Unraveling Inconsistencies in the Standard LCDM Model

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Cosmology 2023 in Miramare

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THE ROYAL SOCIETY

The ΛCDM model

Out of various cosmological models proposed in literature,
the Lambda cold dark matter (ΛCDM) 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, ΛCDM 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 ΛCDM, 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 ΛCDM model

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

Hence, as observations become more numerous and accurate, deviations from the ΛCDM model are expected to be detected.
And in fact, discrepancies in important cosmological parameters, such as H0 and S8, 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.

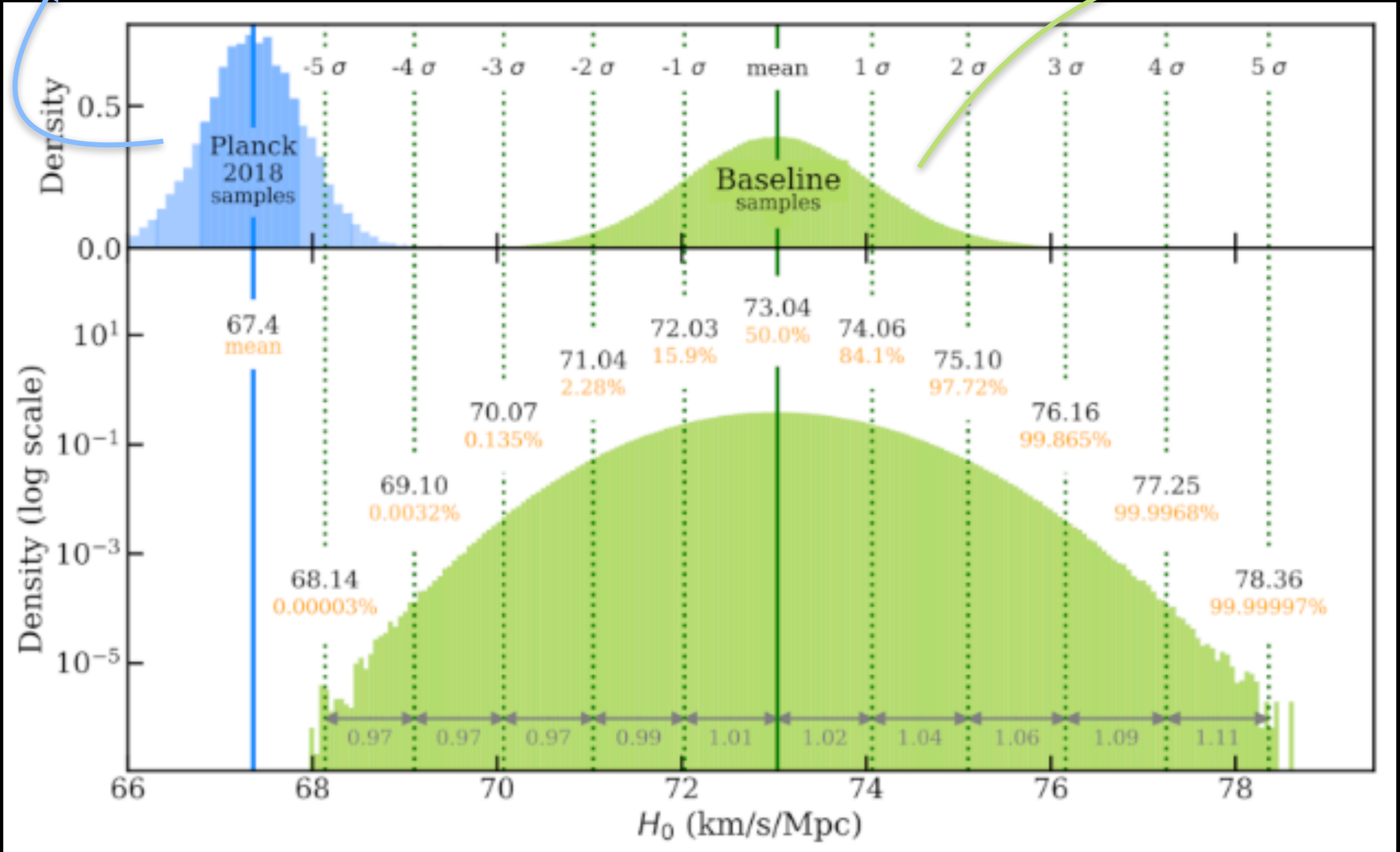
Therefore, the persistence of these tensions could indicate the failure of the canonical ΛCDM model.

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"
ΛCDM cosmological model:
H0 = 67.36 ± 0.54 km/s/Mpc

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



The latest local measurements obtained by the SH0ES collaboration

H0 = 73.04 ± 1.04 km/s/Mpc

Riess et al. arXiv:*2112.04510*

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

Distance Ladder

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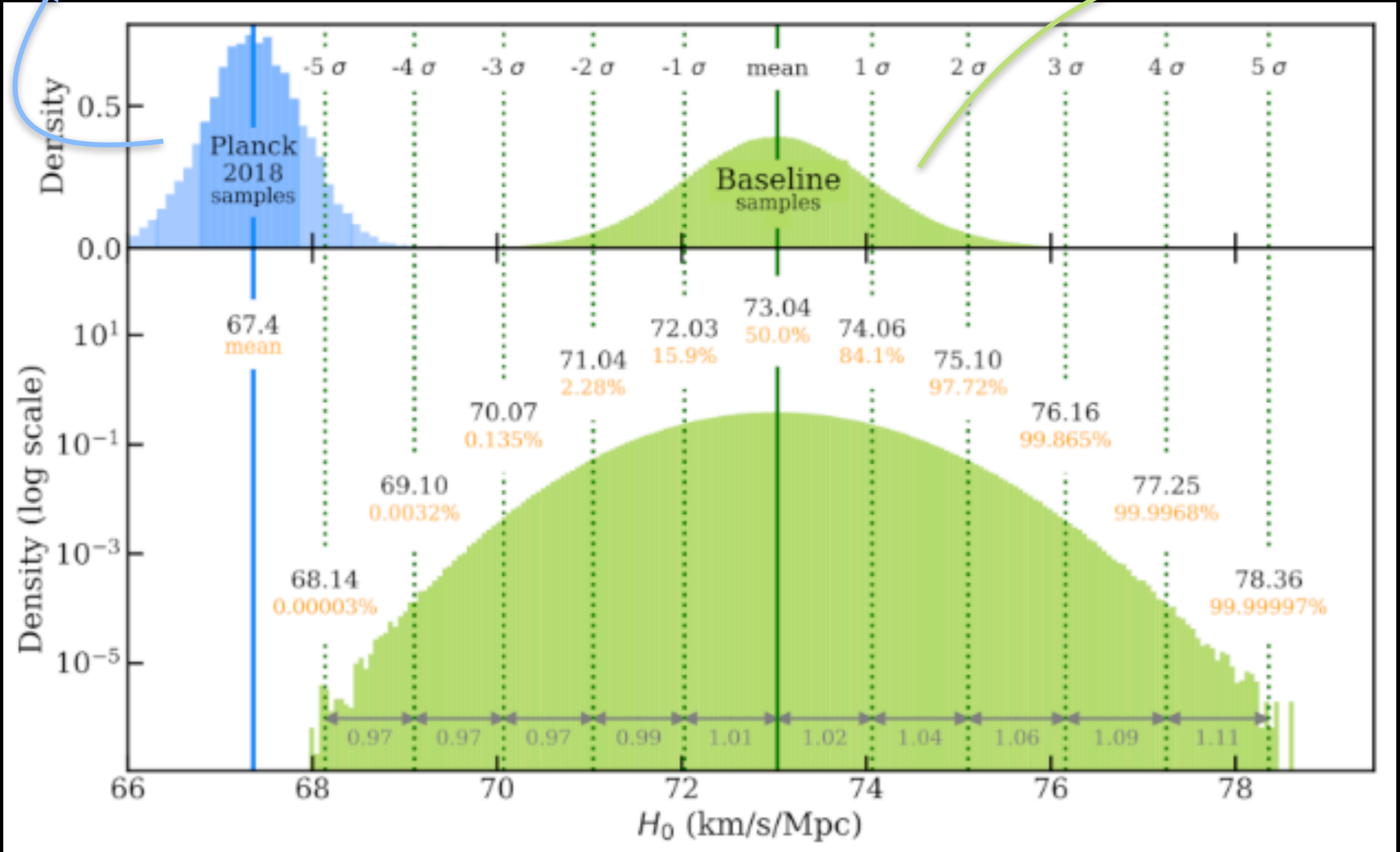

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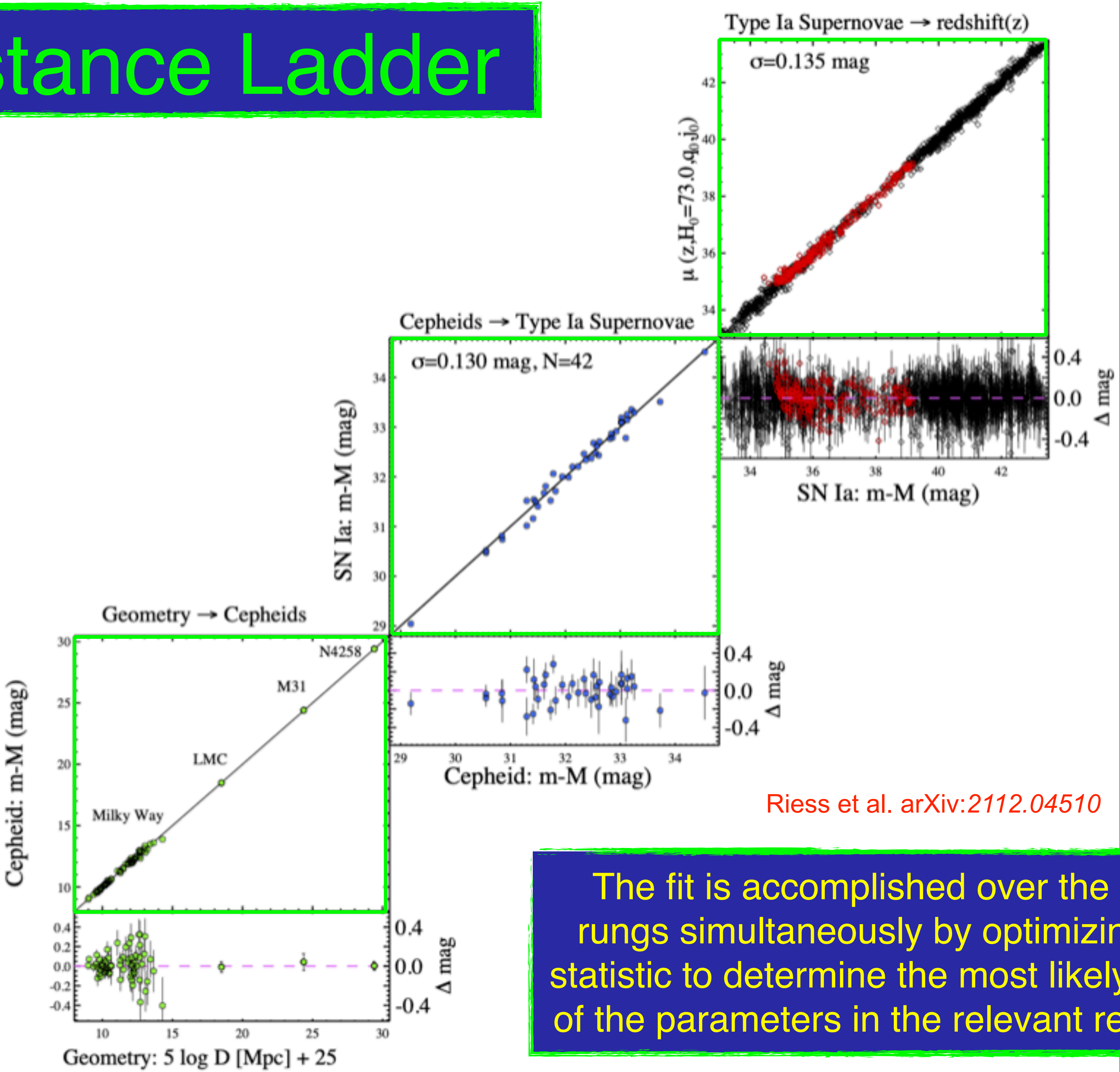
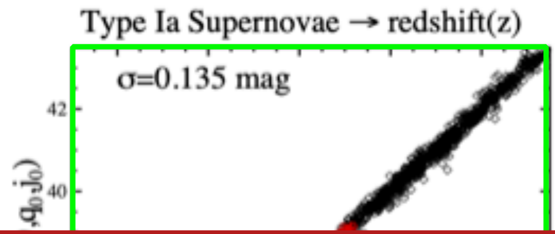
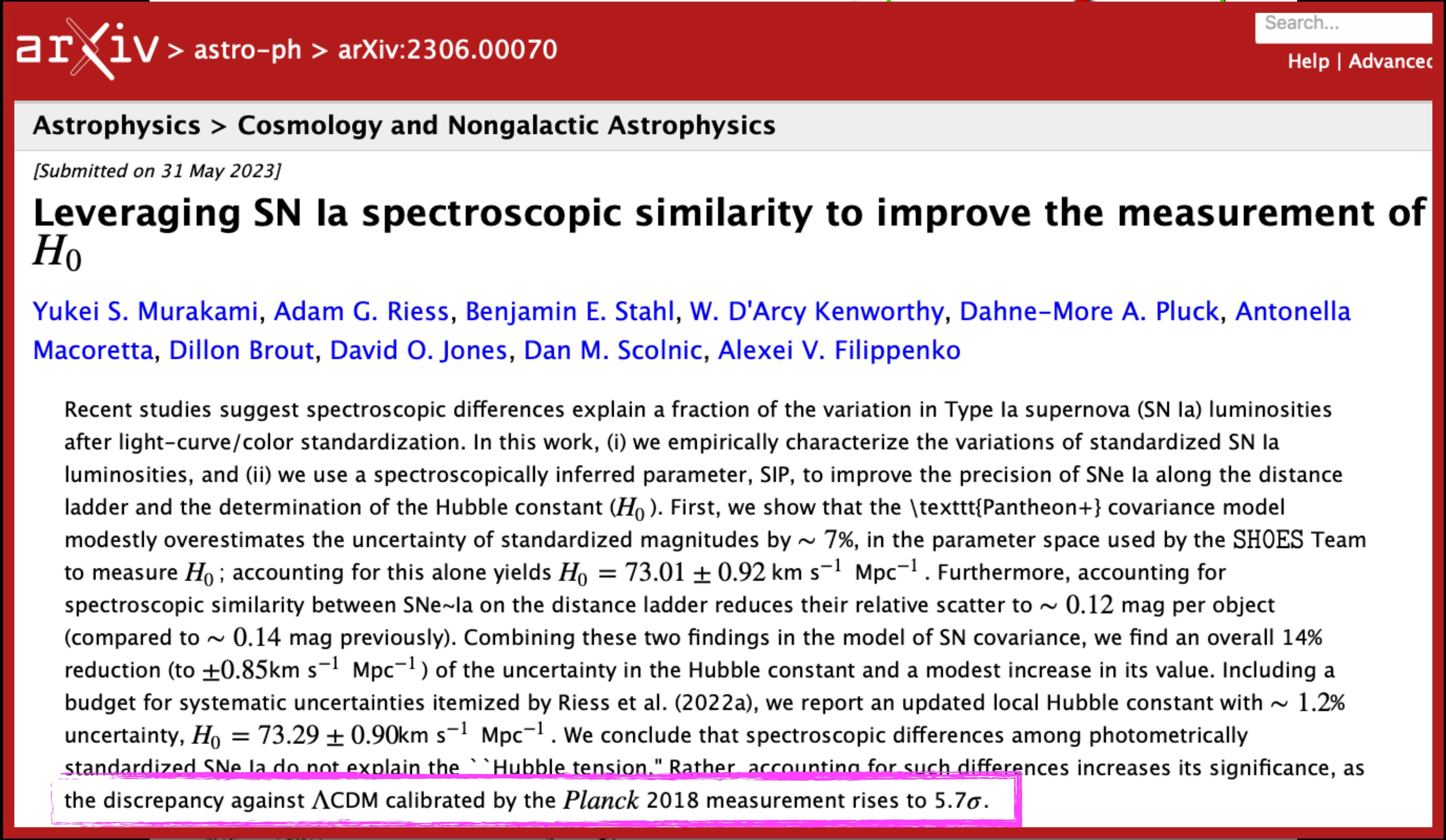


Riess et al. arXiv:*2112.04510*

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

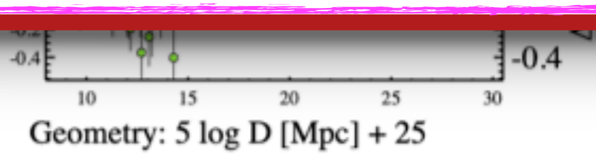
Astrophysics > Cosmology and Nongalactic Astrophysics

[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 \texttt{Pantheon+} covariance model modestly overestimates the uncertainty of standardized magnitudes by $\sim 7\%$, in the parameter space used by the SH0ES Team to measure H_0; accounting for this alone yields $H_0 = 73.01 \pm 0.92$ km s^{-1} Mpc^{-1}. Furthermore, accounting for spectroscopic similarity between SNe~Ia on the distance ladder reduces their relative scatter to ~ 0.12 mag per object (compared to ~ 0.14 mag previously). Combining these two findings in the model of SN covariance, we find an overall 14% reduction (to ± 0.85km s^{-1} 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, $H_0 = 73.29 \pm 0.90$km s^{-1} 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 ΛCDM calibrated by the *Planck* 2018 measurement rises to 5.7σ.



