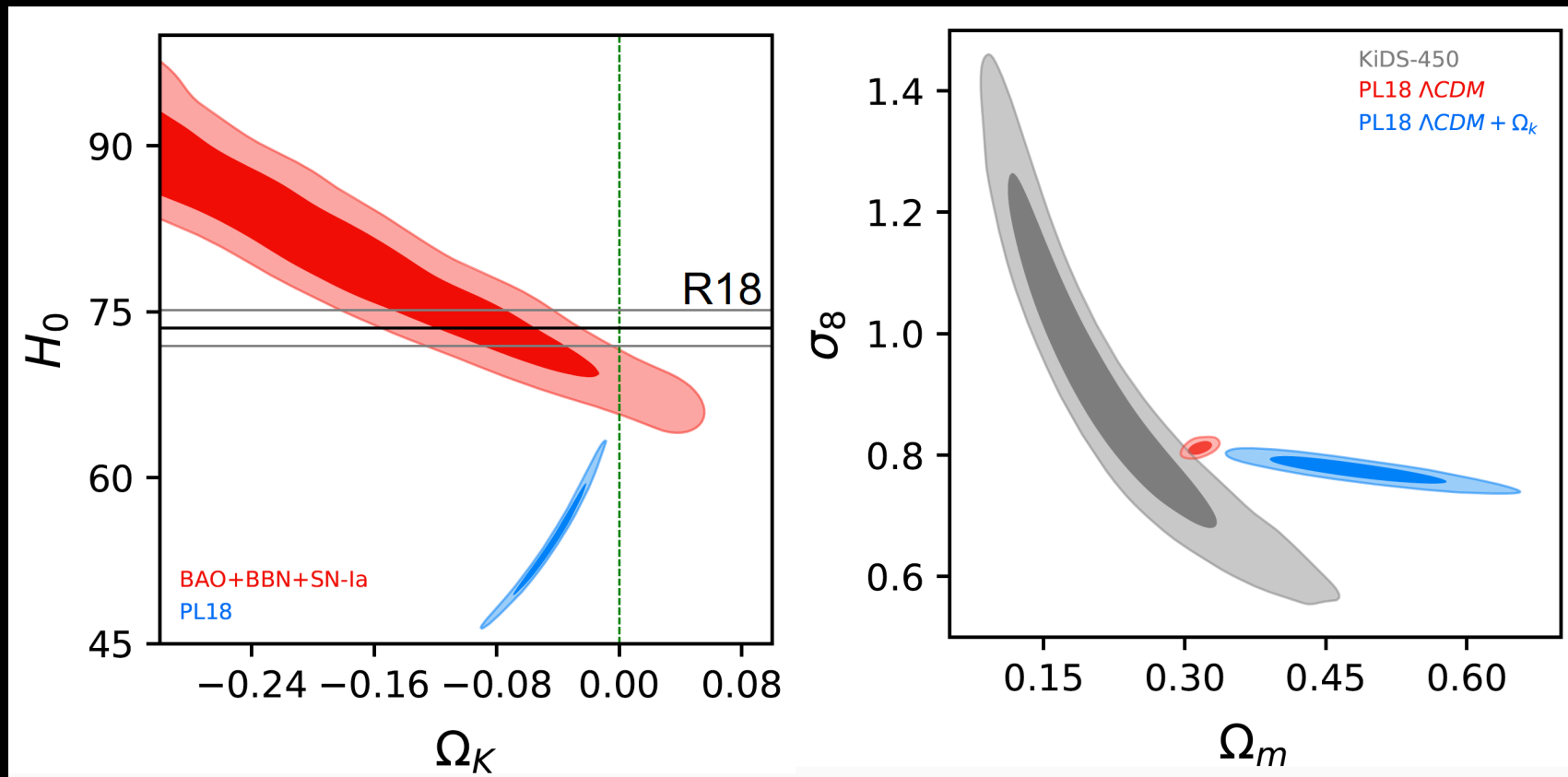
Curvature can explain internal tension



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

In a closed Universe with $\Omega_K = -0.045$, the cosmological parameters derived in the two different multipole ranges are now fully compatible.

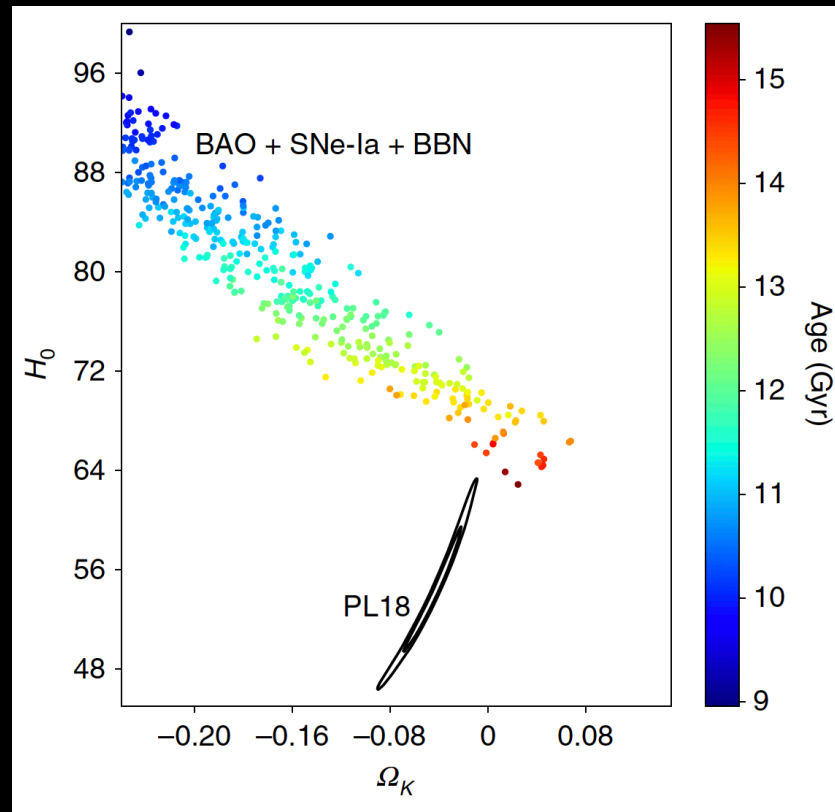
Curvature can't explain external tensions



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

Varying Ω_K , both the well known tensions on H_0 and S_8 are exacerbated. In a Λ CDM + Ω_K model, Planck gives $H_0 = 54.4^{+3.3}_{-4.0}$ km/s/Mpc at 68% cl., increasing the tension with SH0ES at 5.5σ , and S_8 in disagreement at about 3.8σ with KiDS-450, and more than 3.5σ with DES.

What about non-CMB data?



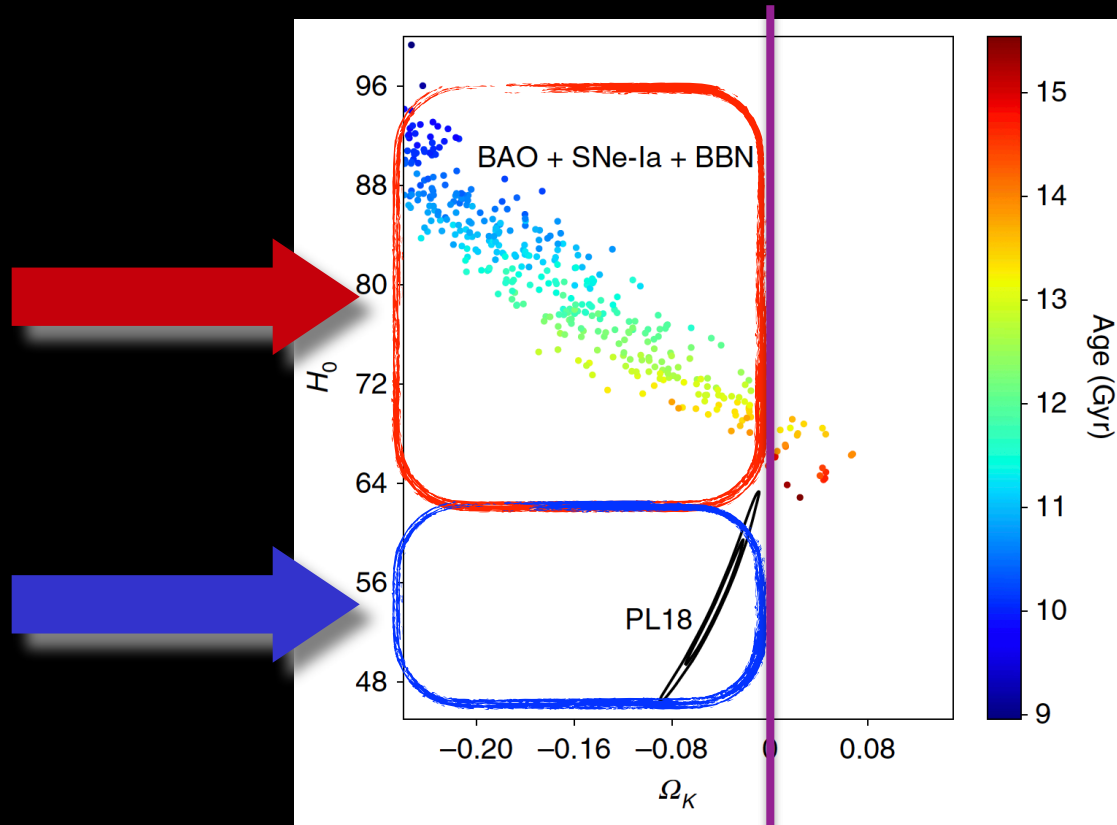
Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203

It is now interesting to address the **compatibility of Planck with combined datasets**, like BAO + type-Ia supernovae + big bang nucleosynthesis data.