CMB constraints

The Planck estimate assuming a “vanilla"
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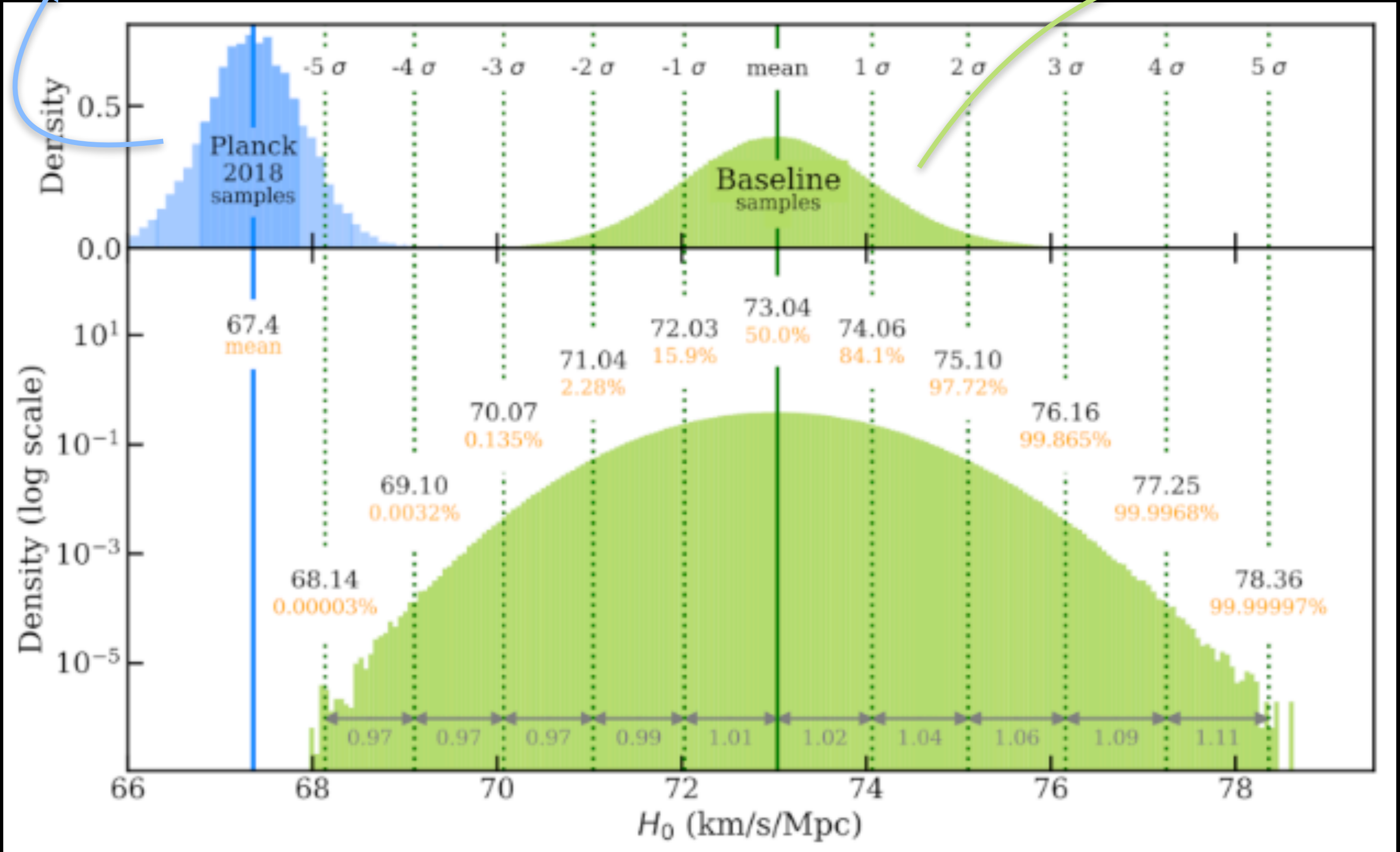
Planck 2018, Astron.Astrophys. 641 (2020) A6



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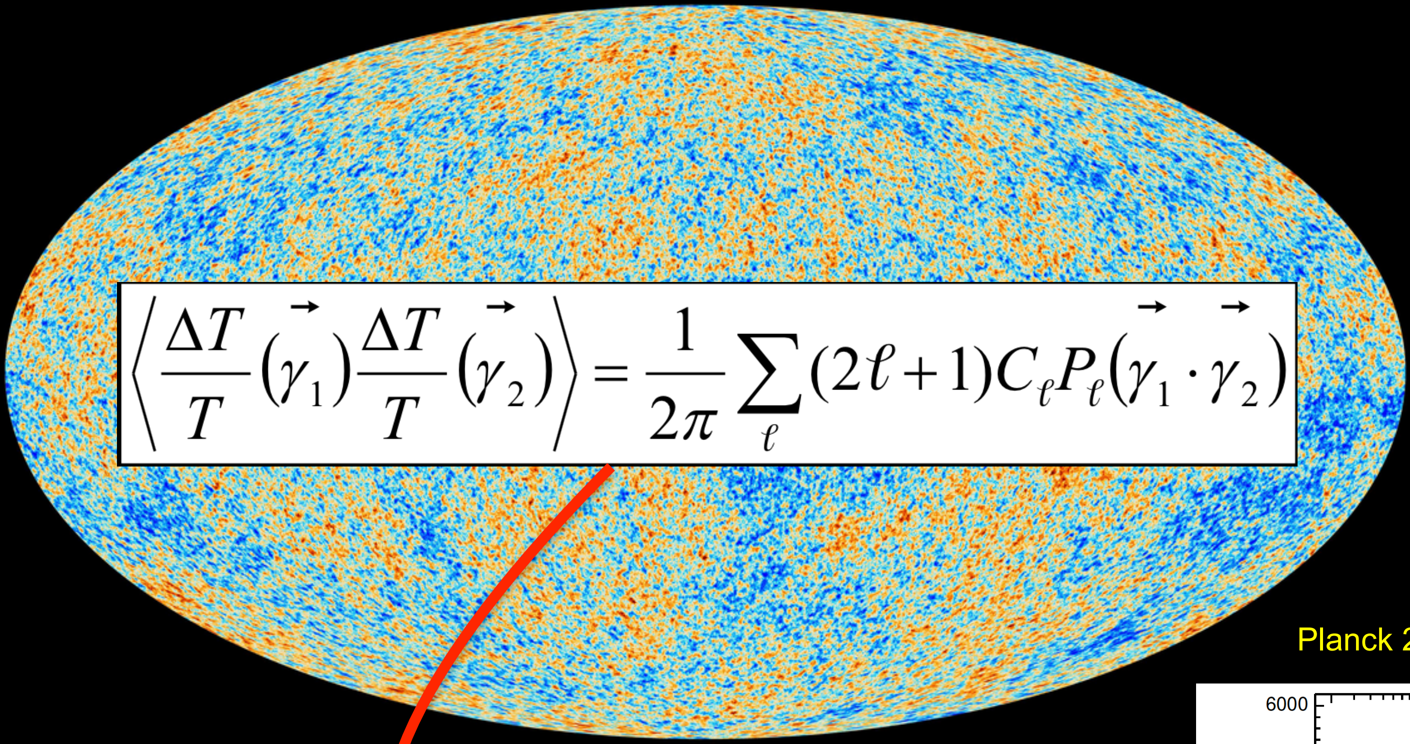
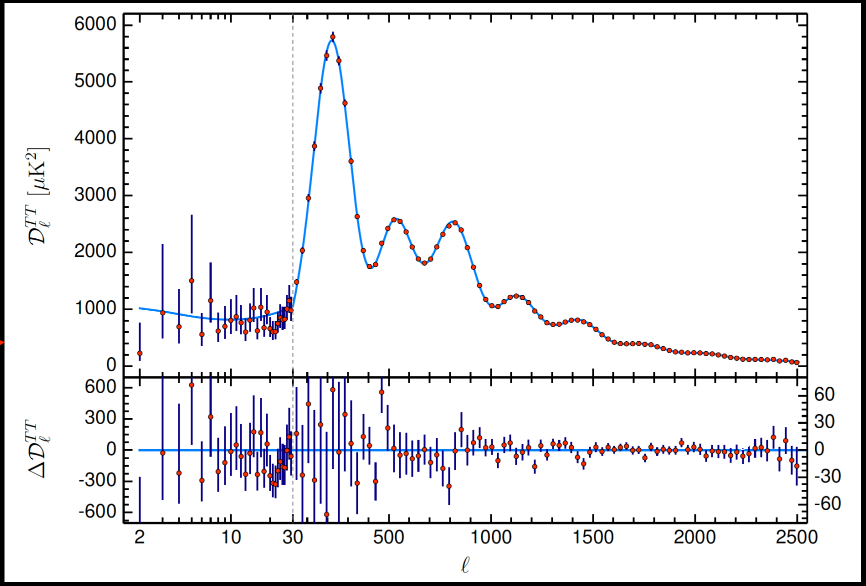


$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$

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

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



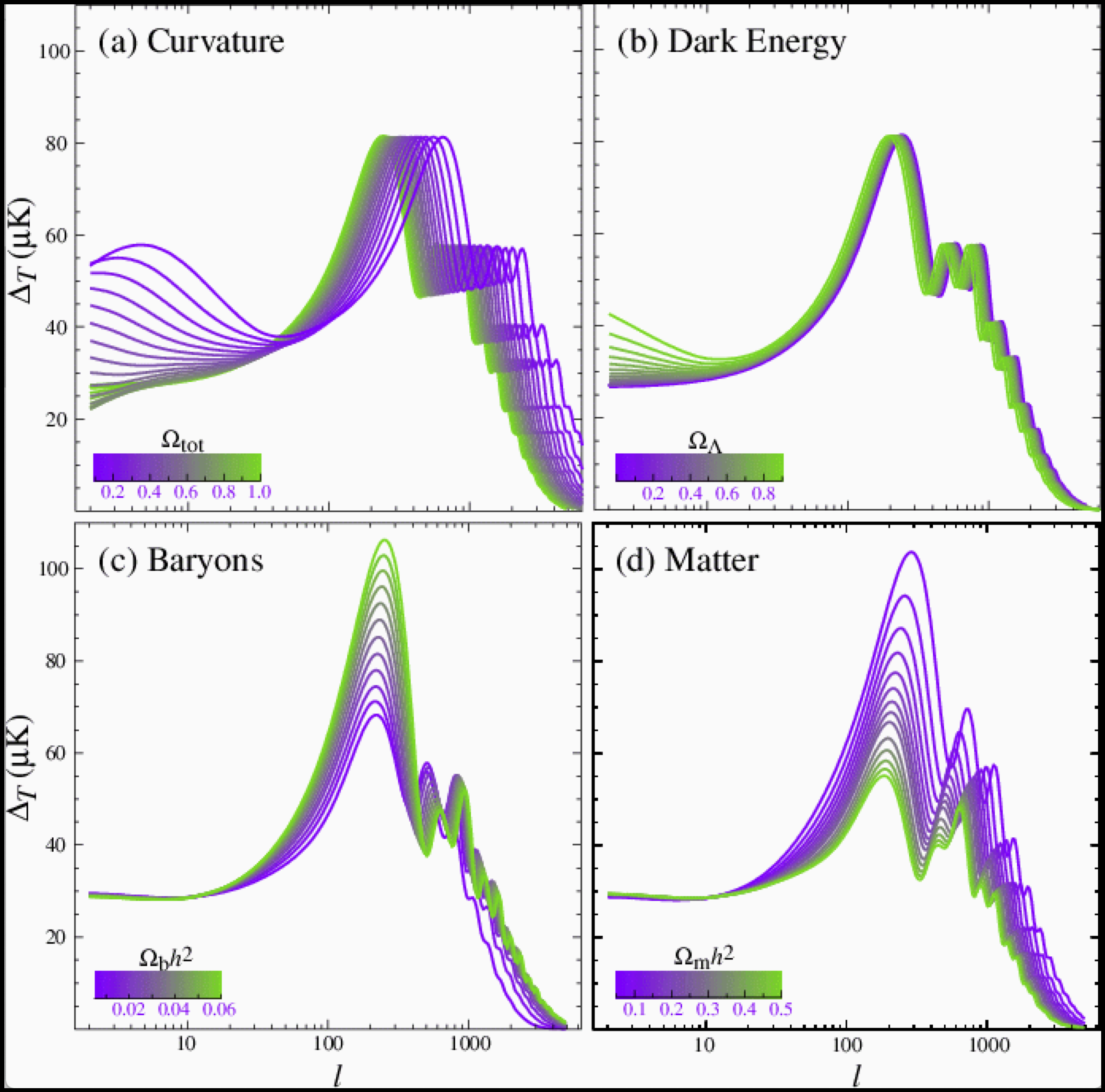
Cosmological parameters:
($\Omega_b h^2$, $\Omega_m h^2$, H0, n_s, τ, As)

Theoretical model

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

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

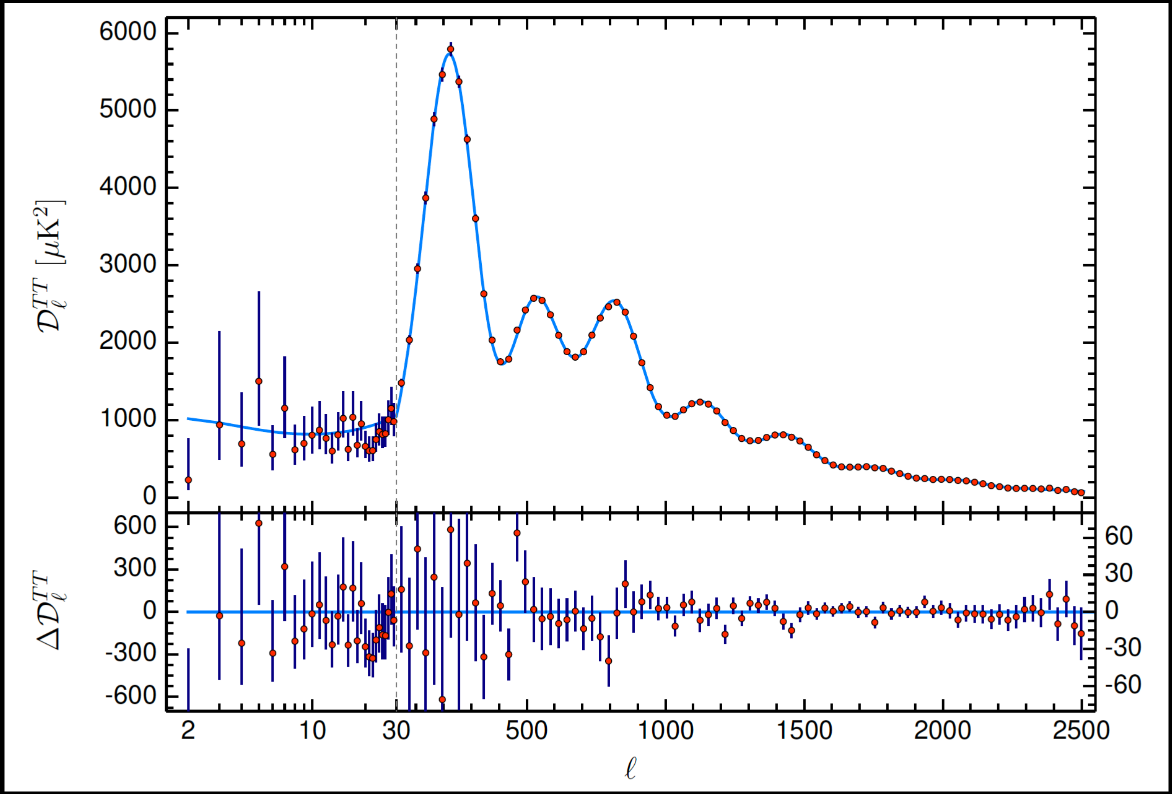
Wayne Hu's tutorial



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

Theoretical model

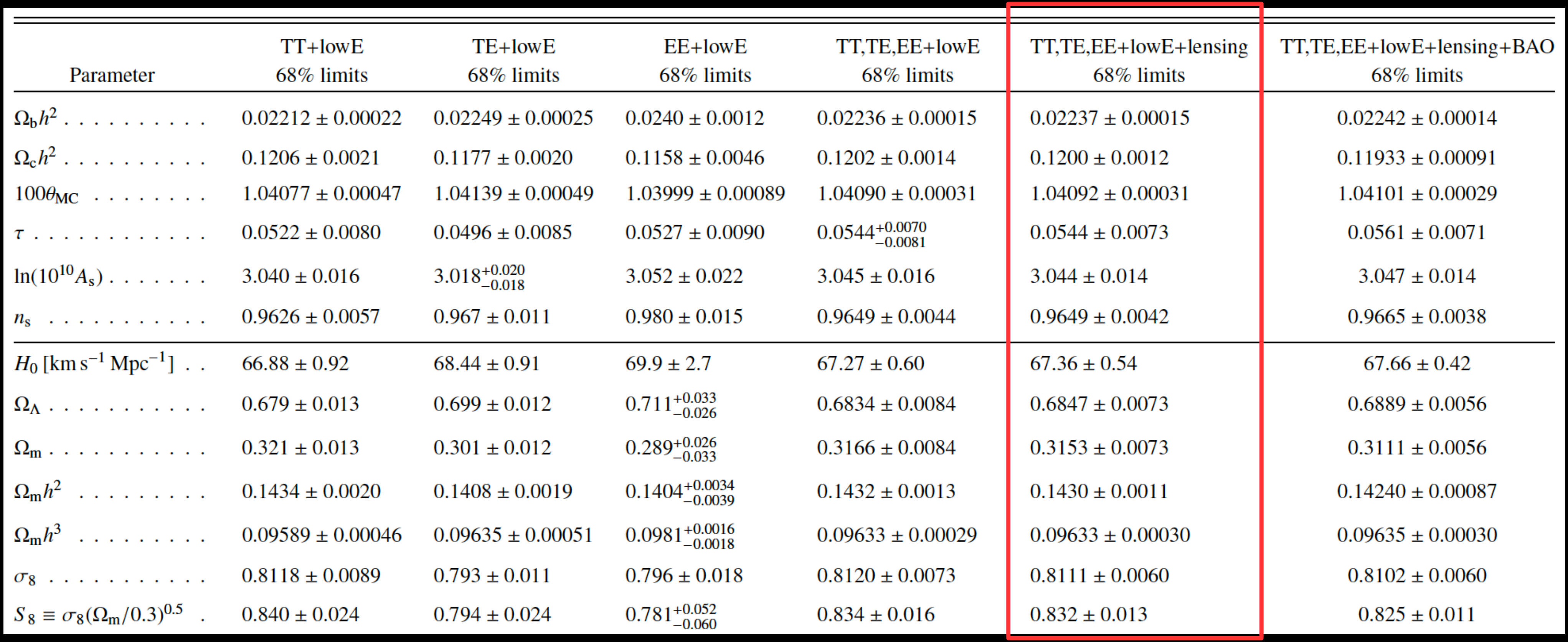
We compare the angular power spectra we computed with the data and, using a bayesian analysis, we get a combination of cosmological parameter values in agreement with these.



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

Parameter constraints

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
$H_0\,[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$	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

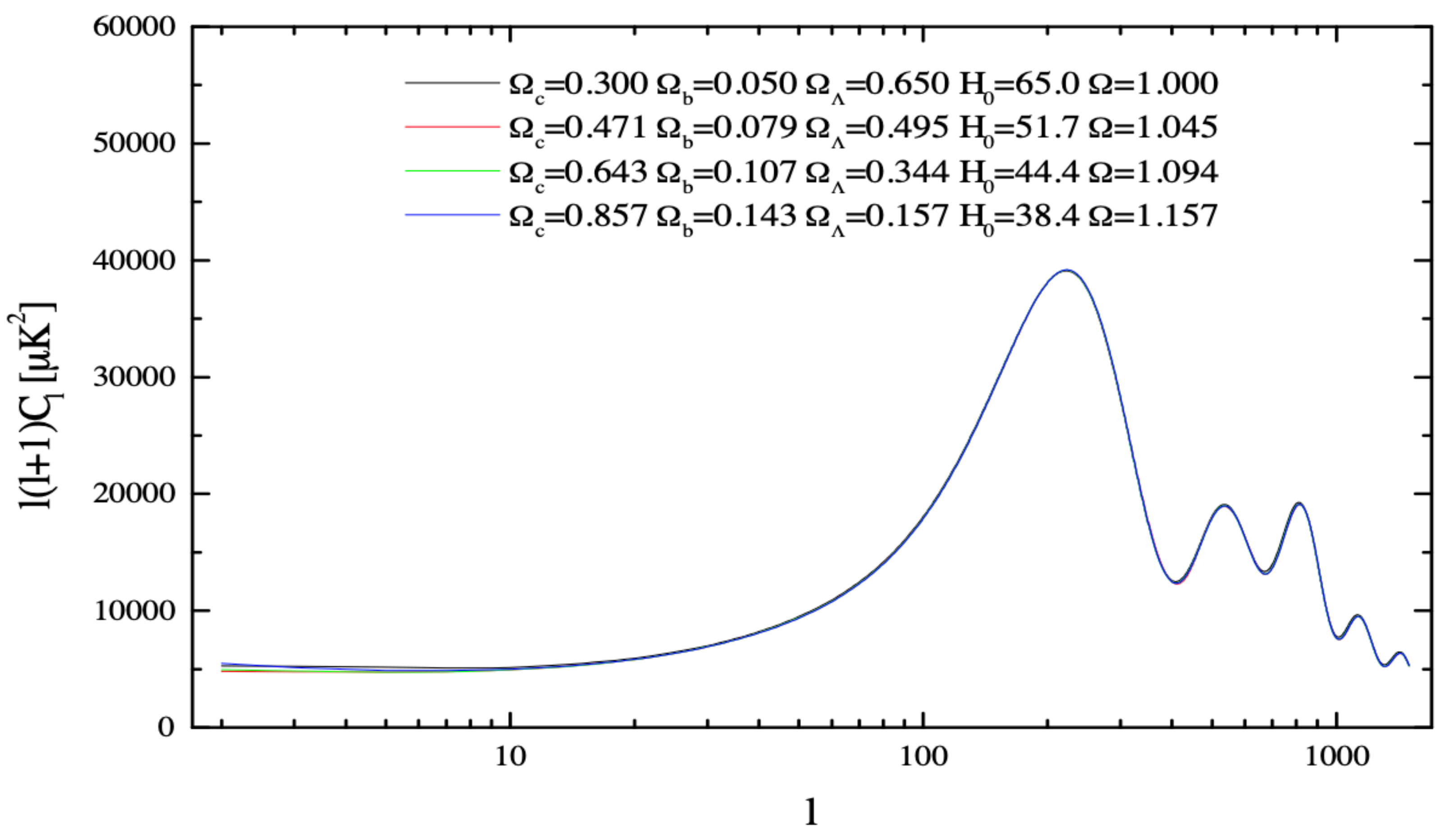
Planck 2018, Astron.Astrophys. 641 (2020) A6