In principle, **each dataset prefers a closed universe**,

but **BAO+SN-Ia+BBN gives $H_0 = 79.6 \pm 6.8$ km/s/Mpc** at 68%cl, perfectly consistent with SH0ES, but at 3.4σ tension with Planck.

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

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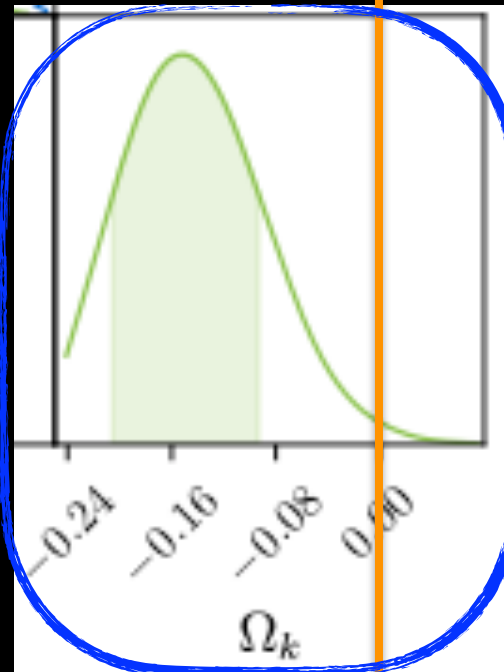
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129

BAO+SNIa+BBN+R18 gives $\Omega_K = -0.091 \pm 0.037$ at 68%cl.

EFTofLSS to investigate FS data

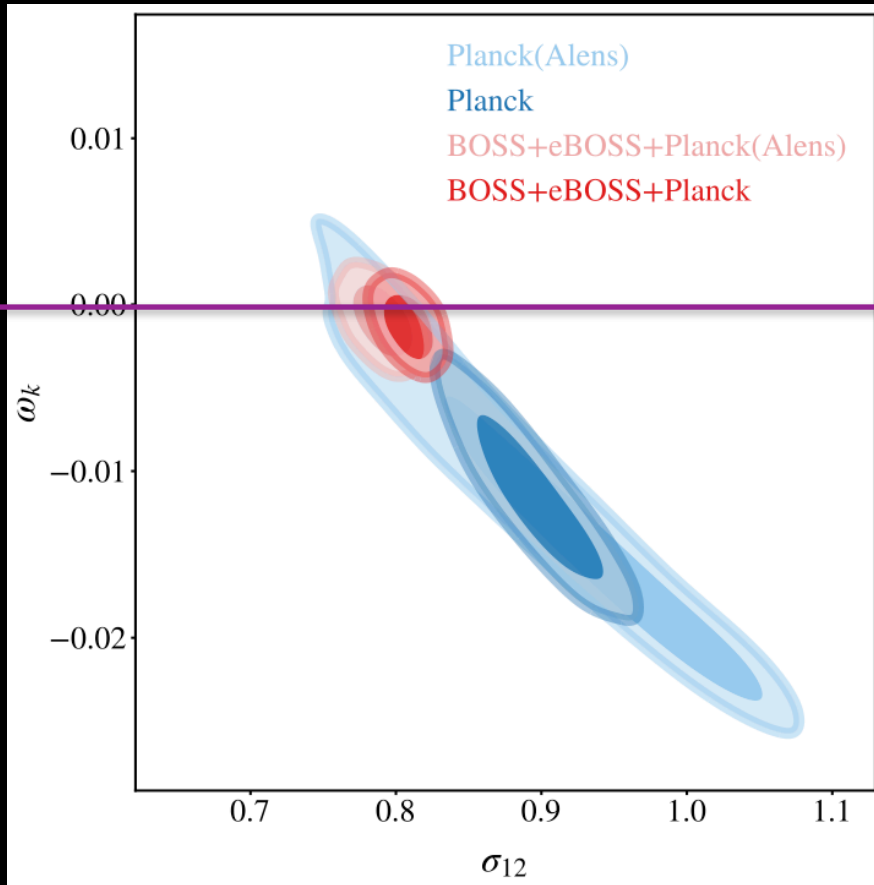
	$\ln(10^{10} A_s)$	h	$\Omega_{cdm} h^2$	Ω_m	Ω_k	n_s	$2 * \log(\mathcal{L})$
Flat, fixed n_s	$2.85^{+0.11}_{-0.12}$ (3.03)	$0.667^{+0.011}_{-0.011}$ (0.672)	$0.114^{+0.005}_{-0.004}$ (0.115)	$0.307^{+0.010}_{-0.011}$ (0.304)	-	-	367.2
Curved, fixed n_s	$2.55^{+0.21}_{-0.22}$ (2.77)	$0.686^{+0.015}_{-0.016}$ (0.665)	$0.115^{+0.004}_{-0.005}$ (0.111)	$0.291^{+0.014}_{-0.013}$ (0.302)	$-0.089^{+0.049}_{-0.046}$ (-0.042)	-	366.3
Flat, varying n_s	$2.80^{+0.14}_{-0.13}$ (2.97)	$0.669^{+0.012}_{-0.011}$ (0.668)	$0.117^{+0.009}_{-0.008}$ (0.114)	$0.312^{+0.017}_{-0.014}$ (0.304)	-	$0.950^{+0.04}_{-0.051}$ (0.972)	367.1
Curved, varying n_s	$2.19^{+0.29}_{-0.28}$ (2.62)	$0.707^{+0.021}_{-0.021}$ (0.686)	$0.127^{+0.011}_{-0.009}$ (0.116)	$0.300^{+0.016}_{-0.014}$ (0.295)	$-0.152^{+0.059}_{-0.053}$ (-0.089)	$0.878^{+0.053}_{-0.055}$ (0.932)	364.8



Glanville et al., [arXiv:2205.05892](https://arxiv.org/abs/2205.05892)

In this paper they use EFTofLSS to simultaneously constrain measurements from the 6dFGS, BOSS, and eBOSS catalogues, in order to remove some of the assumptions of flatness that enter into other large-scale structure analyses. Fitting the FS data with a BBN prior they measure a $>2\sigma$ preference for a closed universe.

Beyond six parameters: extending Λ CDM+ Ω_k



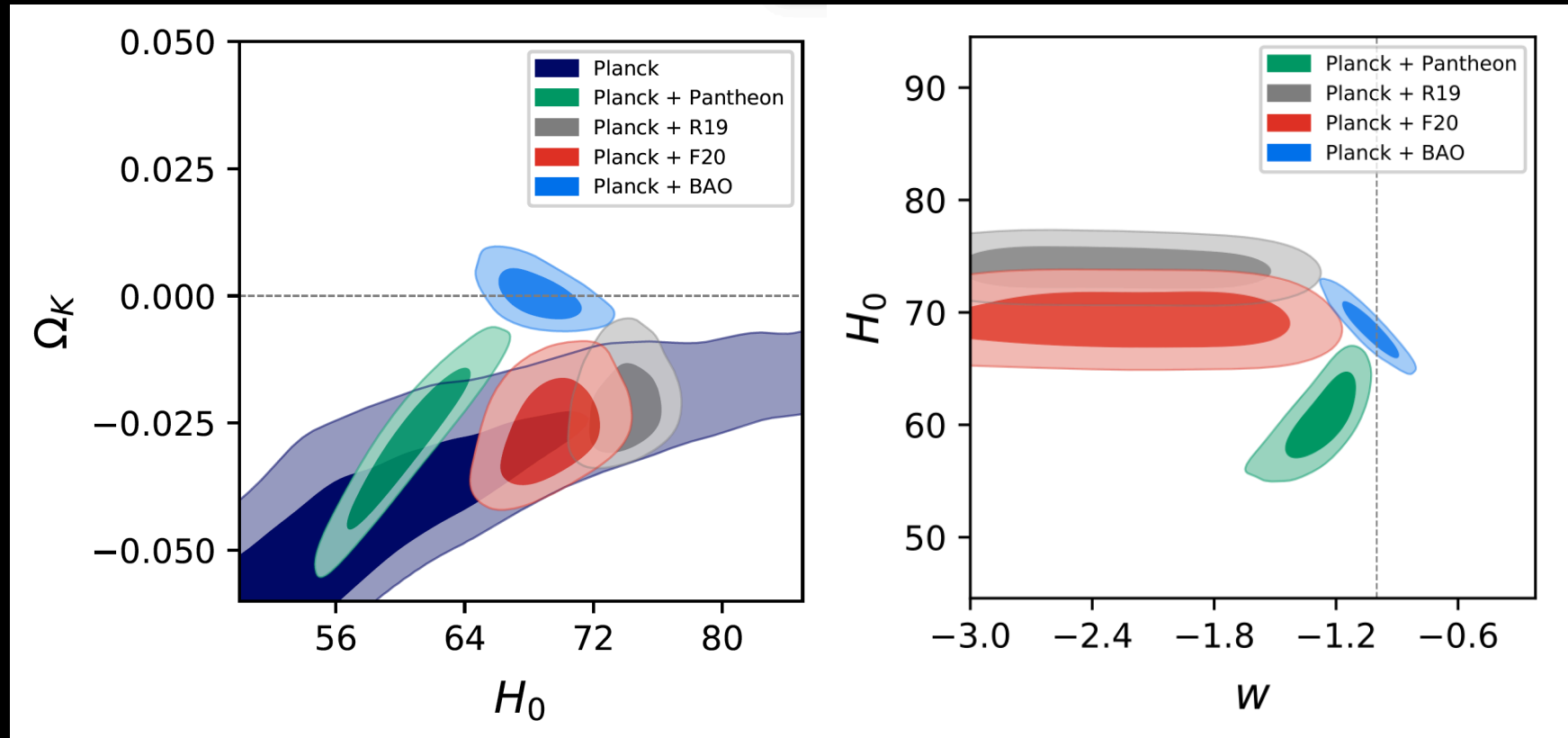
Semenaite et al., arXiv:2210.07304

A similar result has been obtained by analysing a w KCDM model, and the parameter $\omega_K = \Omega_k h^2$ that gives

$$\omega_K = -0.0116^{+0.0029}_{-0.0036}$$

i.e. a 4σ preference for a closed universe.

Evidence for a **phantom closed** Universe at more than 99% CL!!



It is interesting to note that if a closed universe increases the fine-tuning of the theory, the removal of a cosmological constant reduces it. It is, therefore, difficult to decide whether a **phantom closed** model is less or more theoretically convoluted than Λ CDM.

So... is the Universe closed?

What about Planck PR4 (NPIPE) with CamSpec?

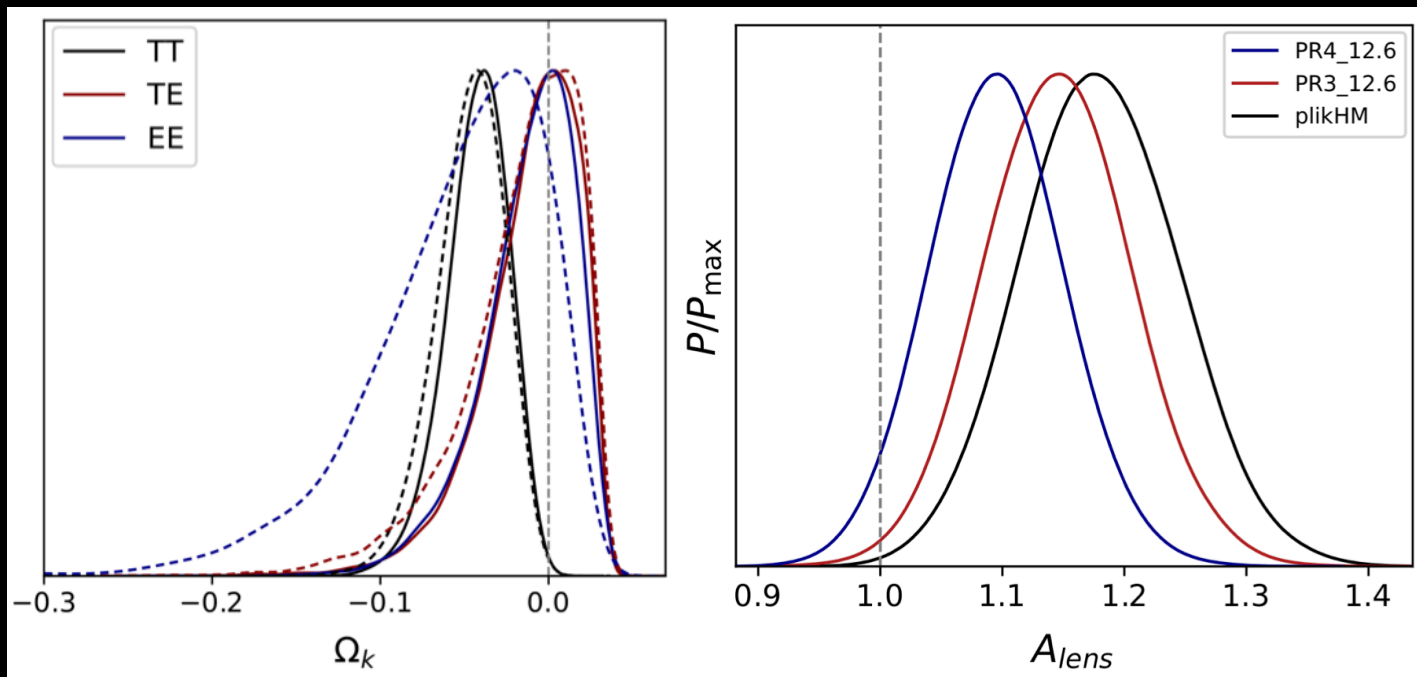
Astrophysics > Cosmology and Nongalactic Astrophysics

[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 $\sim 10\%$ tighter constraints, and we see both smaller error bars and a shift toward the LCDM values for beyond-LCDM parameters including Ω_K and A_{Lens} .

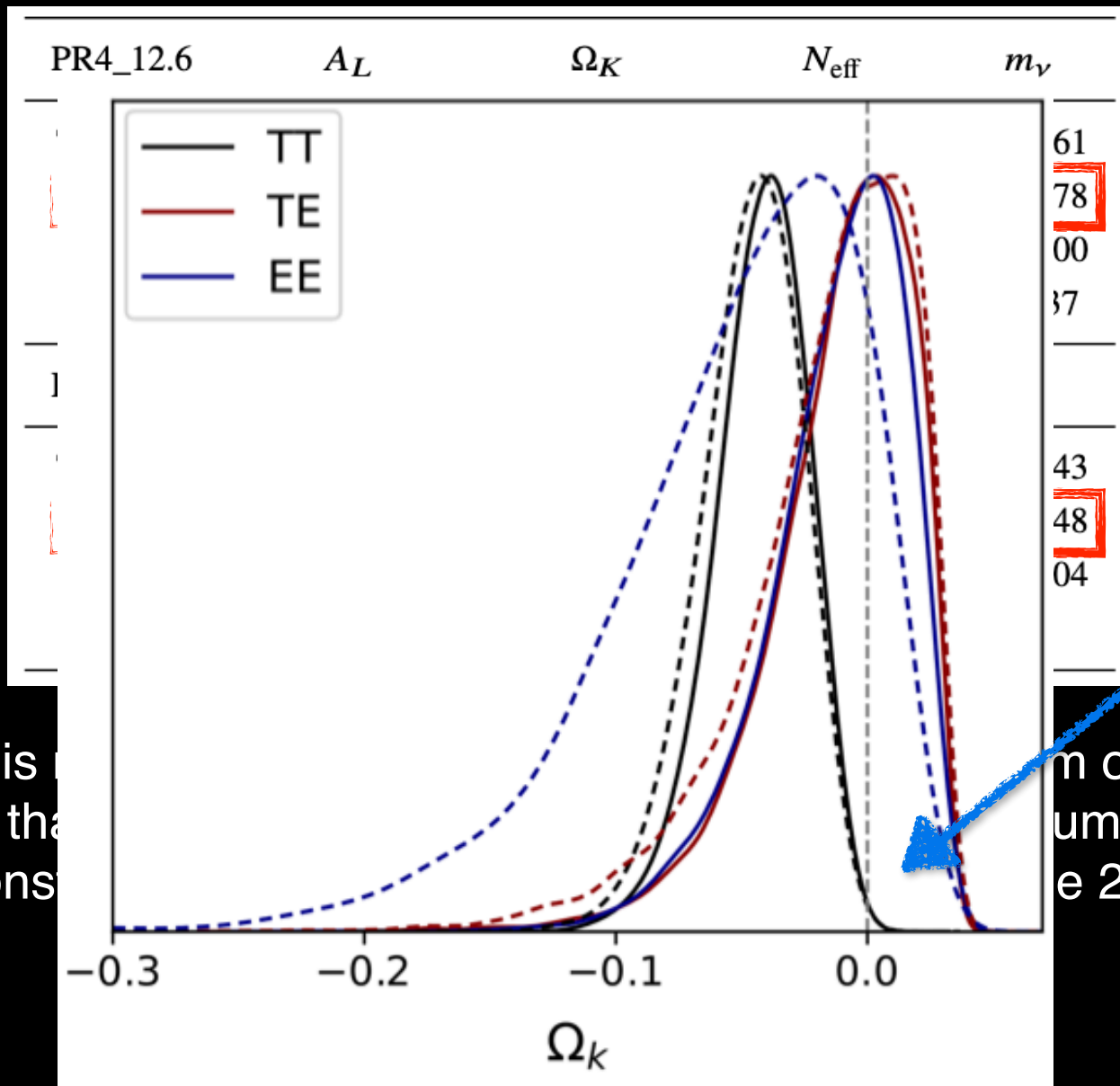


Planck PR4 (NPIPE) with CamSpec

PR4_12.6	A_L	Ω_K	N_{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_{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	$-0.053^{+0.063}_{-0.029}$	$2.46^{+0.94}_{-1.7}$	-

...but this new likelihood is not really solving the problem of A_L/Ω_K , that is mainly coming from the TT power spectrum. And the constraints coming from TT are not changing in the 2 releases...