2018 Planck results are a wonderful confirmation of the
flat standard ΛCDM 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

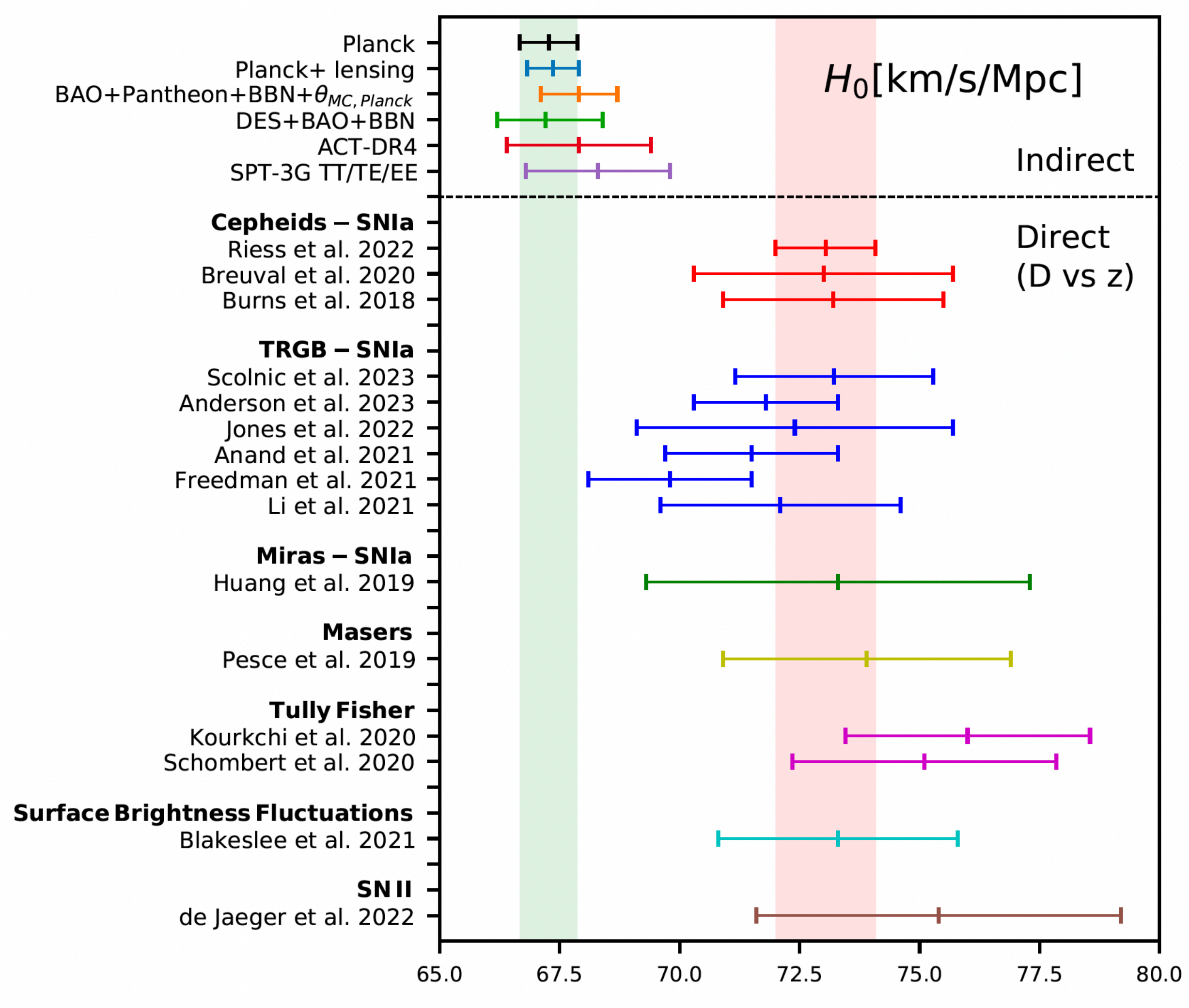
Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$						0091
$100\theta_{MC}$						0029
τ						071
$\ln(10^{10} A_s)$						14
n_s						038
H_0 [km s^{-1} Mpc^{-}						42
Ω_Λ						056
Ω_m						056
$\Omega_m h^2$						0087
$\Omega_m h^3$						0030
σ_8						060
$S_8 \equiv \sigma_8(\Omega_m/0.3$						11



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

Are there other H0 estimates?

Latest H0 measurements



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

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

Abdalla et al., *JHEAp* 34 (2022) 49-211

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 ΛCDM scenario.

The H0 tension

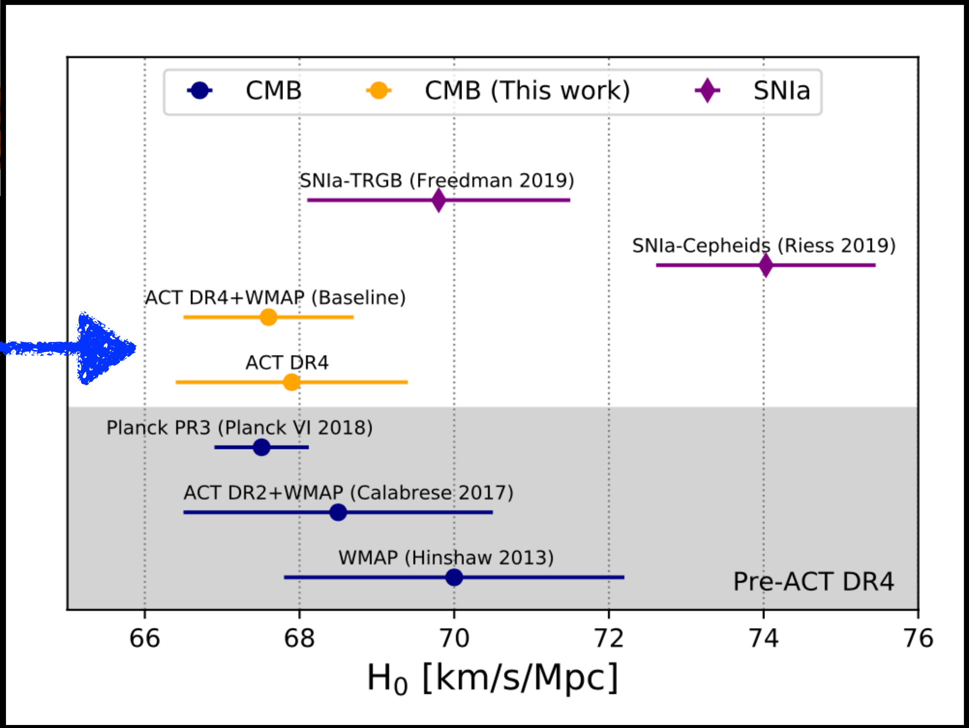
On the same side of Planck, i.e. preferring smaller values of H_0 we have:

Ground based CMB telescope

ACT-DR4:
H0 = 67.9 ± 1.5 km/s/Mpc in ΛCDM

ACT-DR4 + WMAP:
H0 = 67.6 ± 1.1 km/s/Mpc in ΛCDM

ΛCDM - dependent



ACT-DR4 2020, *JCAP* 12 (2020) 047

The H0 tension

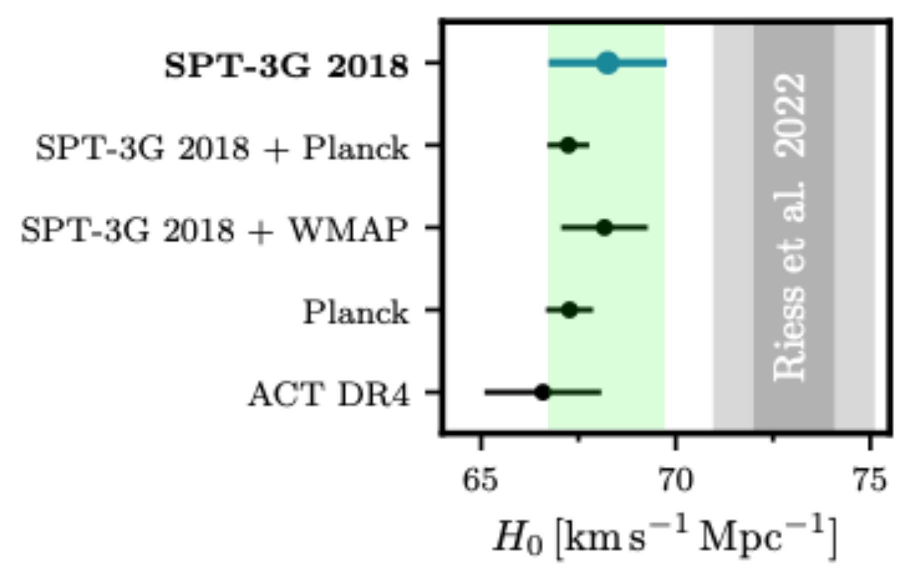
On the same side of Planck, i.e. preferring smaller values of H_0 we have:

CMB Polarization Measurements with SPTpol

Nicholas Harrington
UC Berkeley

Ground based CMB telescope

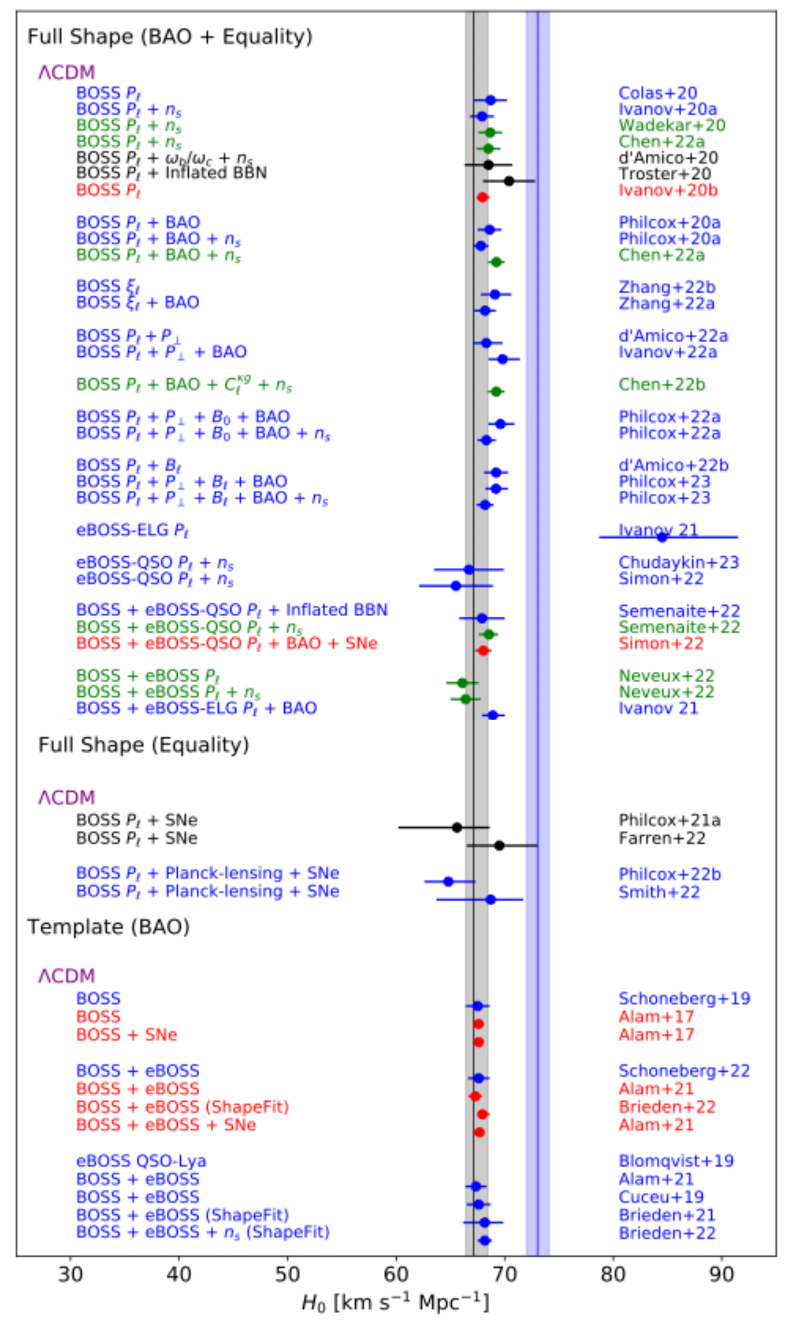
SPT-3G TT/TE/EE:
H0 = 68.3 ± 1.5 km/s/Mpc in ΛCDM



SPT-3G collaboration, arXiv:2212.05642

ΛCDM - dependent

The H0 tension



Ivanov and Philcox, arXiv:2305.07977

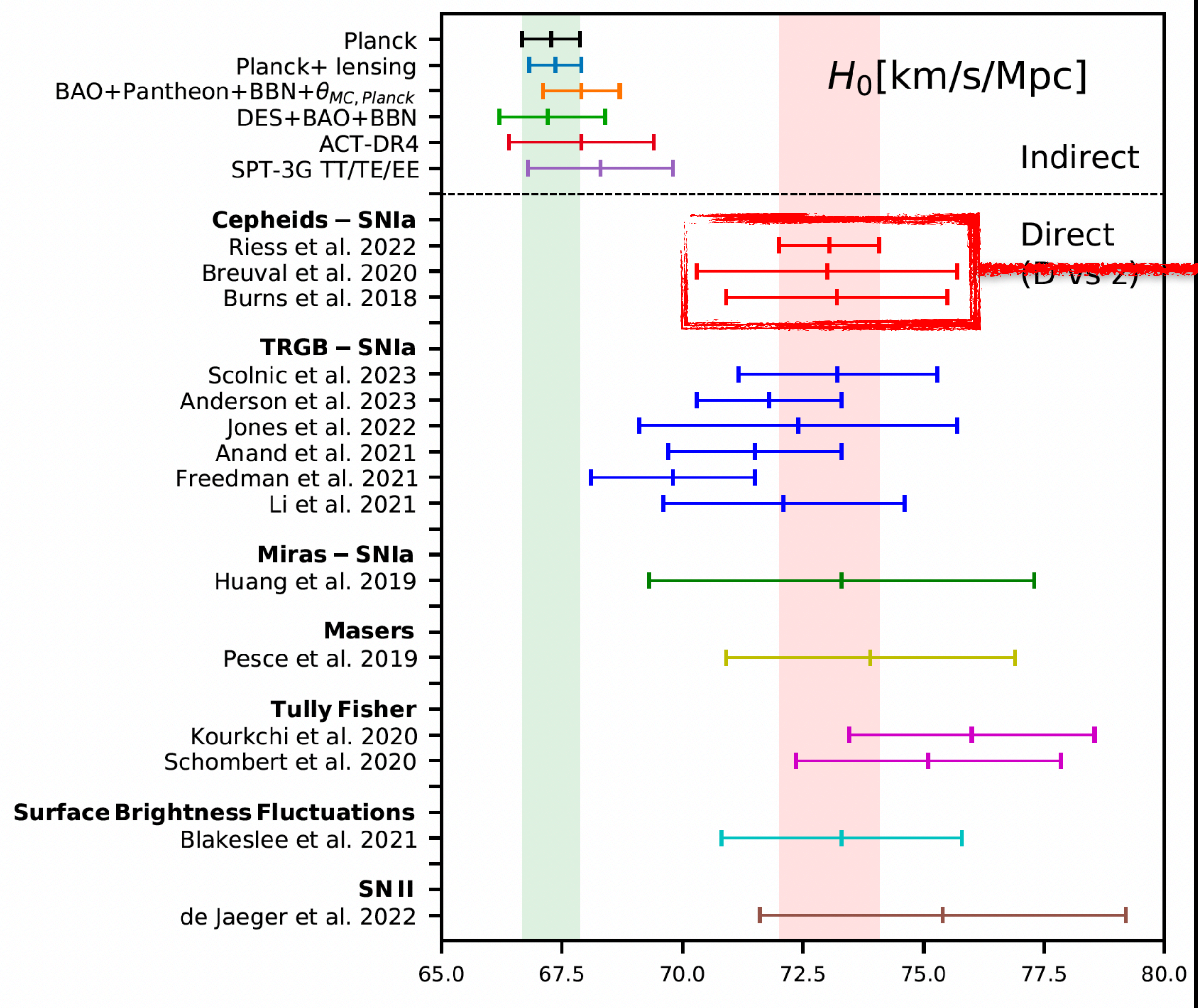
On the same side of Planck, i.e.
preferring smaller values of H0 we have:

Spectroscopic Surveys
BAO and Full Shape from BOSS and eBOSS

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

ΛCDM - dependent

Late universe measurements since 2020



Cepheids-SN Ia:

H0 = 73.04 ± 1.04 km/s/Mpc

Riess et al., arXiv:*2112.04510*

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

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

Abdalla et al., *JHEAp* 34 (2022) 49-211

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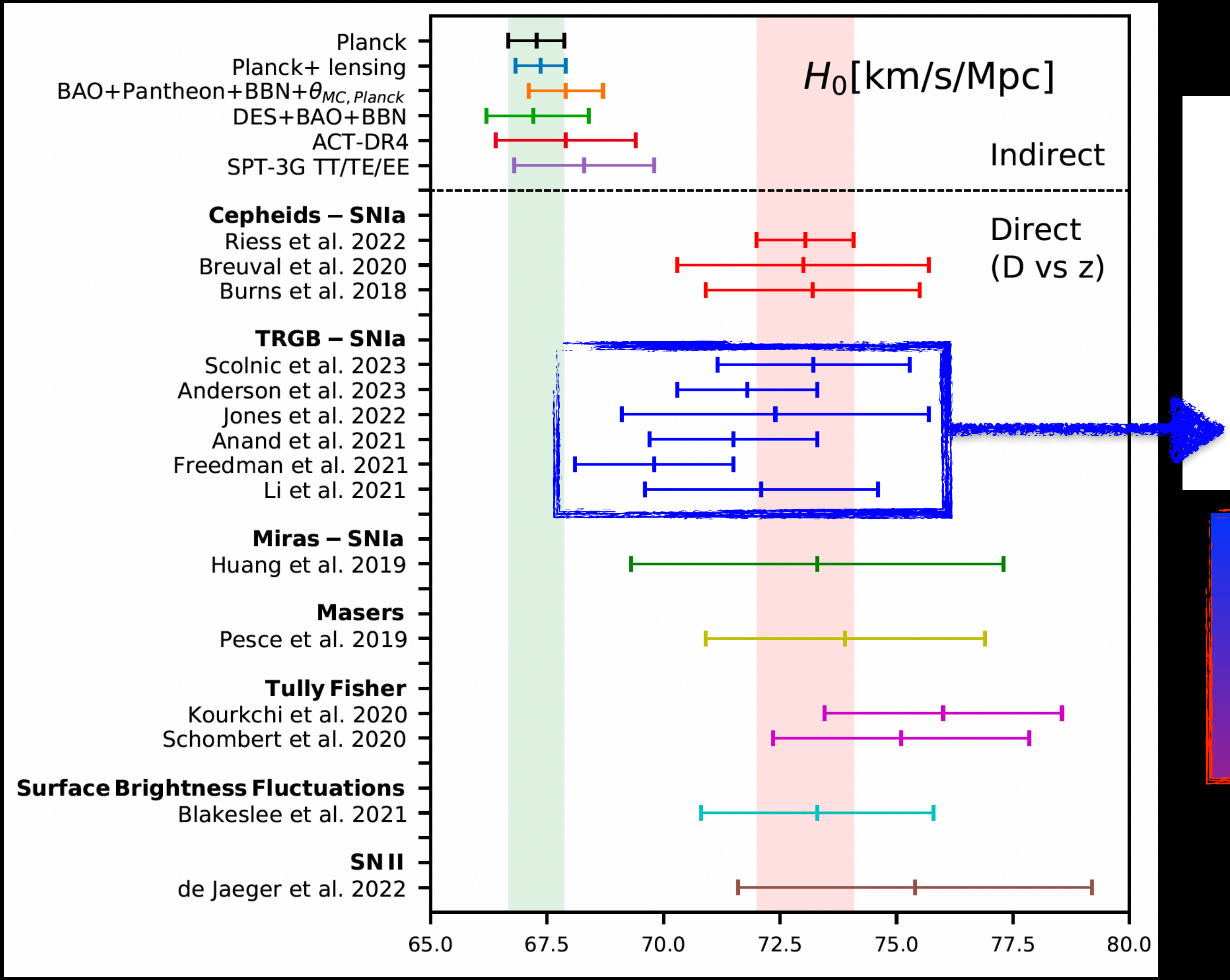

The Tip of the Red Giant Branch (TRGB) is the peak brightness reached by red giant stars after they stop using hydrogen and begin fusing helium in their core.