Planck PR4 (NPIPE) with CamSpec



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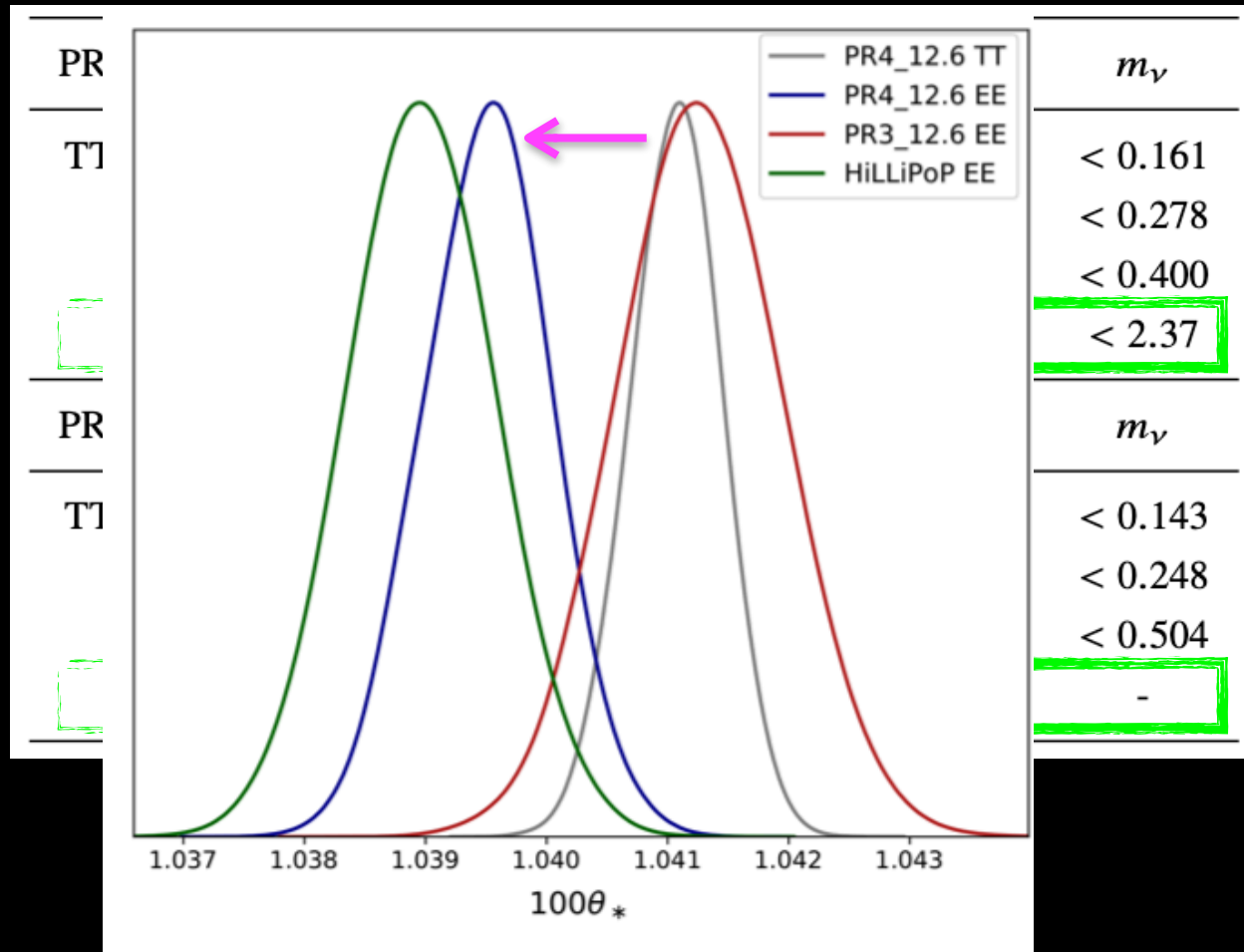
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And the constraints coming from TT are not changing in the 2 releases...

The constraints derived from the EE power spectrum are instead those pulling all the parameters towards Λ CDM and thus alleviating the tensions.

Planck PR4 (NPIPE) with CamSpec



However, this change in EE is producing a significant shift of the acoustic scale parameter θ , and an internal tension at 2.8σ between TT and EE, that becomes more than $3.2-3.3\sigma$ when AL/Ω_K vary.

Planck PR4 (NPIPE) with CamSpec

	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.

..but more significantly, the reduced χ^2 values show a more than 4σ tension of the data with the best-fit obtained by TTTEEE assuming a Λ CDM model.

Should we really prioritize enhancing the agreement with the Λ CDM model over preventing an internal inconsistency and a worse fit of the data?

A_L for different data releases

Table 1. Posterior A_L Constraints from Analyses of Planck Temperature and Polarization Data since 2018 Release

Reference	Data Version	Likelihood	Data Combination	A_L	' $N\sigma$ ' Preference for $A_L > 1$
Planck Collaboration VI (2020)	PR3/2018	plik	TTTEEE+lowl/lowE	1.180 ± 0.065	2.8σ
	PR3/2018	plik	TT+lowl/lowE	1.243 ± 0.096	2.5σ
Rosenberg et al. (2022)	PR3/2018	CamSpec	TTTEEE+lowl/lowE	1.146 ± 0.061	2.4σ
	PR3/2018	CamSpec	TT+lowl/lowE	1.215 ± 0.089	2.4σ
	PR4/NPIPE	CamSpec	TTTEEE+lowl/lowE	1.095 ± 0.056	1.7σ
	PR4/NPIPE	CamSpec	TT+lowl/lowE	1.198 ± 0.084	2.4σ
Tristram et al. (2023)	PR4/NPIPE	HiLLiPoP	TTTEEE+lowl/LoLLiPoP ^a	1.036 ± 0.051	0.7σ
	PR4/NPIPE	HiLLiPoP	TT+lowl/LoLLiPoP	1.068 ± 0.081	0.8σ

Addison et al, arXiv:2310.03127

$$S_8 = 0.834 \pm 0.016$$

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

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

$$S_8 = 0.819 \pm 0.014$$

$$H_0 = 67.64 \pm 0.52 \text{ km/s/Mpc}$$

Tristram et al., arXiv:2309.10034 [astro-ph.CO]

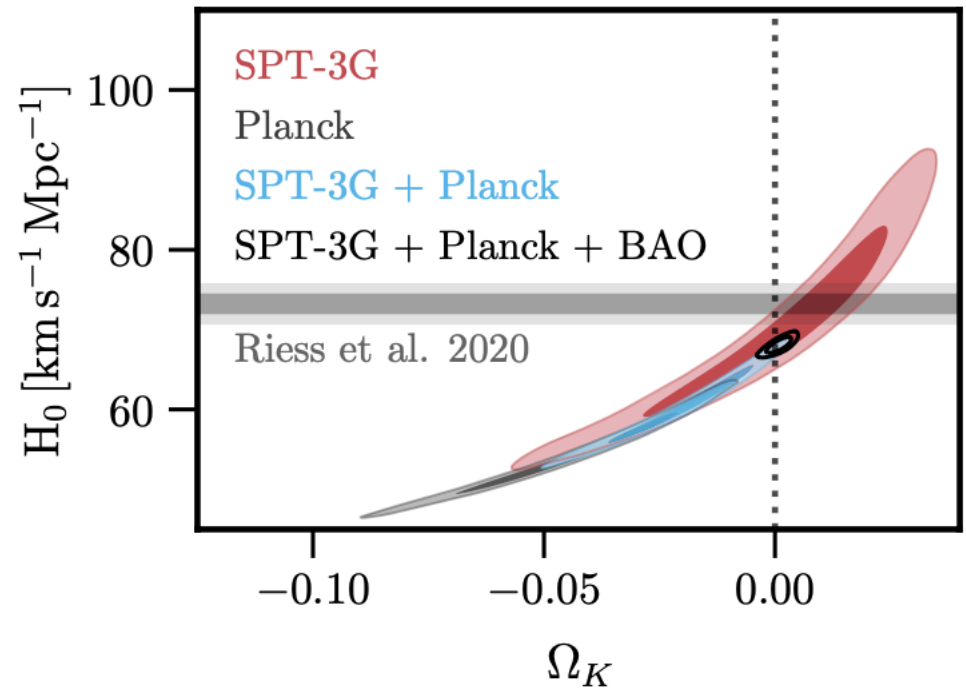
What about the alternative CMB experiments?