H0 = 73.22±2.06 km/s/Mpc

Scolnic et al., arXiv:2304.06693

H0 = 71.8±1.5 km/s/Mpc

Anderson et al., arXiv:2303.04790

H0 = 72.4±3.3 km/s/Mpc

Jones et al., arXiv:2201.07801

H0 = 71.5±1.8 km/s/Mpc

Anand et al., arXiv:2108.00007

H0 = 69.8±1.7 km/s/Mpc

Freedman, arXiv:2106.15656

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

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

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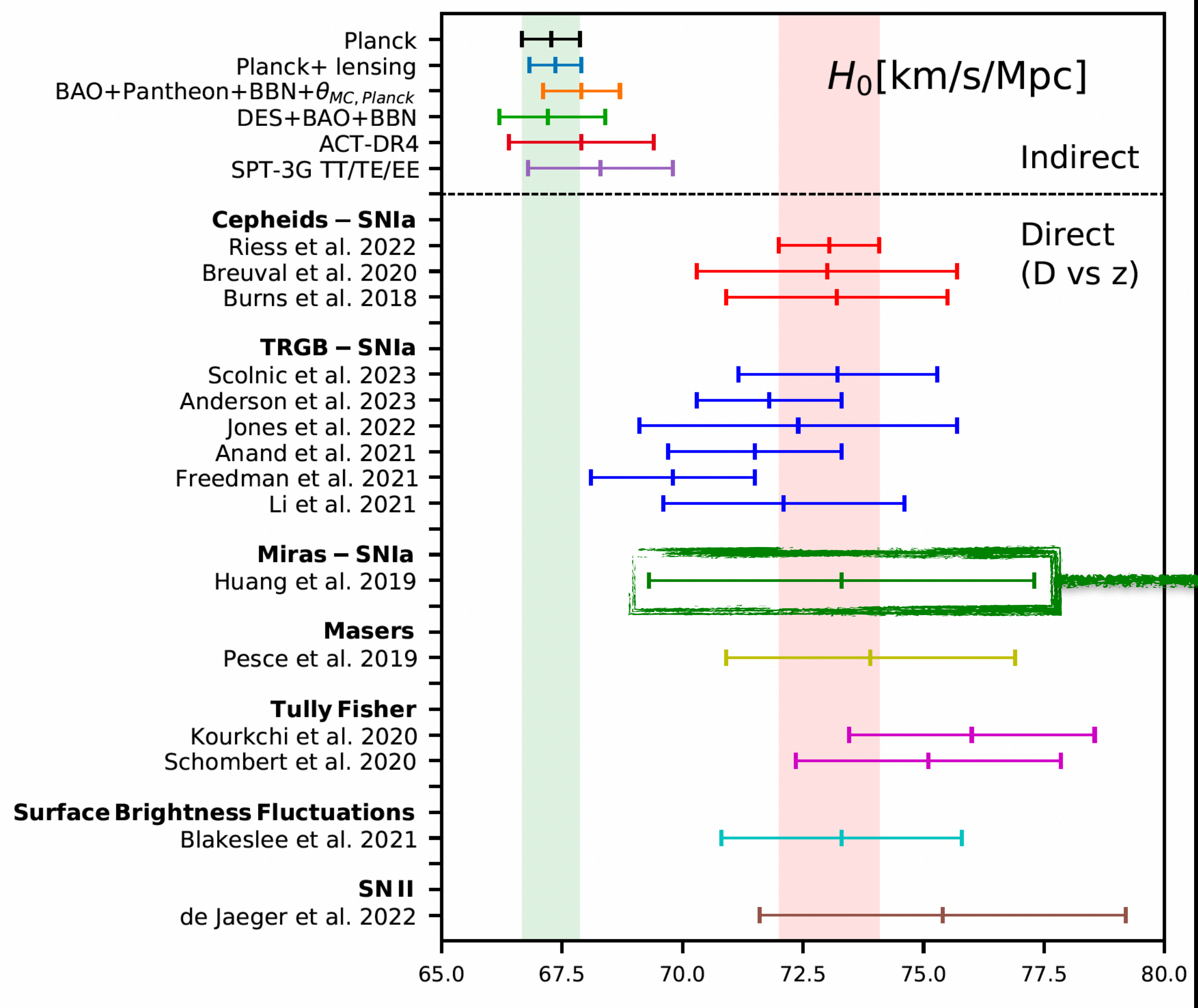

MIRAS
variable red giant stars from older stellar populations

H0 = 73.3 ± 4.0 km/s/Mpc

Huang et al., arXiv:1908.10883 [astro-ph.CO]

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

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

Abdalla et al., *JHEAp* 34 (2022) 49-211

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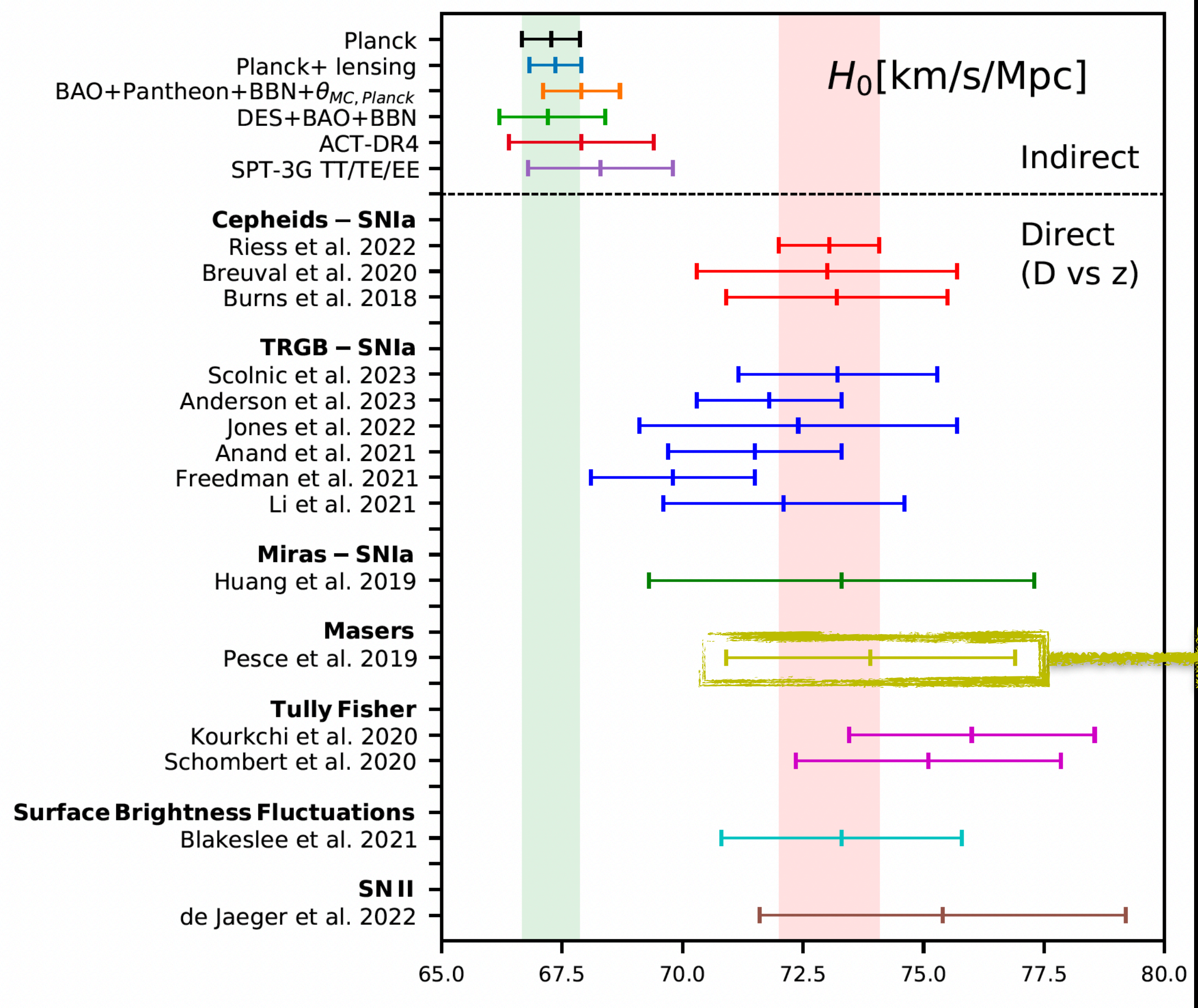

H0 = 73.9 ± 3.0 km/s/Mpc

Pesce et al. arXiv:2001.09213

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

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

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

Abdalla et al., *JHEAp* 34 (2022) 49-211

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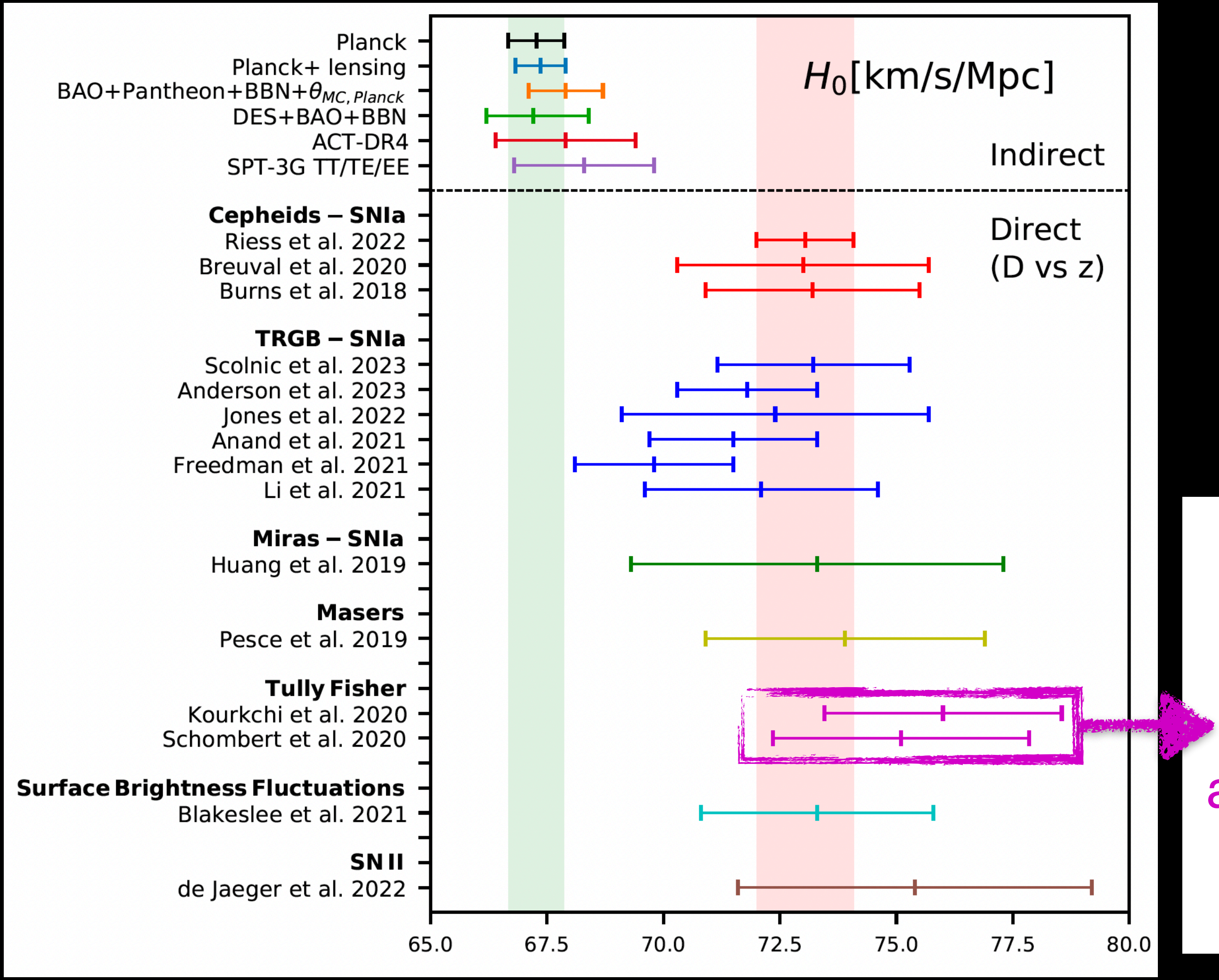


H0 = 76.00 ± 2.55 km/s/Mpc

Kourkchi et al. arXiv:2004.14499

H0 = 75.10 ± 2.75 km/s/Mpc

Schombert et al. arXiv:2006.08615

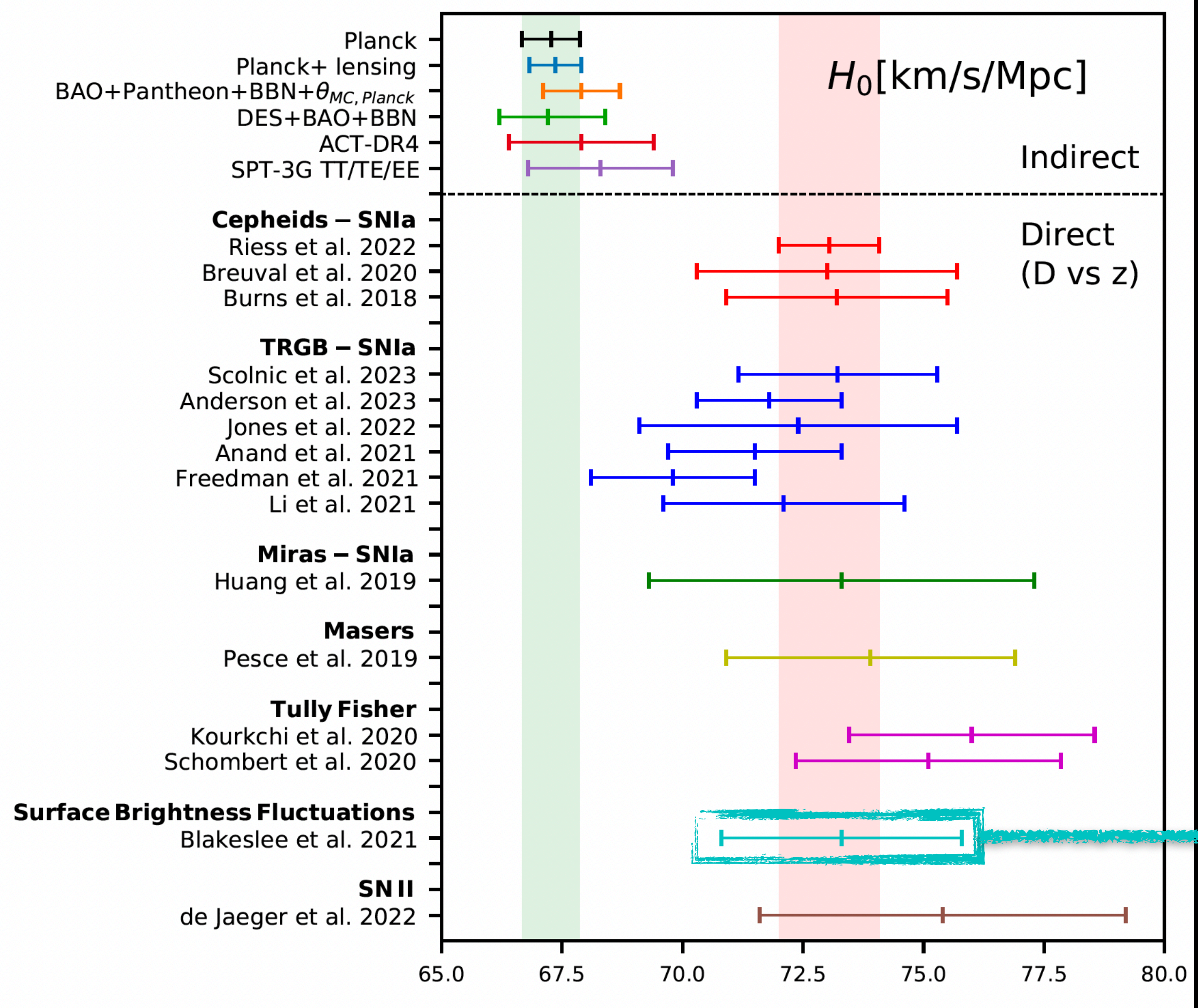
Tully-Fisher Relation (based on the correlation between the rotation rate of spiral galaxies and their absolute luminosity, and using as calibrators Cepheids and TRGB)

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

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

Abdalla et al., *JHEAp* 34 (2022) 49-211

Late universe measurements since 2020



H0 = 73.3 ± 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

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

Abdalla et al., *JHEAp* 34 (2022) 49-211

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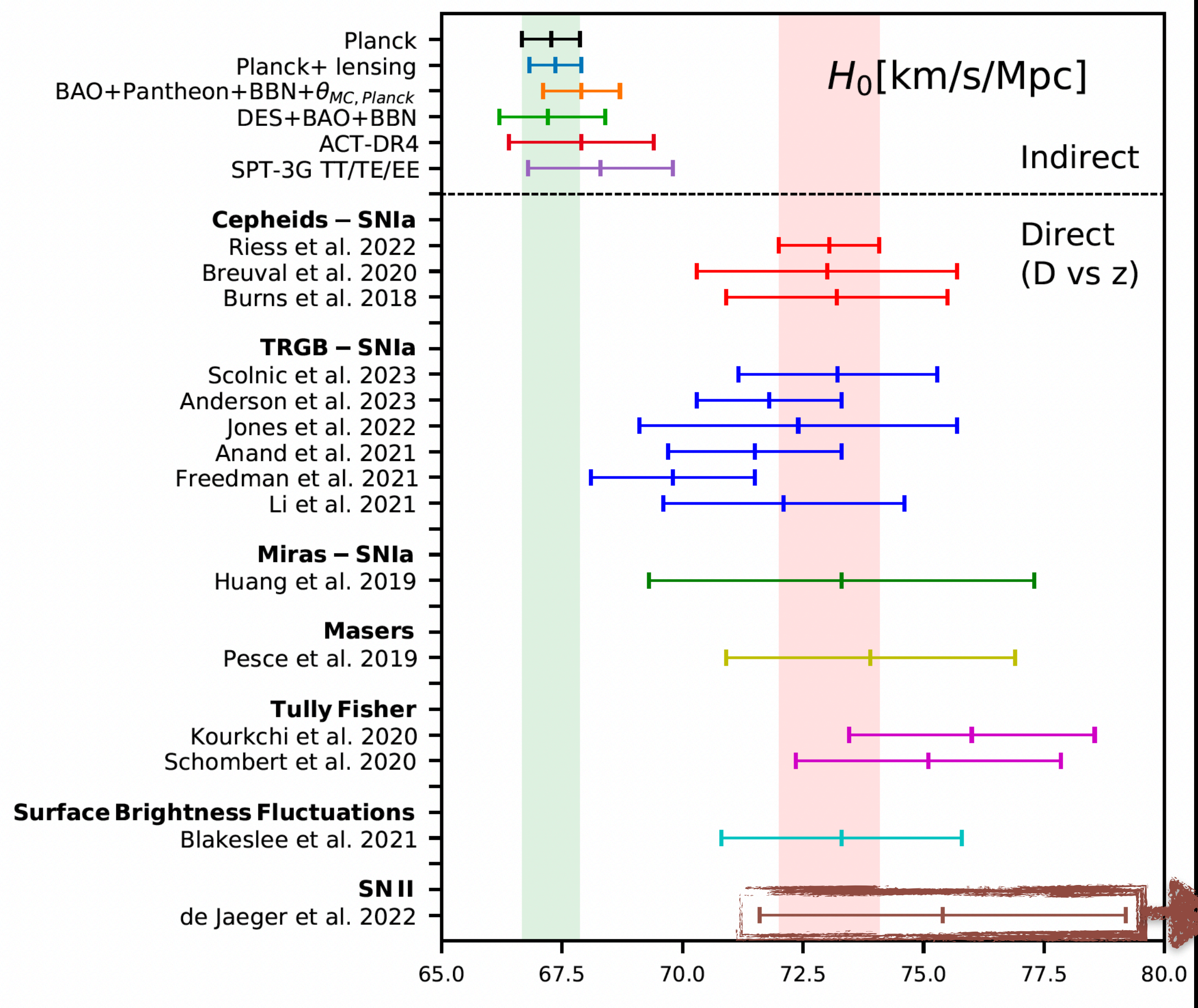