CMB Polarization Measurements with SPTpol

Nicholas Harrington
UC Berkeley

SPT-3G gives at 68% CL:

$$\Omega_K = 0.001^{+0.018}_{-0.019}$$

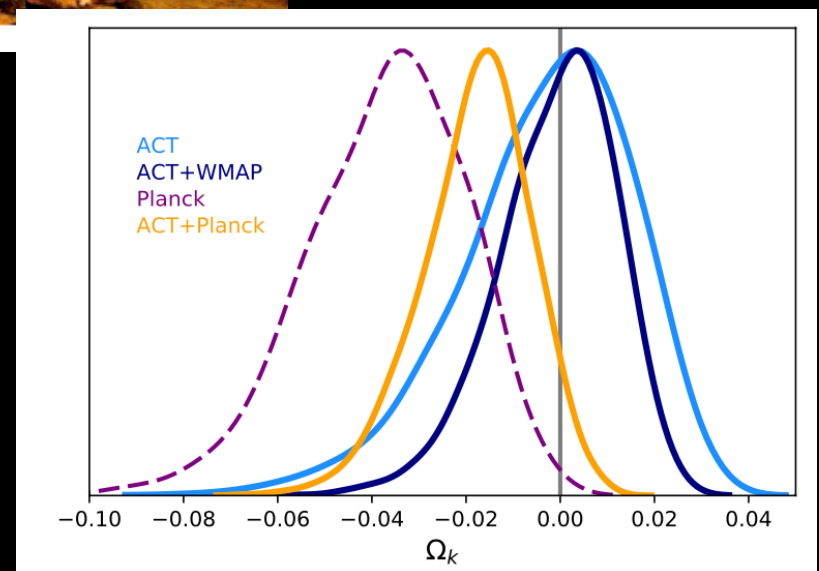


SPT-3G, arXiv:2103.13618 [astro-ph.CO]



ACT-DR4 + WMAP gives at 68% CL

$$\Omega_k = -0.001 \pm 0.012$$



ACT-DR4 2020, Aiola et al., arXiv:2007.07288 [astro-ph.CO]

Harrison-Zel'dovich scale-invariant spectrum?

Dataset	Scalar Spectral Index (n_s)
	Λ CDM
ACT	1.009 ± 0.015
ACT+BAO (DR12)	1.006 ± 0.013
ACT+BAO (DR16)	1.006 ± 0.014
ACT+DESy1	1.007 ± 0.013
ACT+SPT+BAO (DR12)	0.996 ± 0.012
Planck	0.9649 ± 0.0044
Planck+BAO (DR12)	0.9668 ± 0.0038
Planck+BAO (DR16)	0.9677 ± 0.0037
Planck ($2 \leq \ell \leq 650$)	0.9655 ± 0.0043
Planck ($\ell > 650$)	0.9634 ± 0.0085

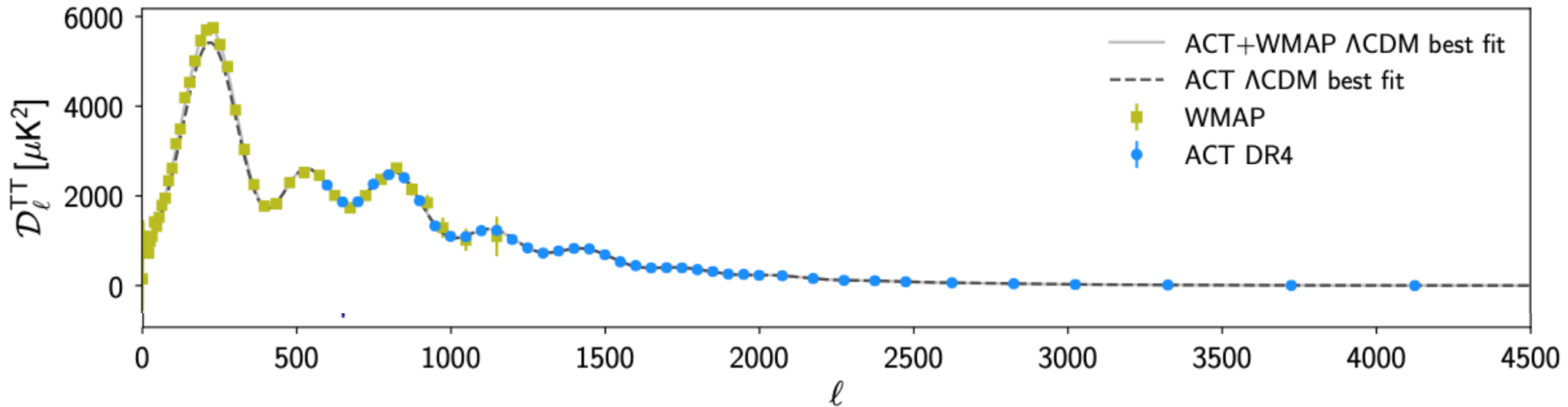
ACT shows a preference for a larger spectral index consistent with a Harrison-Zel'dovich scale-invariant spectrum $n_s=1$ of primordial density perturbations introducing a tension with a significance of 2.7σ with the results from the Planck satellite.

Giare, Renzi, Mena, Di Valentino, and Melchiorri,
MNRAS 521 (2023) 2, 2911

Harrison-Zel'dovich scale-invariant spectrum?

In ACT-DR4 2020, [arXiv:2007.07288](https://arxiv.org/abs/2007.07288) [astro-ph.CO] this discrepancy was interpreted as a consequence of the **lack of information concerning the first acoustic peak** of the temperature power spectrum.

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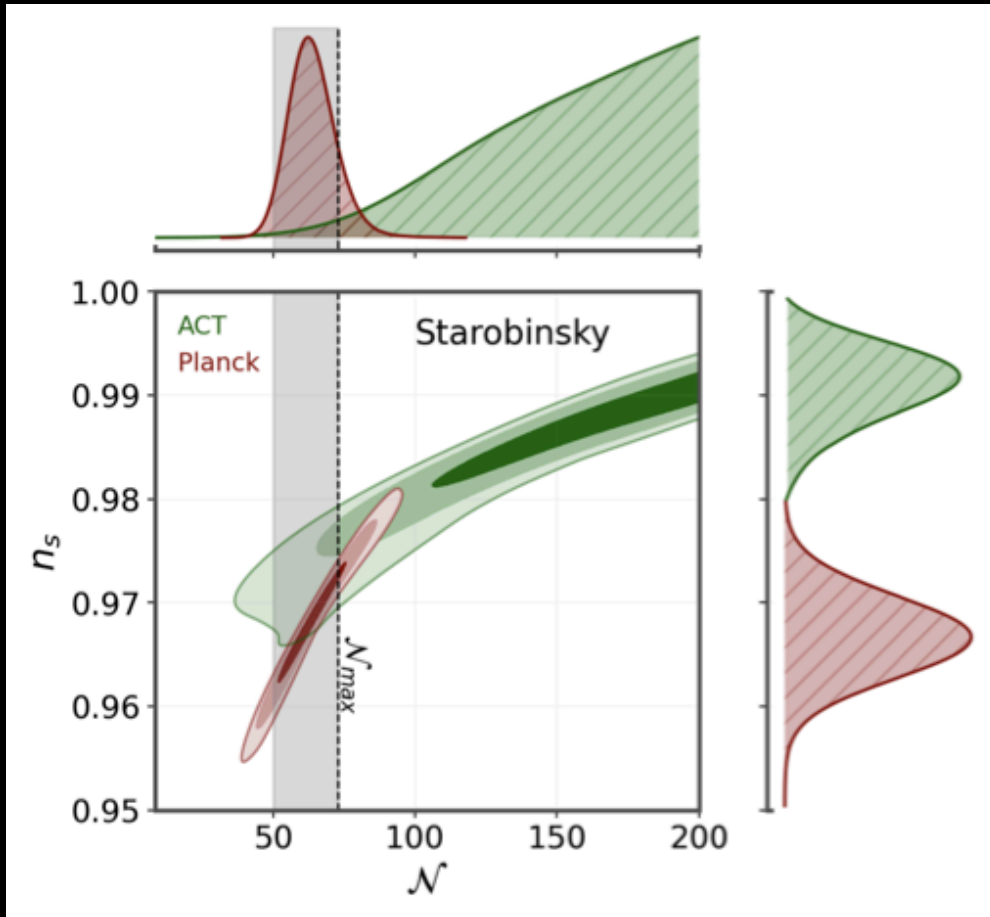
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MNRAS 521 (2023) 2, 2911

In ACT-DR4 2020, arXiv:2007.07288 [astro-ph.CO] this discrepancy was interpreted as a consequence of the lack of information concerning the first acoustic peak of the temperature power spectrum.

To verify this origin of the discrepancy in the CMB values of n_s , we have performed two separate analyses of the Planck observations, splitting the likelihood into low $2 < \ell < 650$ and high $\ell > 650$ multipoles. We find that the discrepancy still persists at the level of 3σ (2σ) for low (high) multiple temperature data.

Planck data still prefer a value of the scalar spectral index smaller than unity at $\sim 4.3\sigma$ when the information about the first acoustic peak is removed.

We tested some models of inflation regarded as well - established benchmark scenarios and found out that they are ruled out by ACT at more than 3σ .

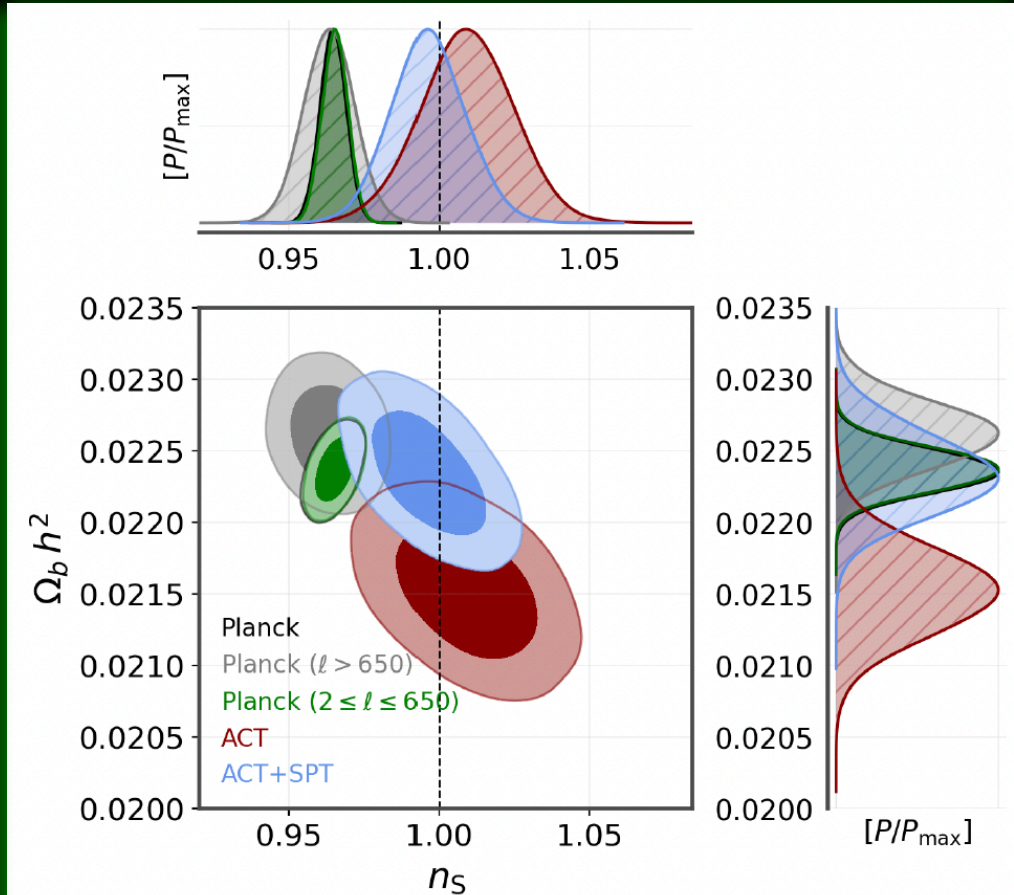
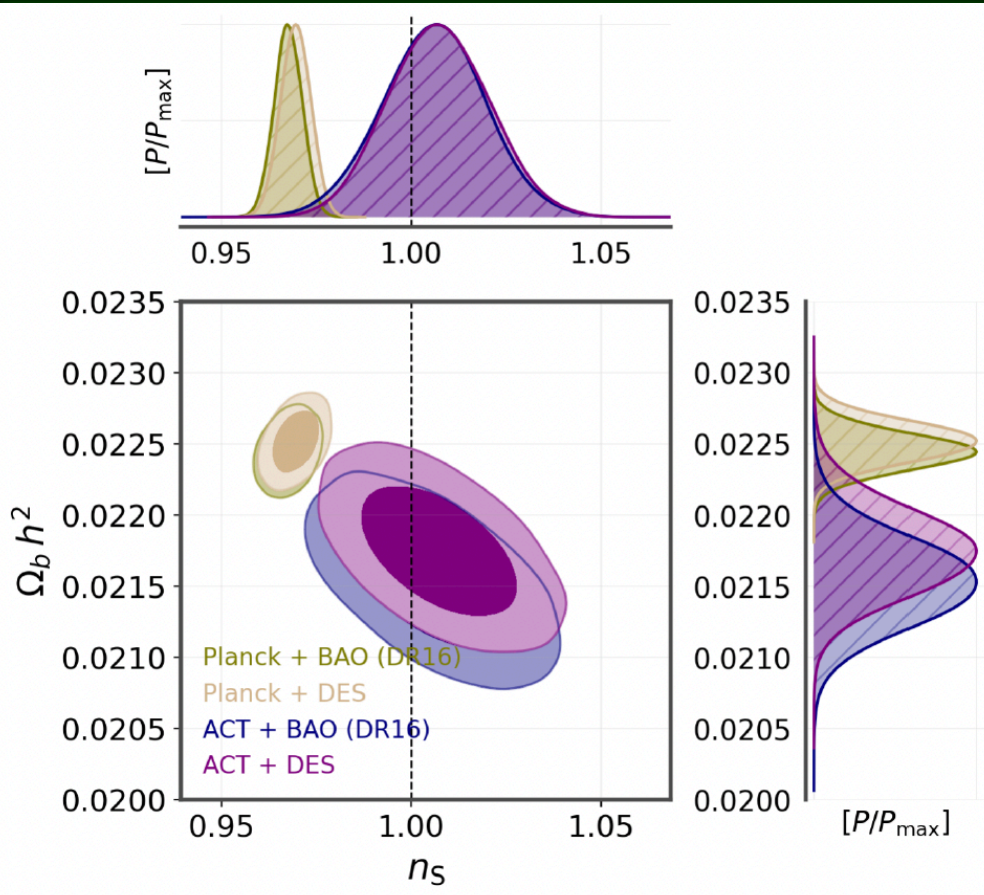


Giarè, Pan, Di Valentino, Yang, de Haro, and Melchiorri,
arXiv:2305.15378

In the plot we show for example the 2D contours at 68%, 95%, and 99% CL and 1D posteriors in the (n_s, N_{efolds}) plane for the Starobinsky model. The grey vertical band refers to the typical range of folds expansion $N_{\text{efolds}} \in [50, N_{\max}]$, expected in standard inflation. The upper limit, $N_{\max} \leq 73$, is represented by the black dashed line.

Very similar results are obtained for all the other potentials, and in particular for ACT we find the following values for the number of e-folds at 68% (95%) CL:

- $\mathcal{N} > 138$ ($\mathcal{N} > 92.8$) for the Starobinsky model;
- $\mathcal{N} > 134$ ($\mathcal{N} > 88.6$) for α -Attractor models;
- $\mathcal{N} > 257$ ($\mathcal{N} > 208$) for Polynomial inflation;
- $\mathcal{N} > 177$ ($\mathcal{N} > 105$) for the SUSY potential.



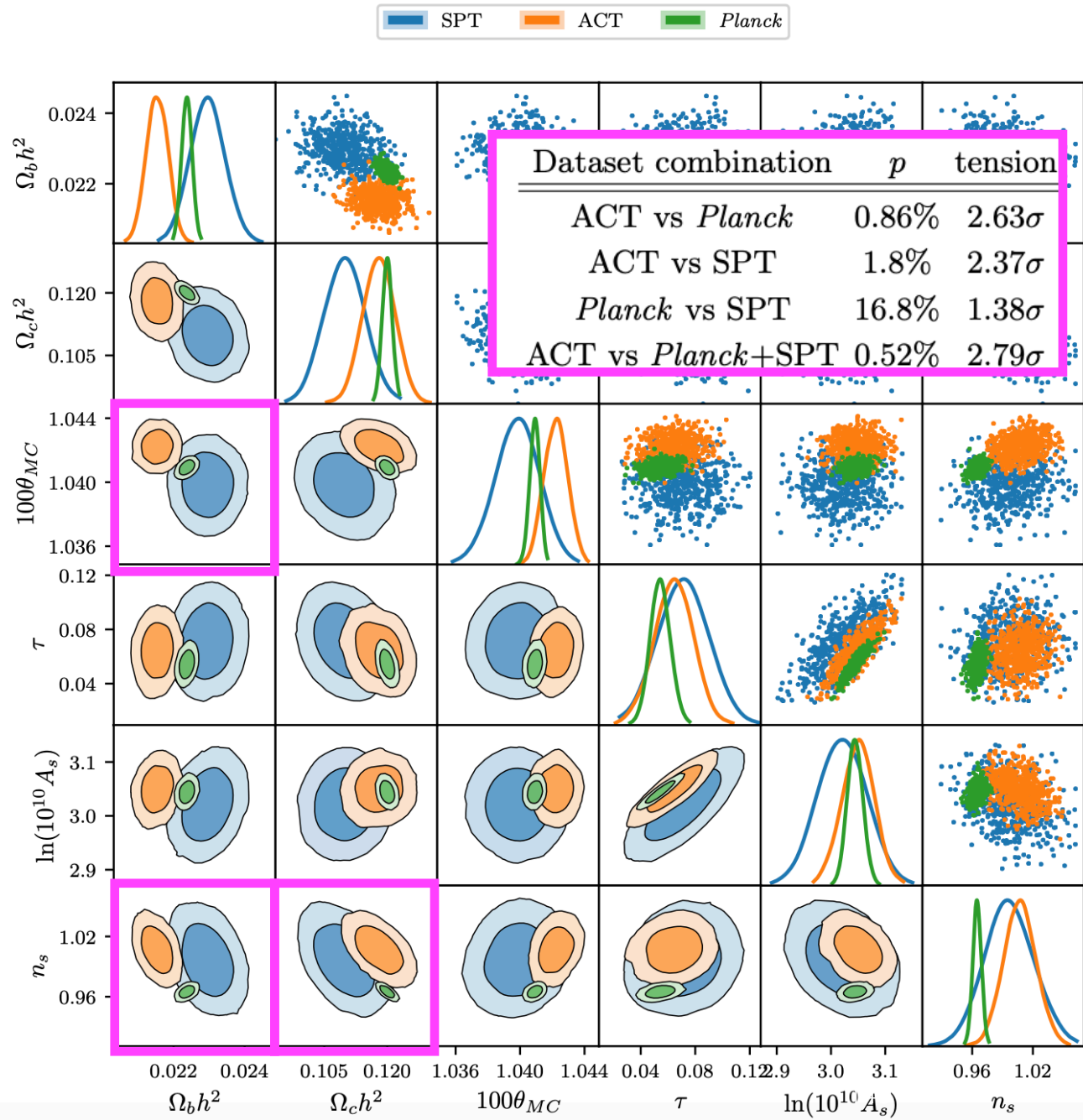
Giarè, Renzi, Mena, Di Valentino, and Melchiorri, MNRAS 521 (2023) 2, 2911

Such preference remains robust under the addition of large scale structure information, and in the two-dimensional plane it can be definitely noted that the direction of the $\Omega_b h^2 - n_s$ degeneracy is opposite for ACT and Planck, and the disagreement here is significantly exceeding 3σ .