$H0 = 75.4^{+3.8}_{-3.7}$ km/s/Mpc

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

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

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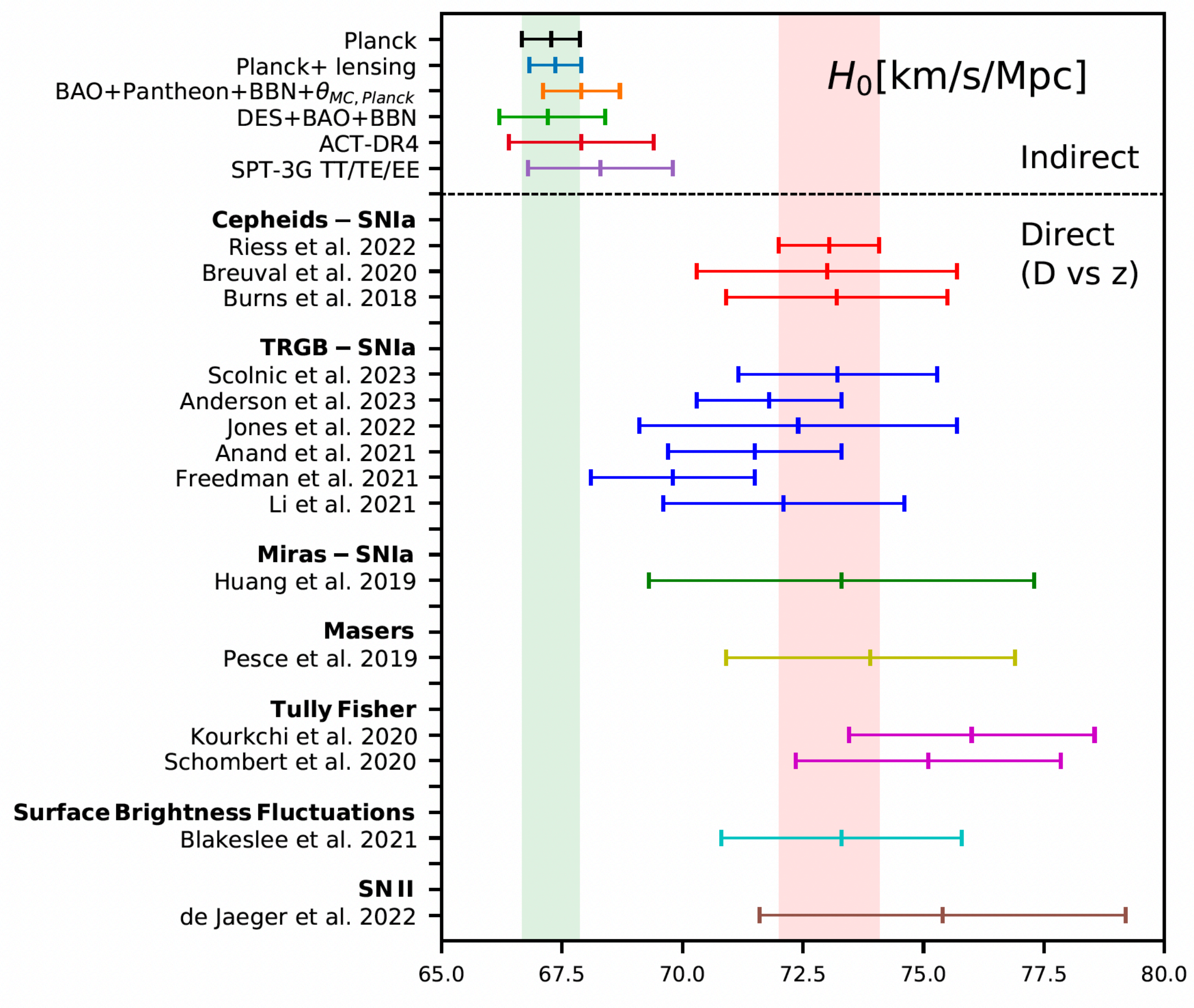


Following the method used in

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073 and Di Valentino, Universe 2022, 8(8), 399

we can combine all of them together and have

6.4σ tension with Planck

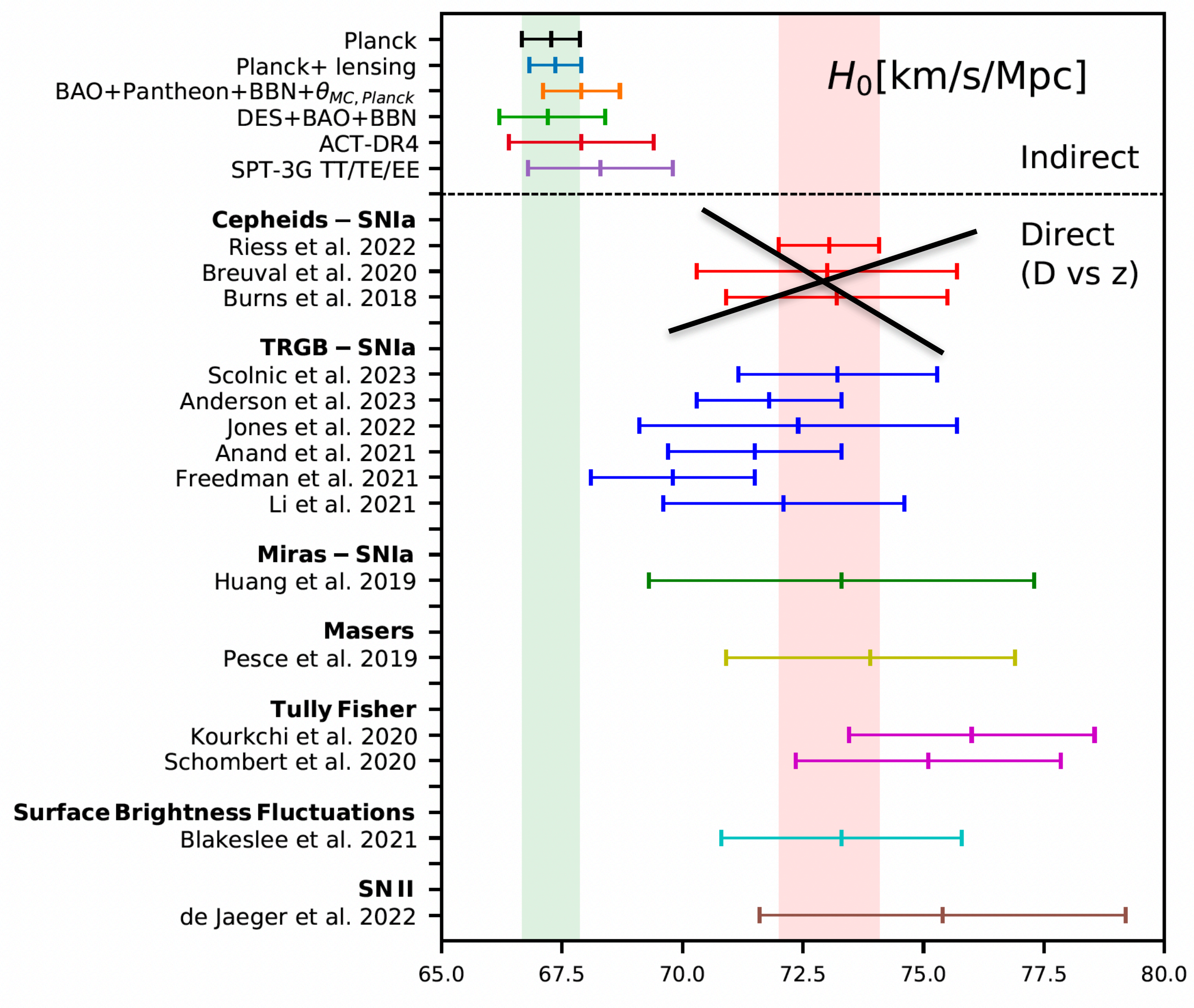
H0 = 73.14 ± 0.72 km/s/Mpc

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

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

Abdalla et al., *JHEAp* 34 (2022) 49-211

Late universe measurements since 2020



Following the method used in Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073 and Di Valentino, Universe 2022, 8(8), 399 excluding one group of data and taking the result with the largest error bar, i.e. excluding the most precise measurements based on Cepheids-SN Ia, we obtain a

conservative estimate (5.3σ tension with Planck)

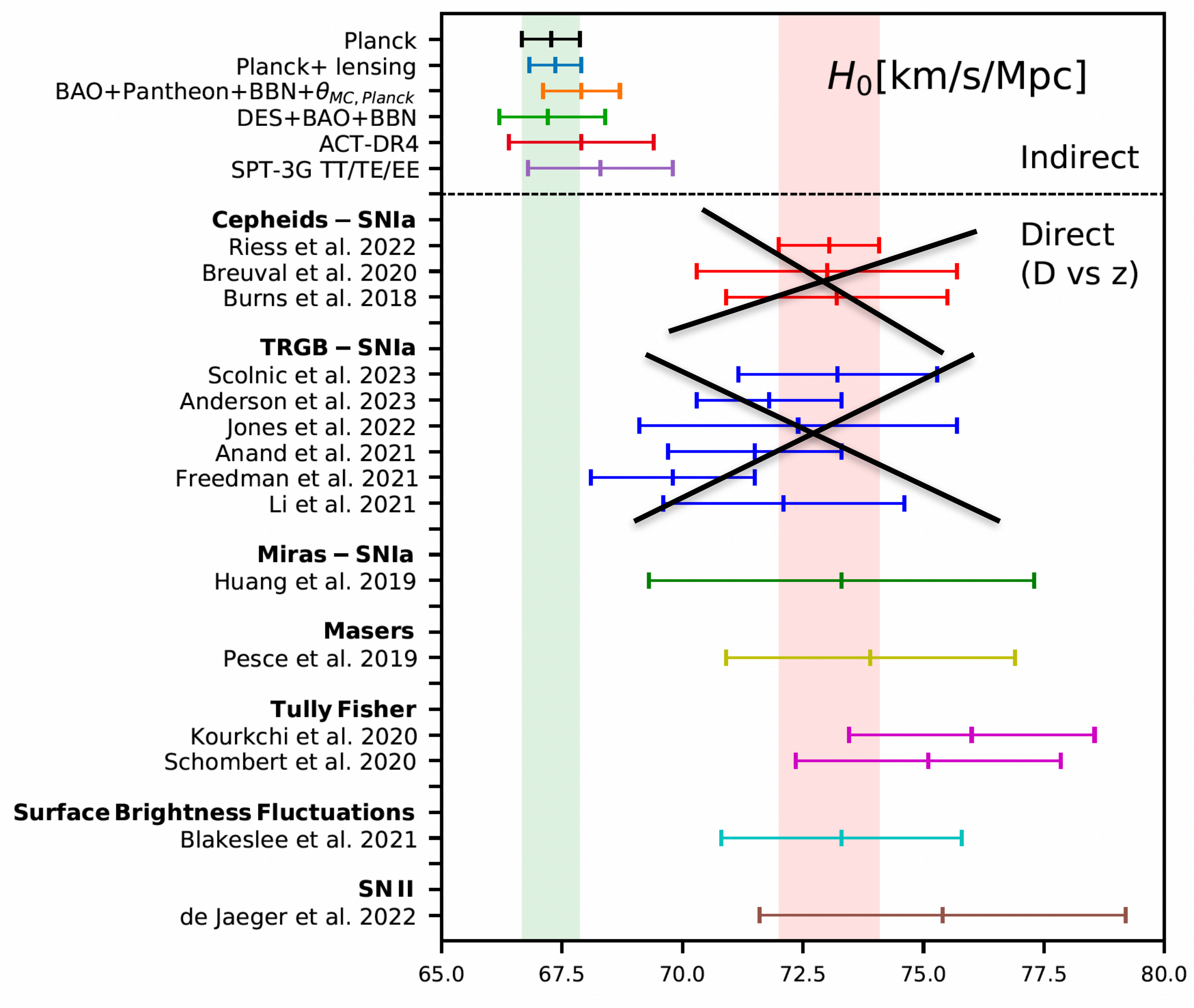
H0 = 73.2 ± 1.0 km/s/Mpc

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

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

Abdalla et al., *JHEAp* 34 (2022) 49-211

Late universe measurements since 2020



Following the method used in Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073 and Di Valentino, Universe 2022, 8(8), 399 excluding one group of data and taking the result with the largest error bar, i.e. excluding the most precise measurements based on Cepheids-SN Ia and TRGB-SN Ia, we obtain an

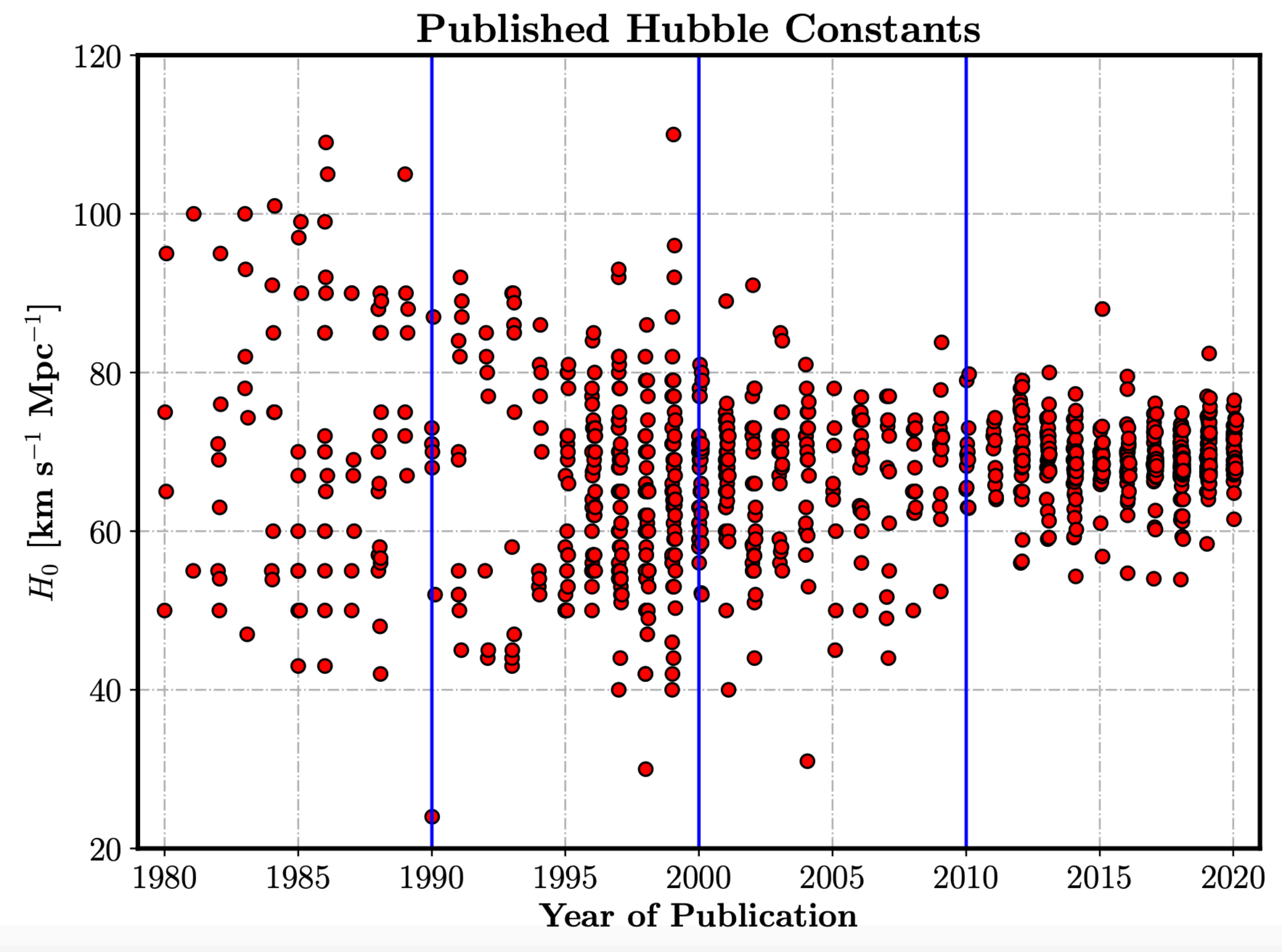
ultra-conservative estimate (5σ tension with Planck)

H0 = 74.3 ± 1.3 km/s/Mpc

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

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

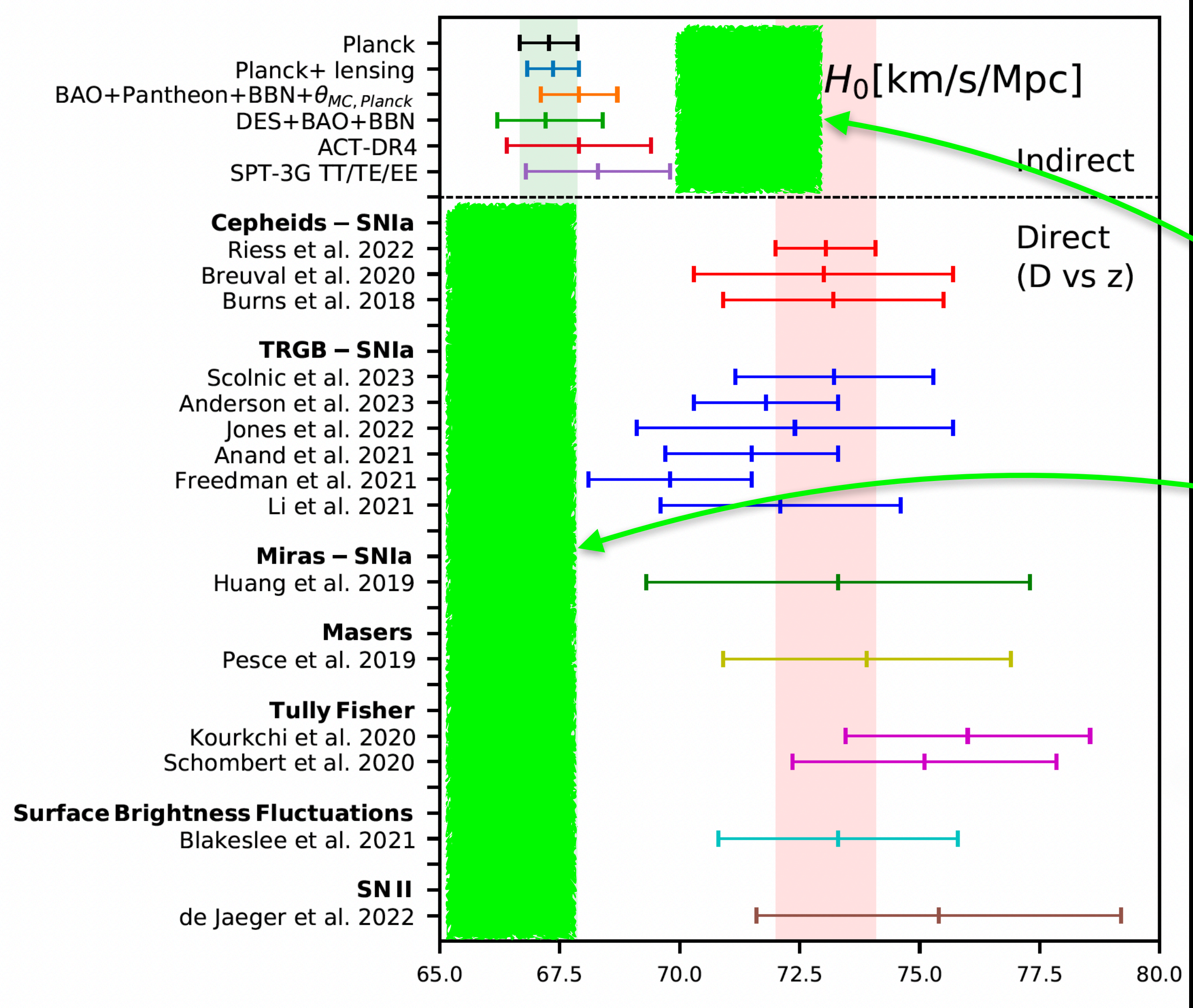
Abdalla et al., *JHEAp* 34 (2022) 49-211



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



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

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

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

Abdalla et al., *JHEAp* 34 (2022) 49-211

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 - 6.4σ 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, mode, 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 ΛCDM model with a few example…

(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.