This tension is partially driven by the ACT polarization data, as we can see replacing it with the SPT polarization measurements, but while the tension is relaxed in the plane $\Omega_b h^2 - n_s$, this combination is still preferring $n_s=1$.

Quantifying global CMB tension

Handley and Lemos, arXiv:2007.08496 [astro-ph.CO]



Global tensions between CMB datasets.

For each pairing of datasets this is the tension probability p that such datasets would be this discordant by (Bayesian) chance, as well as a conversion into a Gaussian-equivalent tension.

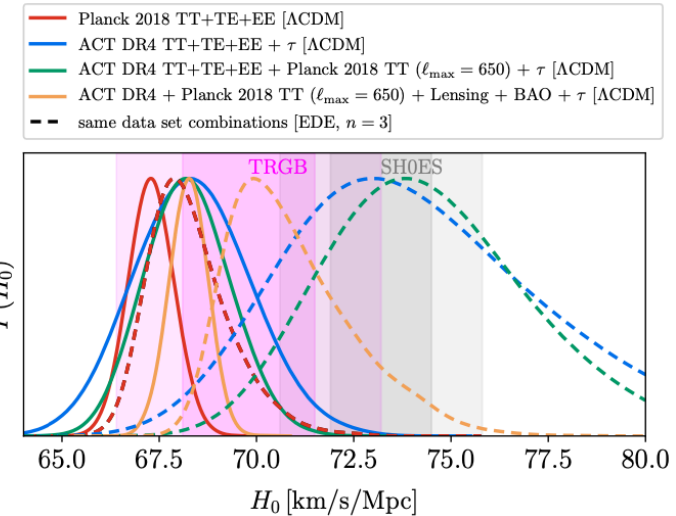
Between *Planck* and ACT there is a 2.6σ tension.

Assuming Λ CDM

ACT-DR4 vs Planck: EDE

Constraints on EDE ($n = 3$)

Parameter	ACT DR4 TT+TE+EE, τ	ACT DR4 TT+TE+EE, Planck 2018 TT ($\ell_{\max} = 650$), τ	ACT DR4 TT+TE+EE, Planck 2018 TT ($\ell_{\max} = 650$), Planck 2018 lensing, BAO, τ	Planck 2018 TT+TE+EE (from Ref. [38])	ACT DR4 TT+TE+EE, Planck 2018 TT+TE+EE (no low- ℓ EE), τ
f_{EDE}	$0.142^{+0.039}_{-0.072}$	$0.129^{+0.028}_{-0.055}$	$0.091^{+0.020}_{-0.036}$	< 0.087	< 0.124
$\log_{10}(z_c)$	< 3.70	< 3.43	< 3.36	$3.66^{+0.24}_{-0.28}$	$3.54^{+0.25}_{-0.20}$
θ_i	> 0.24	< 2.89	< 2.82	> 0.36	> 0.51
$\Omega_c h^2$	$0.1307^{+0.0054}_{-0.0120}$	$0.1291^{+0.0051}_{-0.0080}$	$0.1286^{+0.0027}_{-0.0060}$	$0.1234^{+0.0019}_{-0.0038}$	$0.1244^{+0.0025}_{-0.0051}$
H_0 [km/s/Mpc]	$74.5^{+2.5}_{-4.4}$	$74.4^{+2.2}_{-3.0}$	$70.9^{+1.0}_{-2.0}$	$68.29^{+0.73}_{-1.20}$	$69.17^{+0.83}_{-1.70}$
Ω_m	$0.276^{+0.020}_{-0.023}$	0.274 ± 0.017	0.3000 ± 0.0072	0.3145 ± 0.0086	0.3084 ± 0.0084
σ_8	$0.831^{+0.027}_{-0.043}$	$0.827^{+0.029}_{-0.035}$	$0.829^{+0.013}_{-0.021}$	$0.820^{+0.009}_{-0.013}$	$0.838^{+0.013}_{-0.015}$
S_8	0.796 ± 0.049	$0.791^{+0.040}_{-0.046}$	$0.828^{+0.015}_{-0.018}$	0.839 ± 0.018	0.850 ± 0.017



ACT collaboration, Hill et al. arXiv:2109.04451

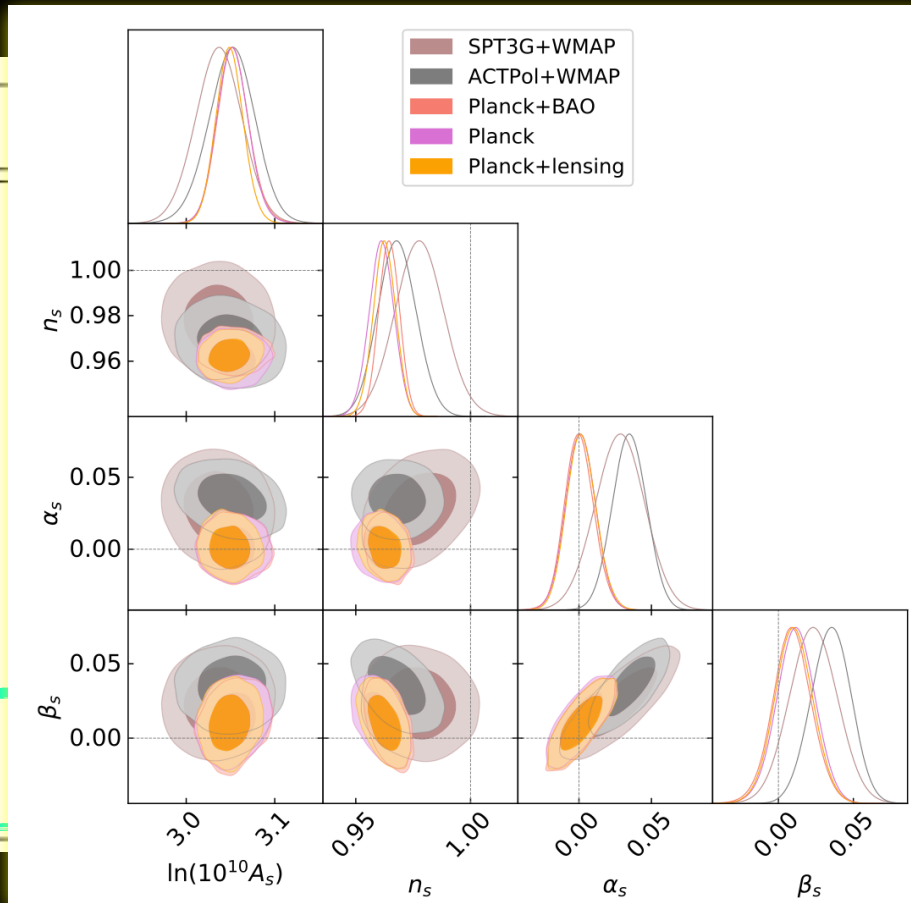
Considering ACT only data or combined with Planck TT up to multipoles 650, there is an evidence for EDE $> 3\sigma$, solving completely the Hubble tension. The evidence for EDE $> 3\sigma$ persists with the inclusion of Planck lensing + BAO data, but shifting H_0 towards a lower value. Once the full Planck data are considered, the evidence for EDE disappears and H_0 is again in tension with SHOES.

The Planck damping tail is in disagreement with EDE different from zero.

ACT-DR4 vs Planck: α_s and β_s

Forconi, Giarè, Di Valentino and Melchiorri, *Phys.Rev.D* 104 (2021) 10, 103528

Parameter	Planck18
$\Omega_b h^2$	0.02235 ± 0.00017
$\Omega_c h^2$	0.1207 ± 0.0015
$\alpha_s \doteq \left[\frac{dn_s}{d \log k} \right]_{k=k_*}$	$\beta_s \doteq \left[\frac{d\alpha_s}{d \log k} \right]_{k=k_*}$
$\log(10^{10} A_s)$	3.053 ± 0.018
n_s	0.9612 ± 0.0054
α_s	0.001 ± 0.010
β_s	0.012 ± 0.013



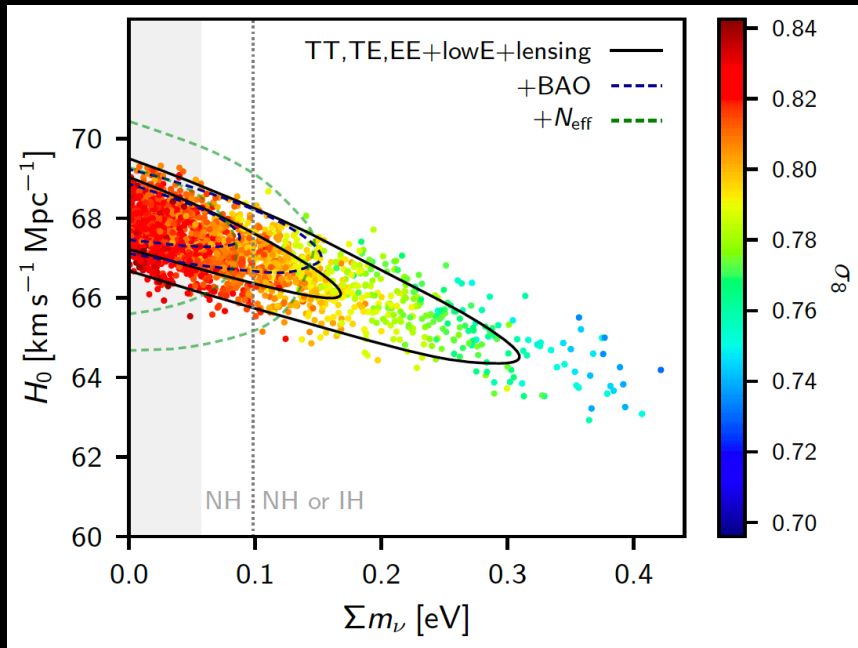
ACTPol + WMAP
0.02195 ± 0.00025
0.1190 ± 0.0029
1.04174 ± 0.00066
0.061 ± 0.013
3.051 ± 0.026
0.9680 ± 0.0082
0.035 ± 0.012
0.035 ± 0.013

ACT-DR4 and SPT-3G are in agreement one with each other, but in disagreement with Planck, for the value of the

running of the scalar spectral index α_s and of the running of the running β_s .

In particular ACT-DR4 + WMAP prefer both a non vanishing running α_s and running of the running β_s at the level of 2.9σ and 2.7σ , respectively.

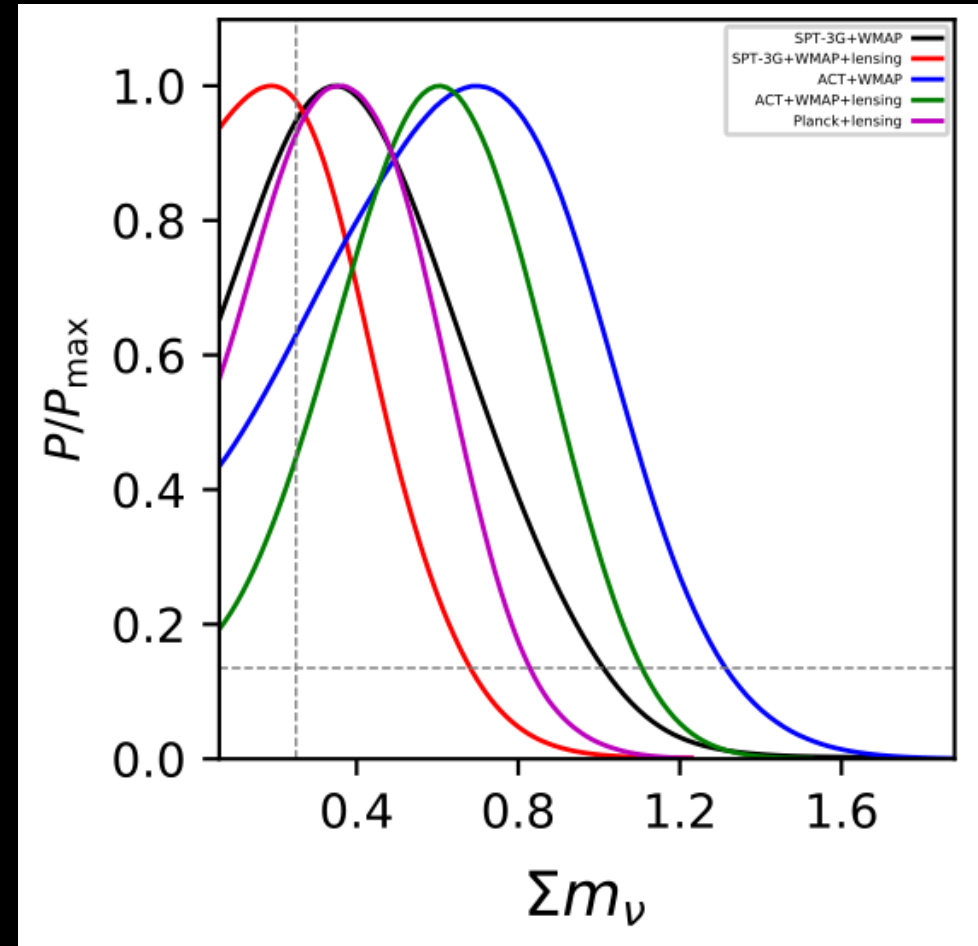
Alternative CMB vs Planck: Σm_ν



$\Sigma m_\nu < 0.24 \text{ eV}$ (95 %, TT,TE,EE+lowE+lensing)

Planck 2018 collaboration, arXiv:1807.06209 [astro-ph.CO]

While we have only an upper limit for Planck on the total neutrino mass, **ACT-DR4, when combined with WMAP and lensing, prefers a neutrino mass different from zero at more than 95% CL.**



Di Valentino and Melchiorri, 2022 *ApJL* **931** L18

Constraints at 68% CL

Dataset	Σm_ν [eV]
ACT-DR4+WMAP+Lensing	0.60 ± 0.25
Planck+Lensing (+ A_{lens})	$0.41^{+0.17}_{-0.25}$

Quantifying global CMB tension

Cosmological model	d	χ^2	p	$\log S$	Tension
Λ CDM	6	16.3	0.012	-5.17	2.51 σ
Λ CDM + A_s	7	18.5	0.00977	-5.77	2.58 σ
Λ CDM + N_{eff}	7	13	0.0719	-3	1.80 σ
Λ CDM + Ω_k	7	16.5	0.0209	-4.75	2.31 σ
w CDM	7	16.8	0.0187	-4.9	2.35 σ
Λ CDM + $\sum m_\nu$	7	20.7	0.00421	-6.86	2.86 σ
Λ CDM + α_s	7	20.6	0.00448	-6.78	2.84 σ
w CDM + Ω_k	8	17.6	0.0249	-4.78	2.24 σ
Λ CDM + $\Omega_k + \sum m_\nu$	8	21.2	0.00651	-6.62	2.72 σ
w CDM + $\Omega_k + \sum m_\nu$	9	19.8	0.0195	-5.38	2.34 σ
w CDM + $\Omega_k + \sum m_\nu + N_{\text{eff}}$	10	18.8	0.0434	-4.38	2.02 σ
w CDM + $\Omega_k + \sum m_\nu + \alpha_s$	10	22	0.015	-6.01	2.43 σ
w CDM + $\Omega_k + N_{\text{eff}} + \alpha_s$	10	20.9	0.0218	-5.45	2.29 σ
w CDM + $\sum m_\nu + N_{\text{eff}} + \alpha_s$	10	31.1	0.000575	-10.5	3.44 σ
w CDM + $\Omega_k + \sum m_\nu + N_{\text{eff}} + \alpha_s$	11	24.7	0.0102	-6.83	2.57 σ

Di Valentino et al., MNRAS 520 (2023) 1, 210-215

Λ CDM + N_{eff}	Planck	-	2.92 ± 0.19
	ACT-DR4	-	$2.35^{+0.40}_{-0.47}$

If we now study the global agreement between Planck and ACT in various cosmological models that differ by the inclusion of different combinations of additional parameters, we can use the Suspiciousness statistic, to quantify their global "CMB tension".

We find that the 2.5σ tension within the baseline Λ CDM is reduced at the level of 1.8σ when N_{eff} is significantly less than 3.044, while it ranges between 2.3σ and 3.5σ in all the other extended models.

Concluding

At this point, given the quality of all the analyses at play, probably these tensions are indicating a problem with the underlying cosmology and our understanding of the Universe, rather than the presence of systematic effects.

Many models have been proposed to solve the H_0 tension. However, looking for a solution by changing the standard model of cosmology is challenging because of some additional complications:

1. The sound horizon problem
2. The S_8 tension
3. The correlation between the parameters and possible fake detection
4. The hidden model dependence of some of the datasets (such as BAO)
5. The Planck AL problem
6. The inconsistency between the different CMB experiments

Therefore, this is presenting a serious limitation to the precision cosmology.

These cosmic discordances call for new observations and stimulate the investigation of alternative theoretical models and solutions.

Thank you!

e.divalentino@sheffield.ac.uk

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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](#)