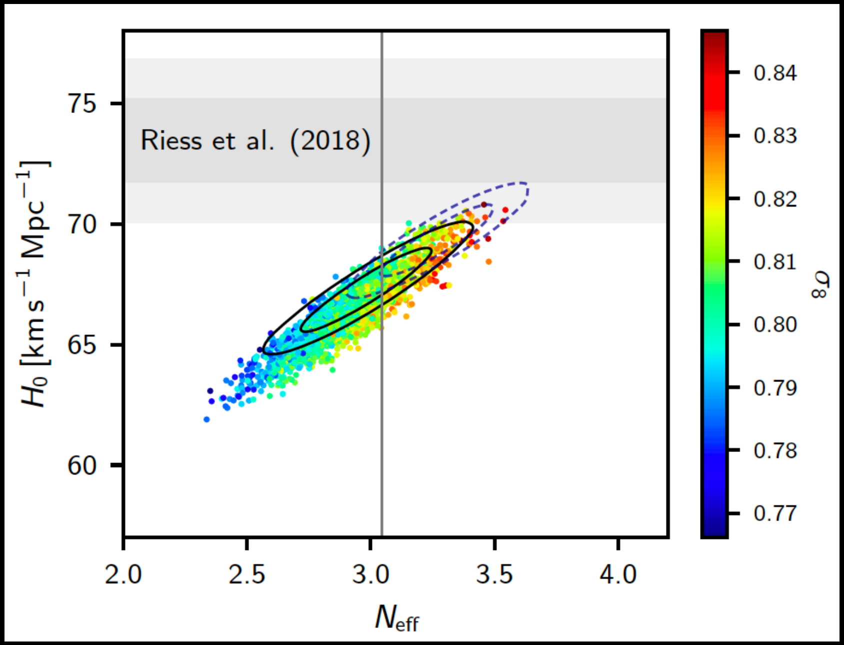
A classical extension is the
effective number of relativistic degrees of freedom,
i.e. additional relativistic matter at recombination,
corresponding to a modification of the expansion history
of the universe at early times.

The Neutrino effective number

The expected value is Neff = 3.044, if we assume standard electroweak interactions and three active massless neutrinos. If we measure a Neff > 3.044, we are in presence of extra radiation.

If we vary Neff, at 68% cl H0 is equal to 66.4 ± 1.4 km/s/Mpc, and the tension with SH0ES is still 3.9σ.

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



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

The Dark energy equation of state

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:

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

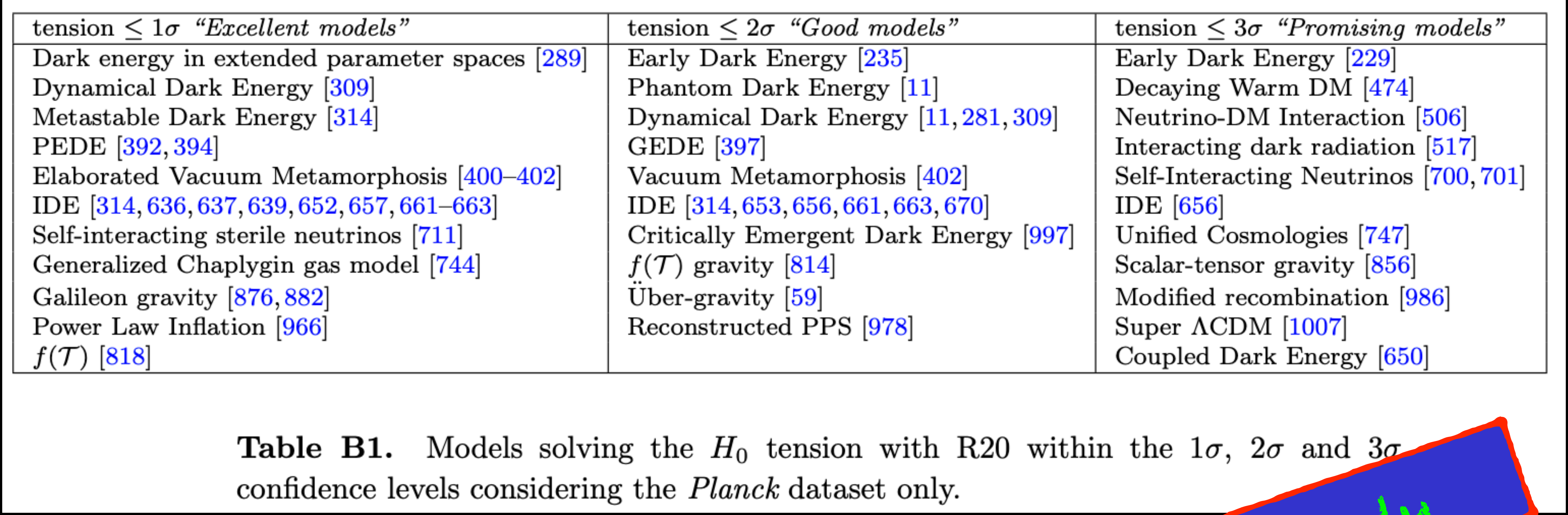
$$H^2 = H_0^2\Big[\Omega_m(1+z)^3+\Omega_r(1+z)^4 + \boxed{\Omega_{\rm de}(1+z)^{3(1+w)}} + \Omega_k(1+z)^2\Big]$$

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 $H0 > 69.9$ 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 $\rho \geq |p|$, 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 H0



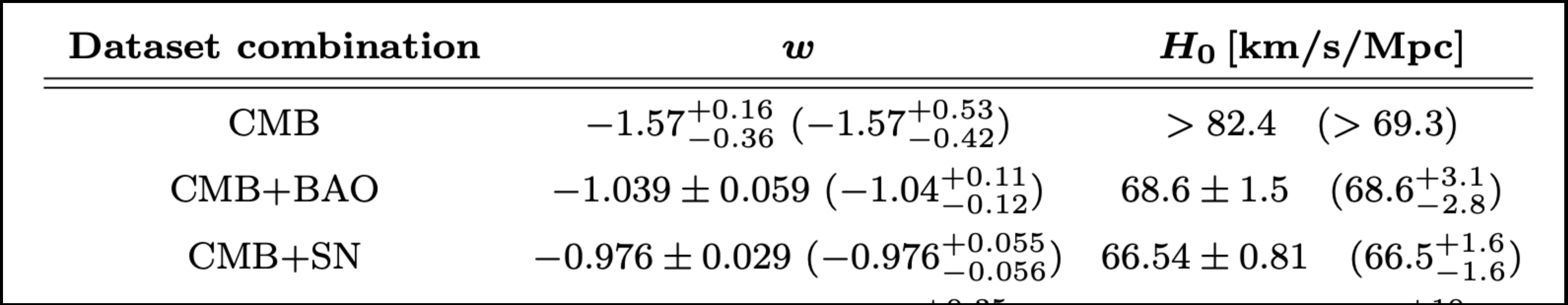
tension $\leq 1\sigma$ *"Excellent models"*	tension $\leq 2\sigma$ *"Good models"*	tension $\leq 3\sigma$ *"Promising models"*
Dark energy in extended parameter spaces [289]	Early Dark Energy [235]	Early Dark Energy [229]
Dynamical Dark Energy [309]	Phantom Dark Energy [11]	Decaying Warm DM [474]
Metastable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

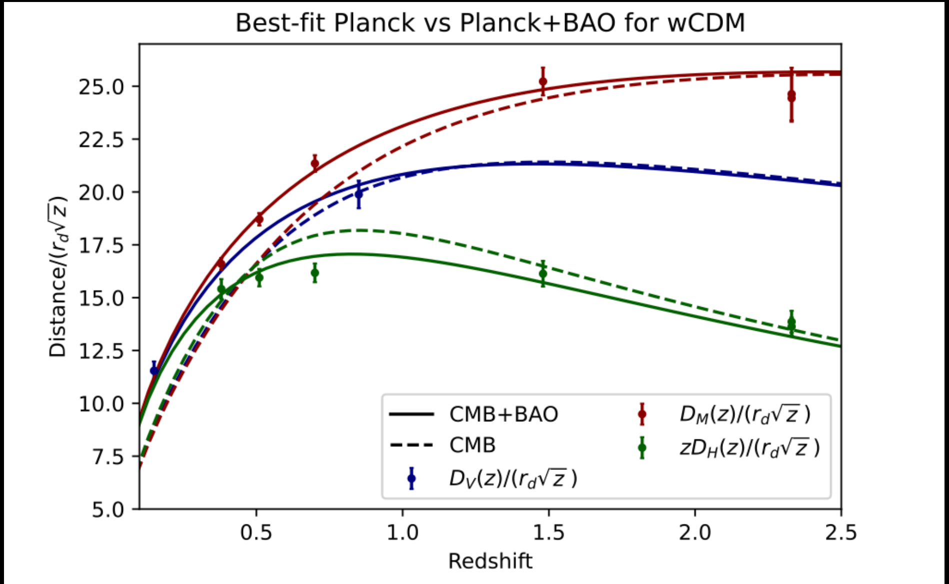


FIG. 5. Best-fit predictions for (rescaled) distance-redshift relations from a wCDM fit to *Planck* CMB data alone (dashed curves) and the CMB+BAO dataset (solid curves). These predictions are presented for the three different types of distances probed by BAO measurements (rescaled as per the y label),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

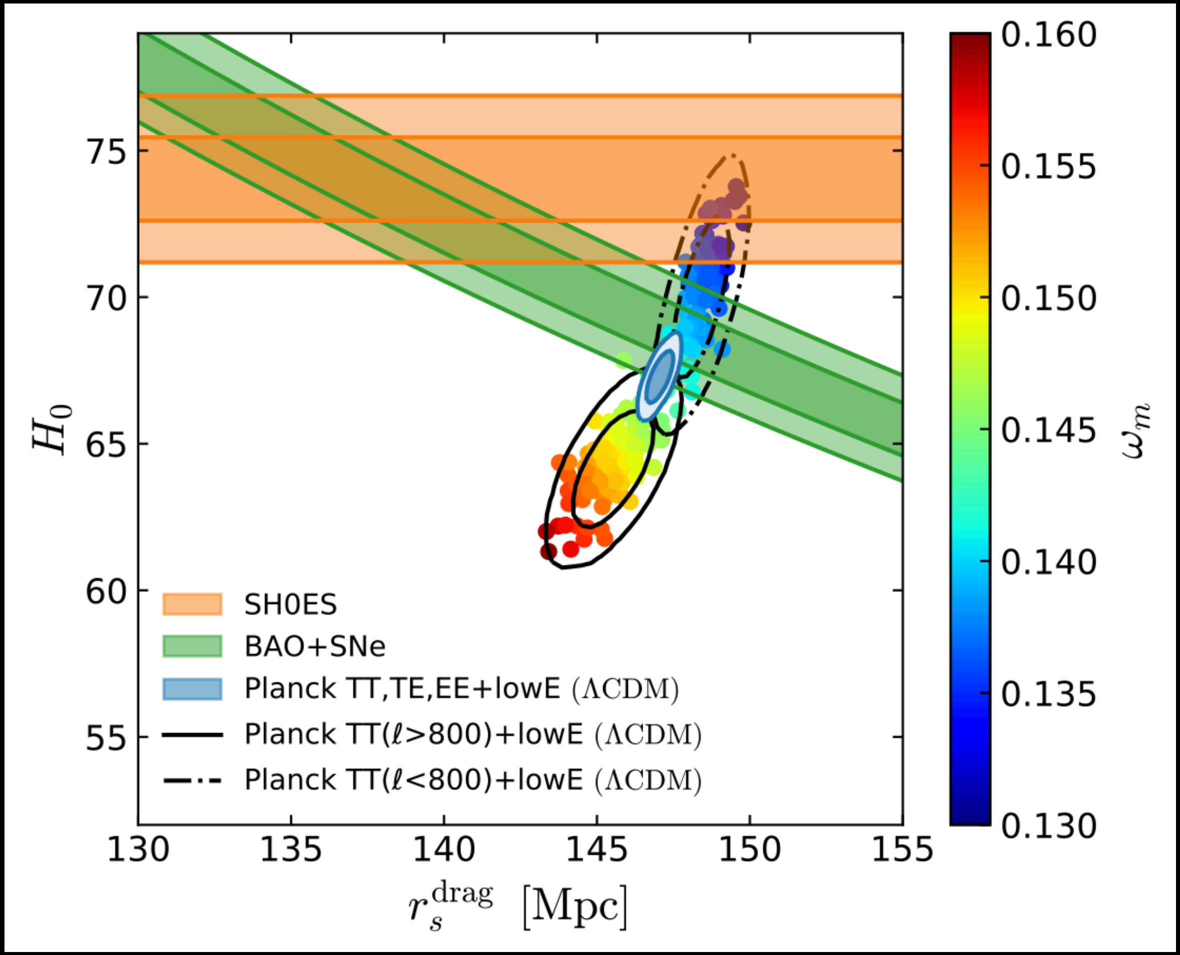
However, if BAO data are included, the wCDM model with w<-1 worsens considerably the fit of the BAO data because the best fit from Planck alone fails in recover the shape of H(z) at low redshifts. Therefore, when the CMB is combined with BAO data, the favoured model is again the LCDM one and the H0 tension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

Complication:
the sound horizon problem

What about BAO+Pantheon?

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

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

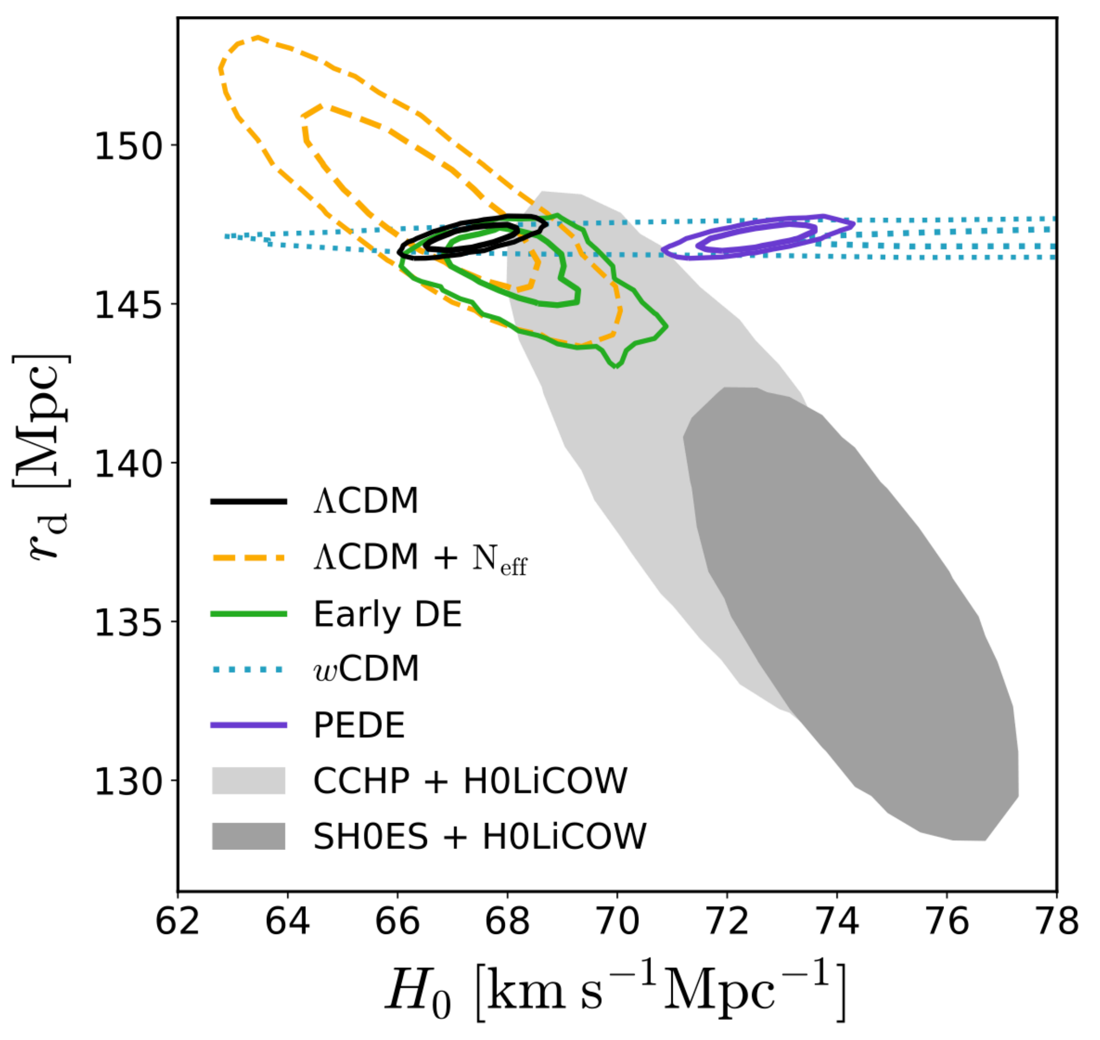


Knox and Millea, *Phys.Rev.D* 101 (2020) 4, 043533

Early vs late time solutions

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

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

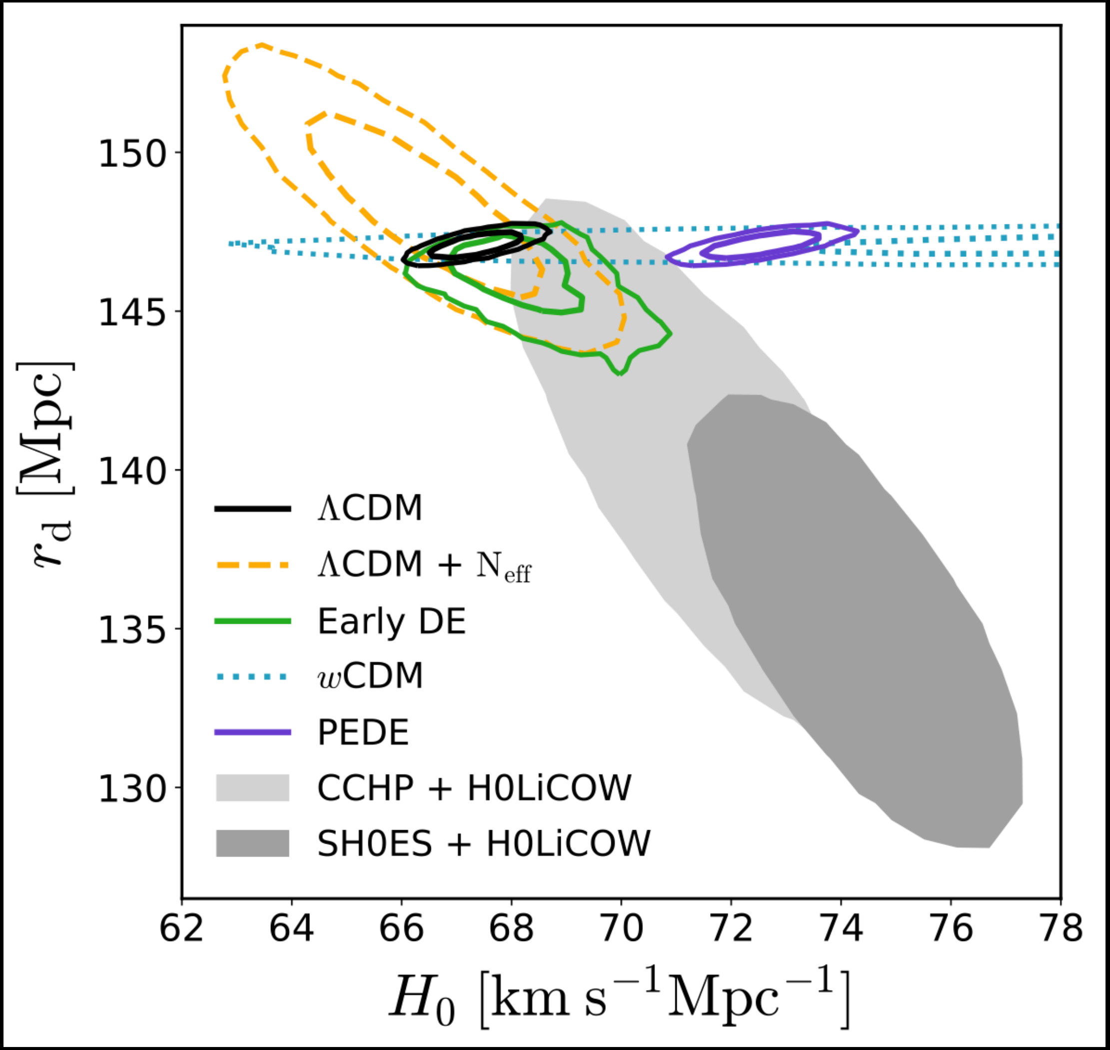


Arendse et al., Astron.Astrophys. 639 (2020) A57

Early vs late time solutions

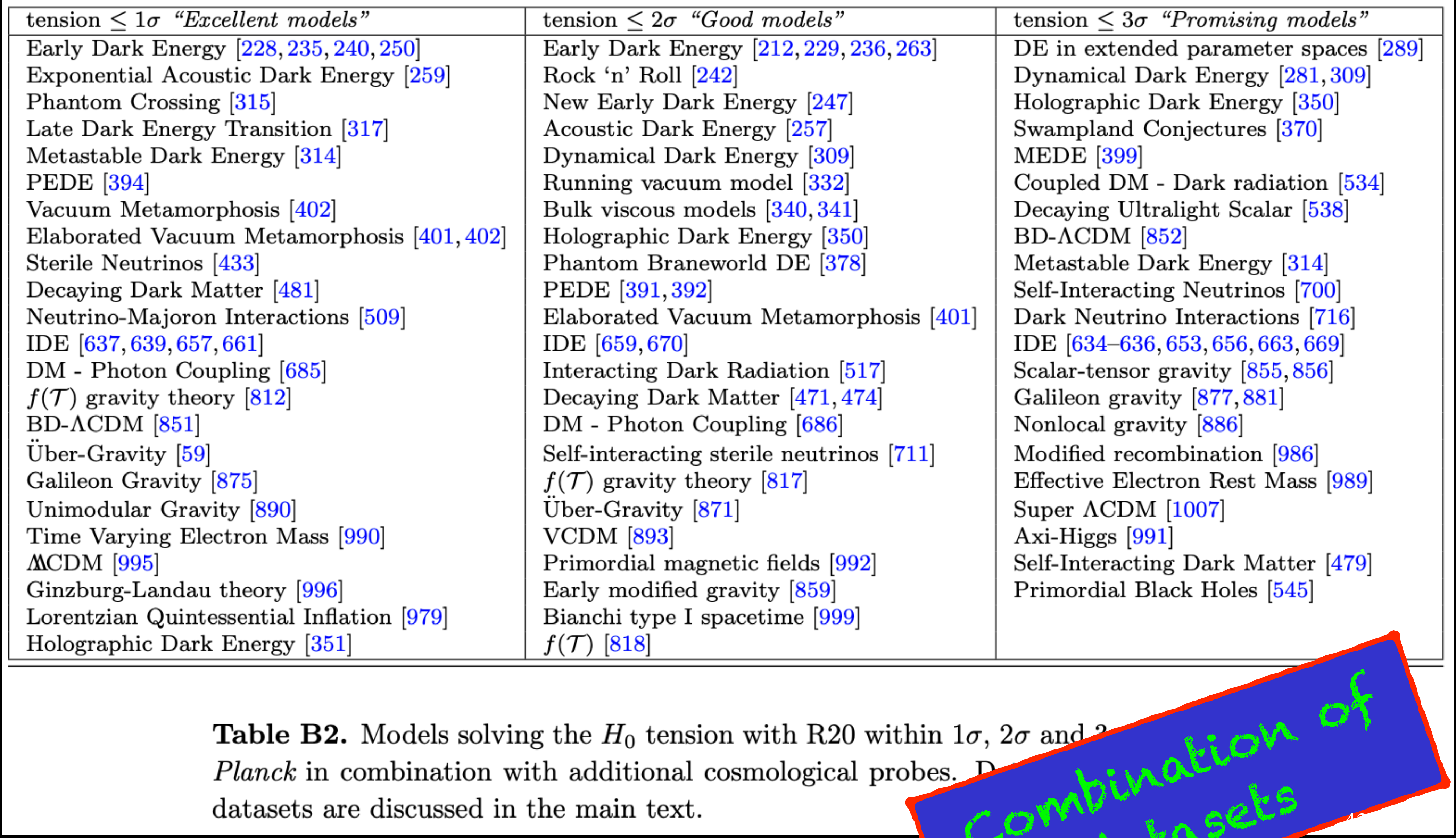
Here we can see the comparison of the 2σ credibility regions of the CMB constraints and the measurements from late-time observations (SN + BAO + H0LiCOW + SH0ES).

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



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

Formally successful models in solving H0



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

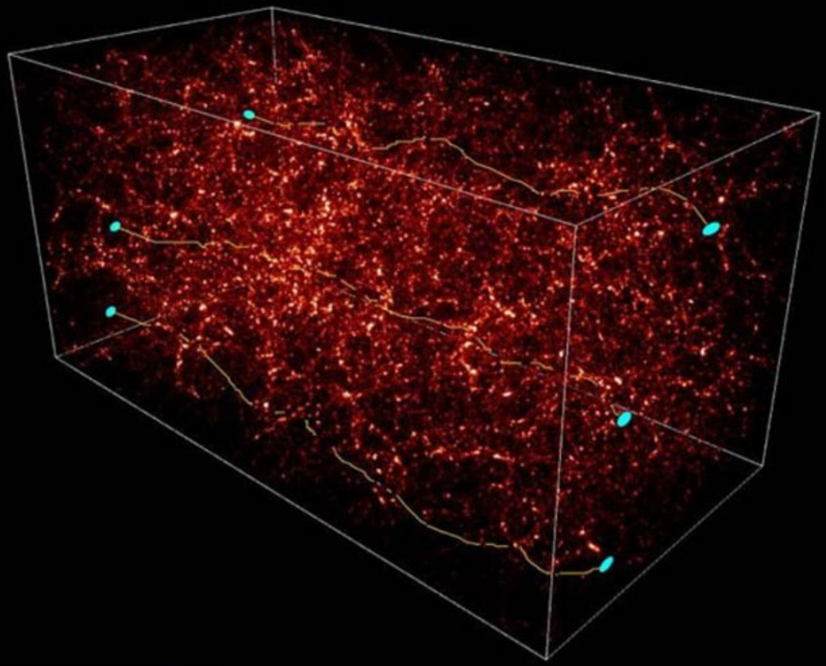
Table B2. Models solving the H_0 tension with R20 within 1σ, 2σ and
Planck in combination with additional cosmological probes. D
datasets are discussed in the main text.

Combination of datasets

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

Additional complication:
the early solutions proposed to alleviate the H0 tension increase the S8 tension!

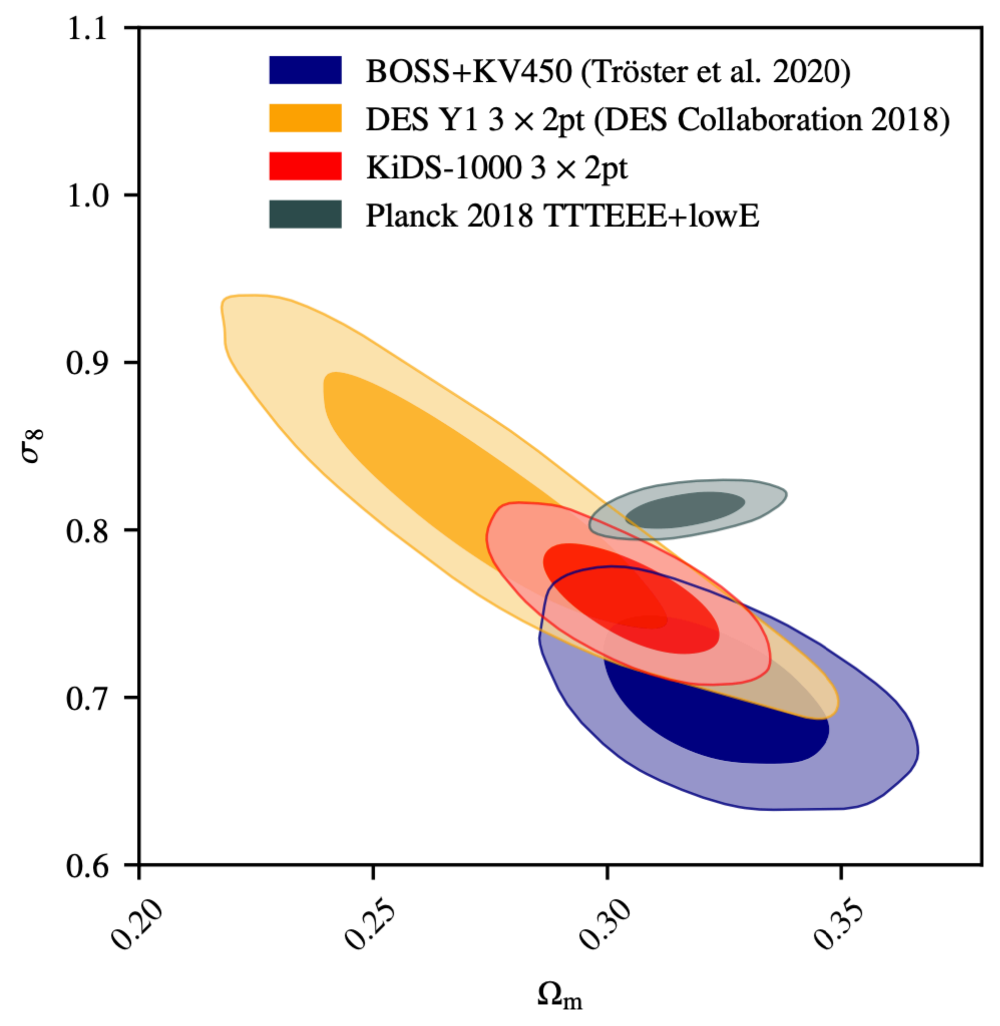
The S8 tension



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

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

The S8 tension



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

The S8 tension is present at 3.4σ between Planck assuming ΛCDM 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]

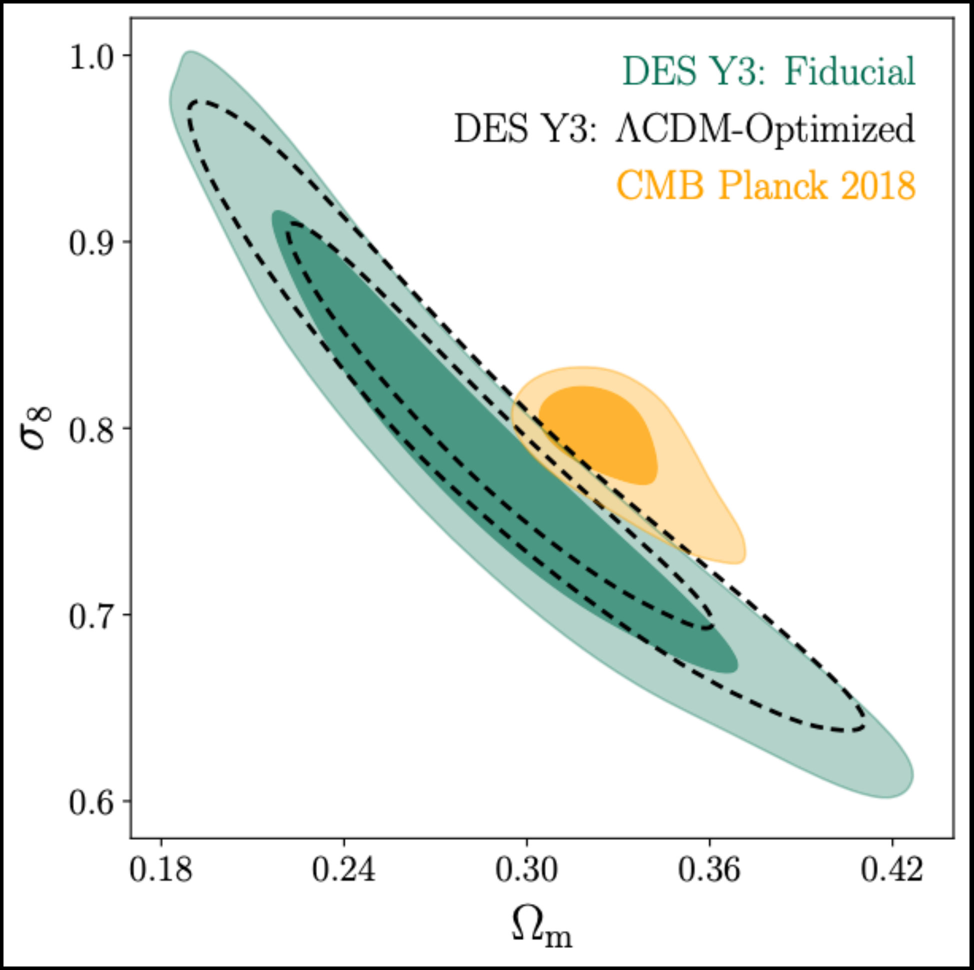
$S_8 = 0.728 \pm 0.045$

Troster 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]

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 ΛCDM and DES-Y3.

$S_8 = 0.834 \pm 0.016$

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

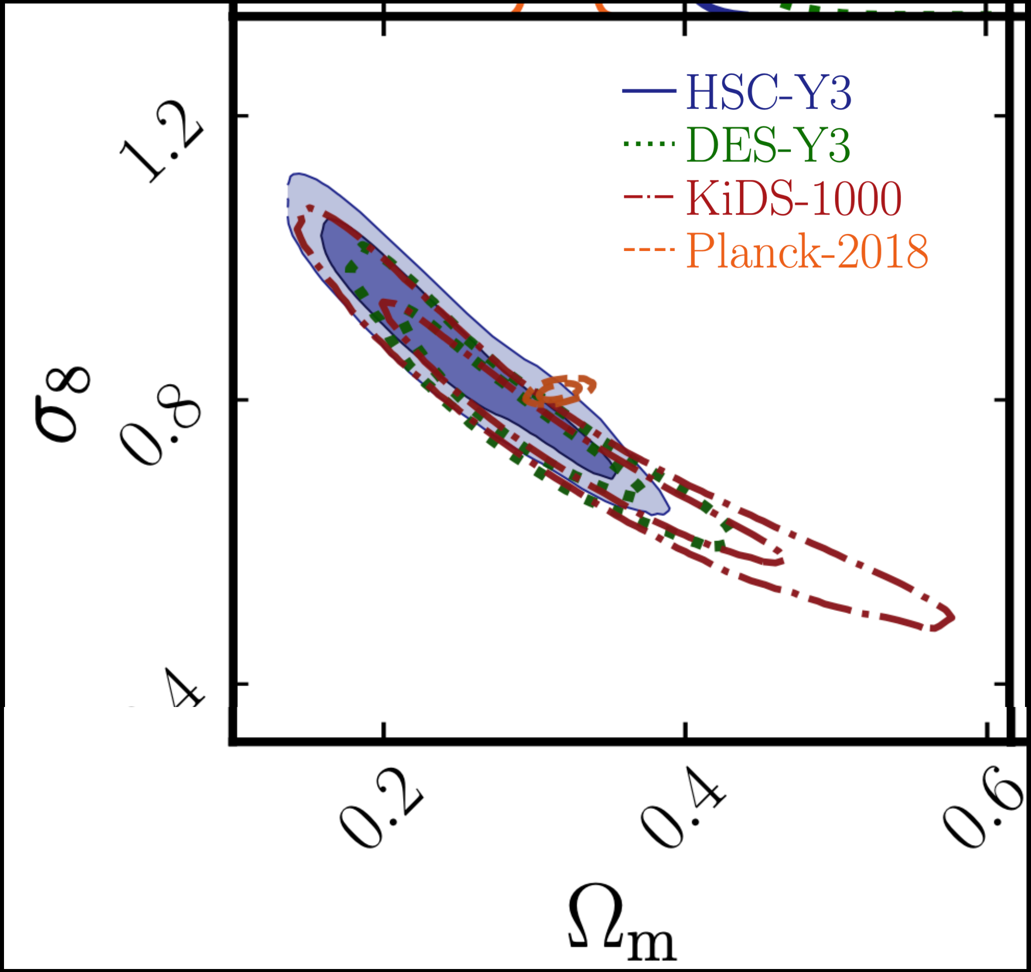
$S_8 = 0.776^{+0.017}_{-0.017}$

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 ΛCDM and HSC-Y3.

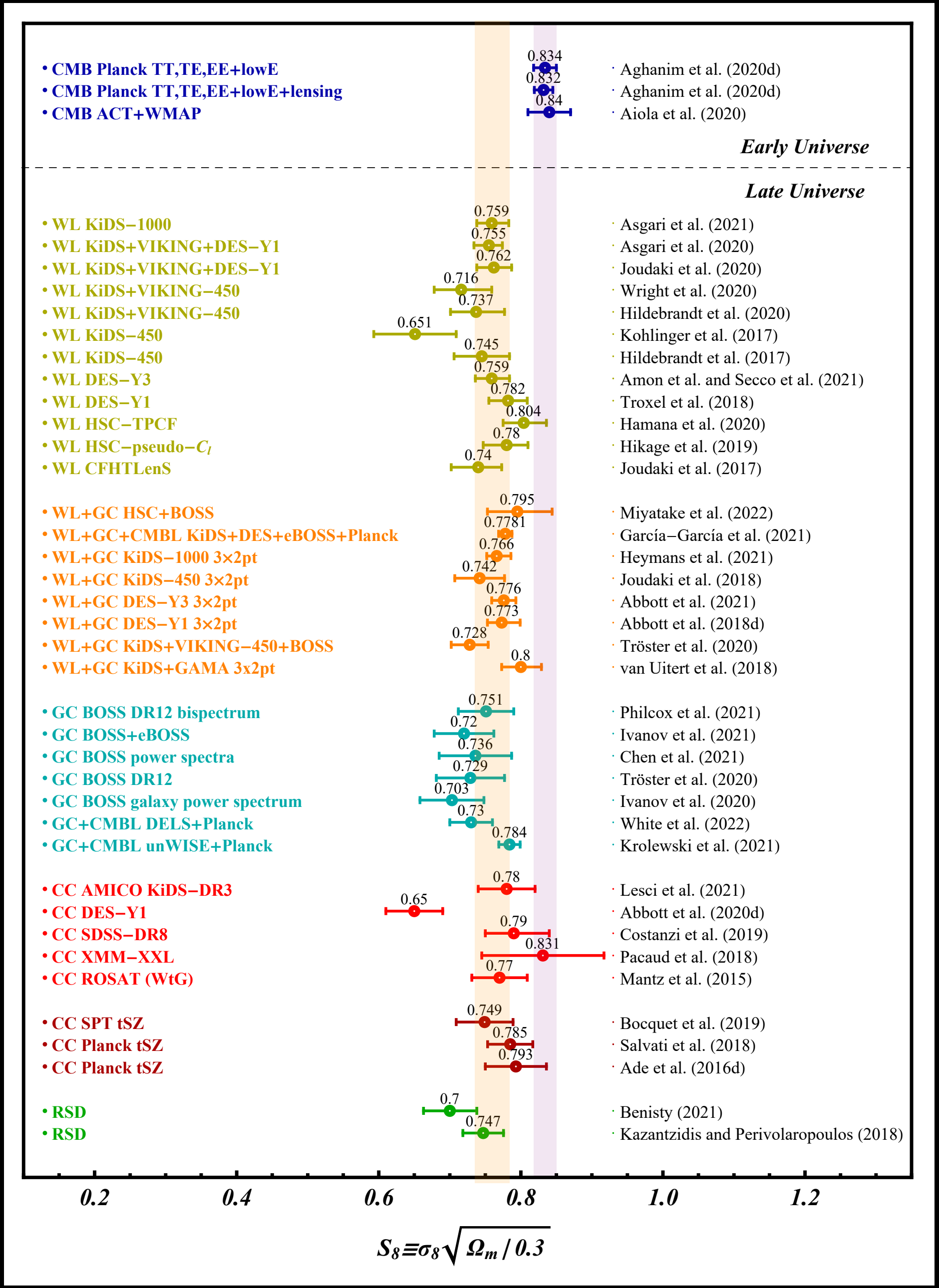
$S_8 = 0.834 \pm 0.016$

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



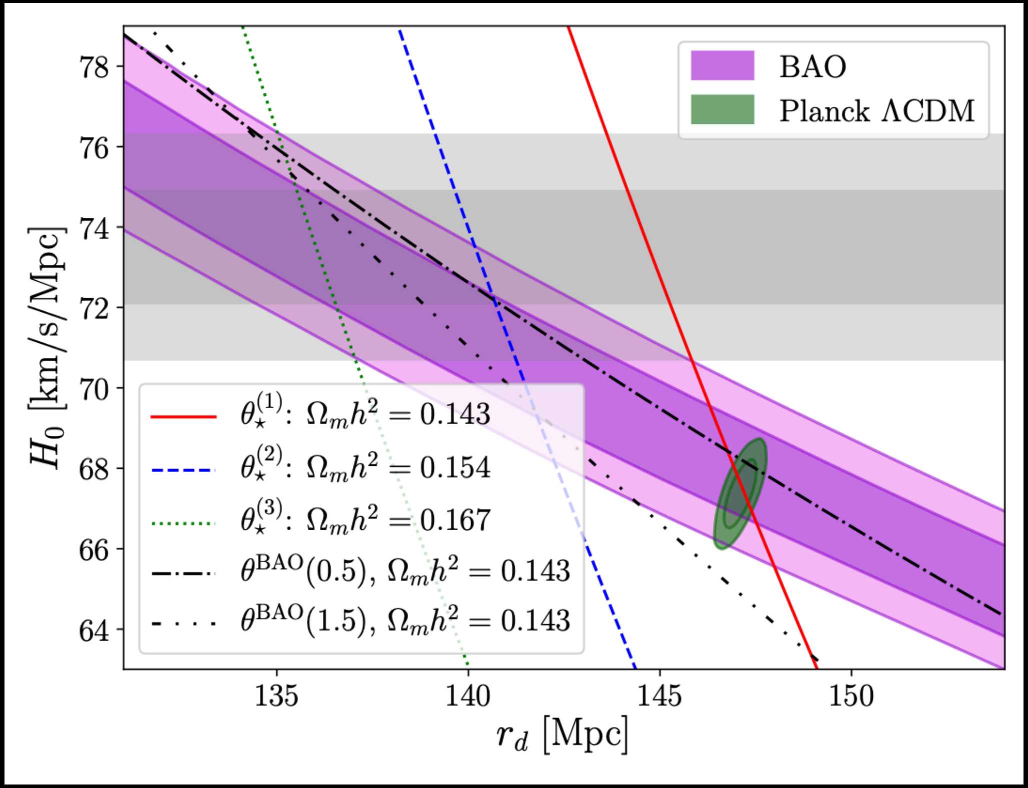
Abdalla et al., *JHEAp* 34 (2022) 49-211

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 rd would not completely resolve the tension, since it will affect the inferred value of Ωm 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 rd requires a higher value of $\Omega_m h^2$.



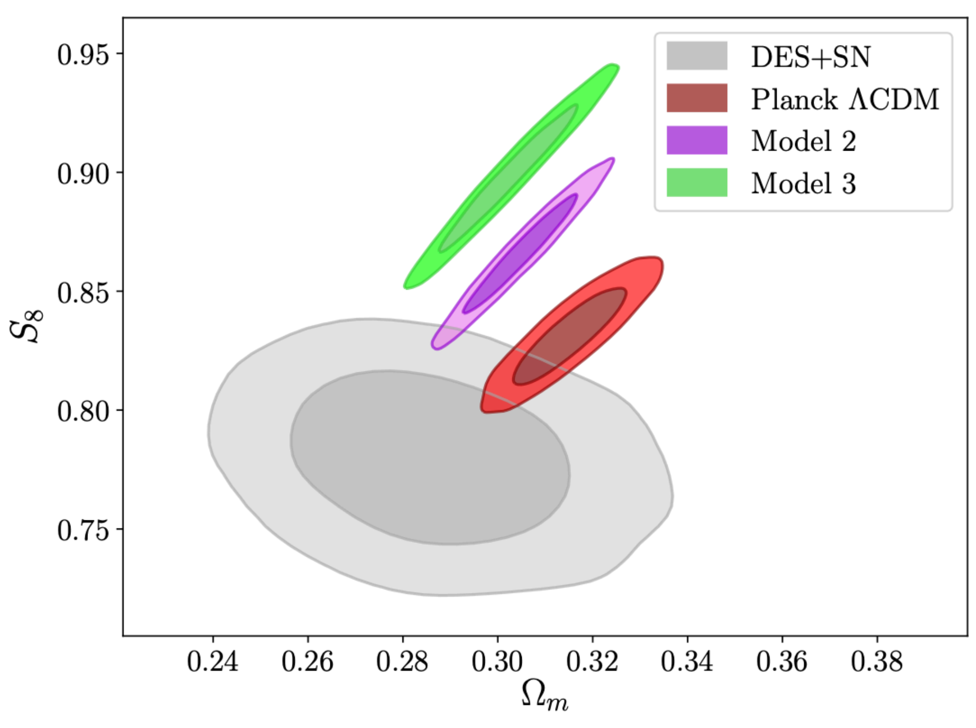
Jedamzik et al., Commun.in Phys. 4 (2021) 123

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 H0–rd, but it should be extended to the parameters triplet H0–rd–Ωm.

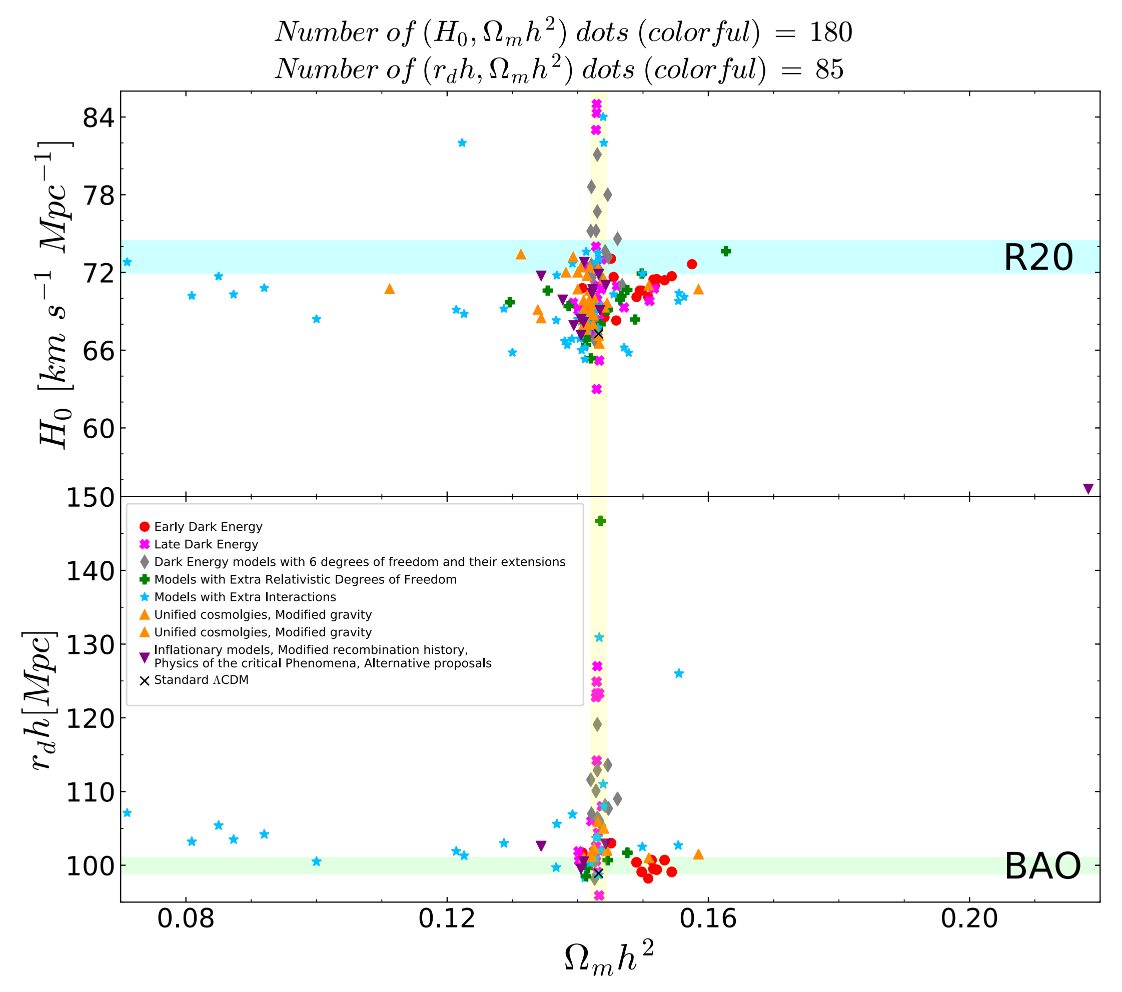
The figure shows that when attempting to find a full resolution of the Hubble tension, with CMB, BAO and SH0ES in agreement with each other, one exacerbates the tension with DES, KiDS and HSC.



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?

IDE can solve the H0 tension

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

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

and we assume the phenomenological form for the interaction rate:

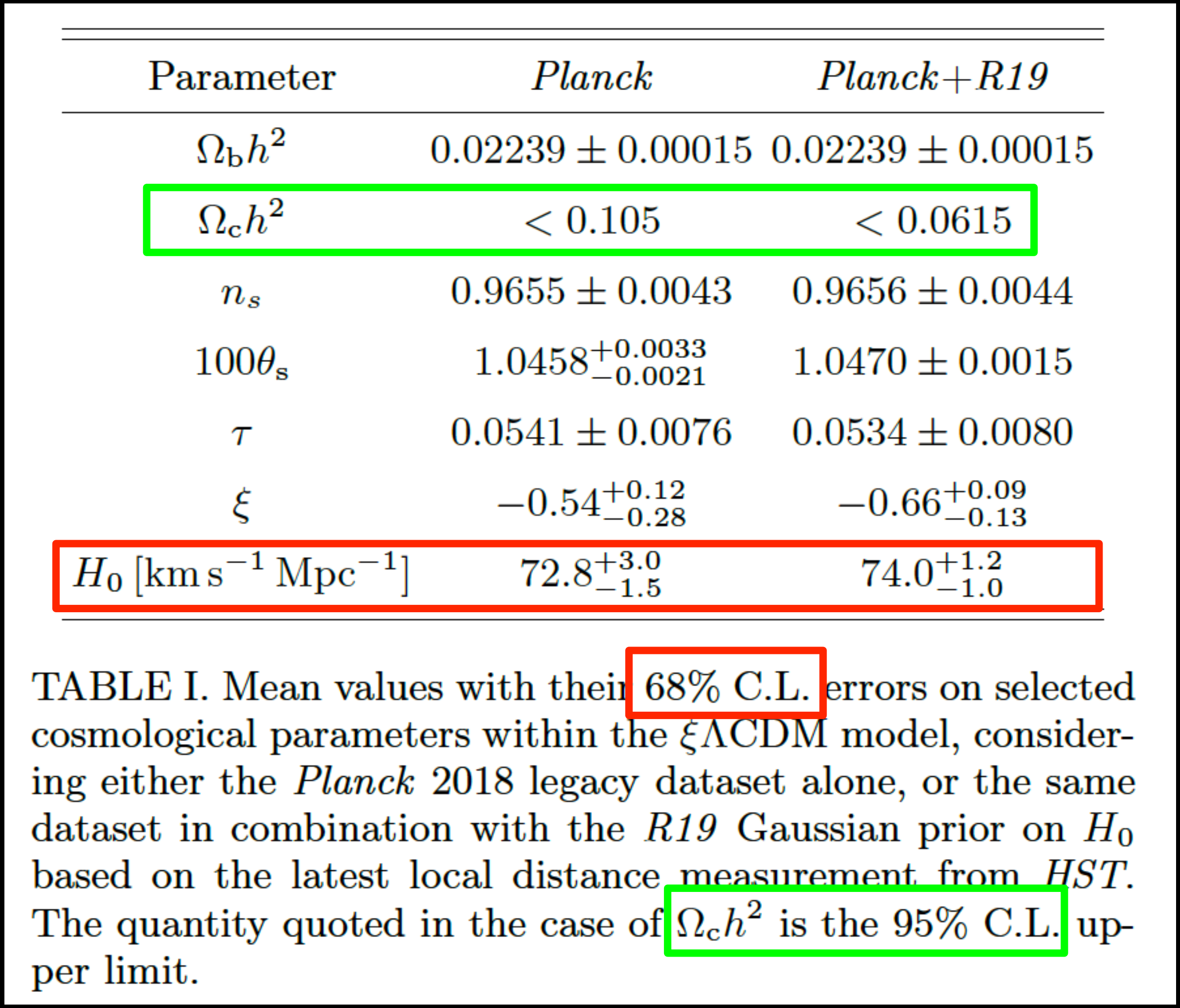
$$Q = \xi \mathcal{H} \rho_x$$

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

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

IDE can solve the H0 tension

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



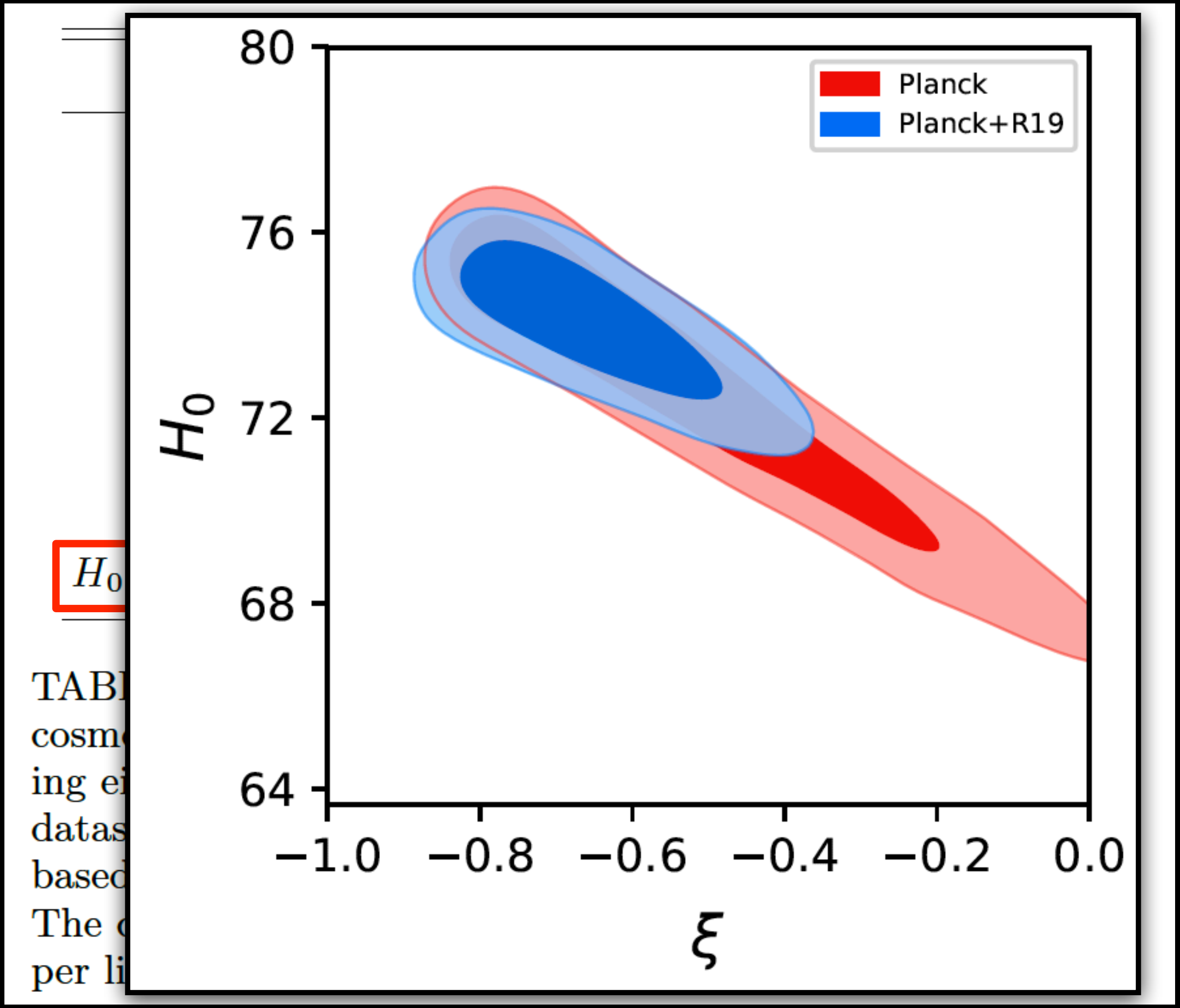
Parameter	*Planck*	*Planck+R19*
$\Omega_b h^2$	0.02239 ± 0.00015	0.02239 ± 0.00015
$\Omega_c h^2$	< 0.105	< 0.0615
n_s	0.9655 ± 0.0043	0.9656 ± 0.0044
$100\theta_s$	$1.0458^{+0.0033}_{-0.0021}$	1.0470 ± 0.0015
τ	0.0541 ± 0.0076	0.0534 ± 0.0080
ξ	$-0.54^{+0.12}_{-0.28}$	$-0.66^{+0.09}_{-0.13}$
$H_0\,[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$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

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

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

IDE can solve the H0 tension

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.



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

IDE can solve the S8 tension

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.

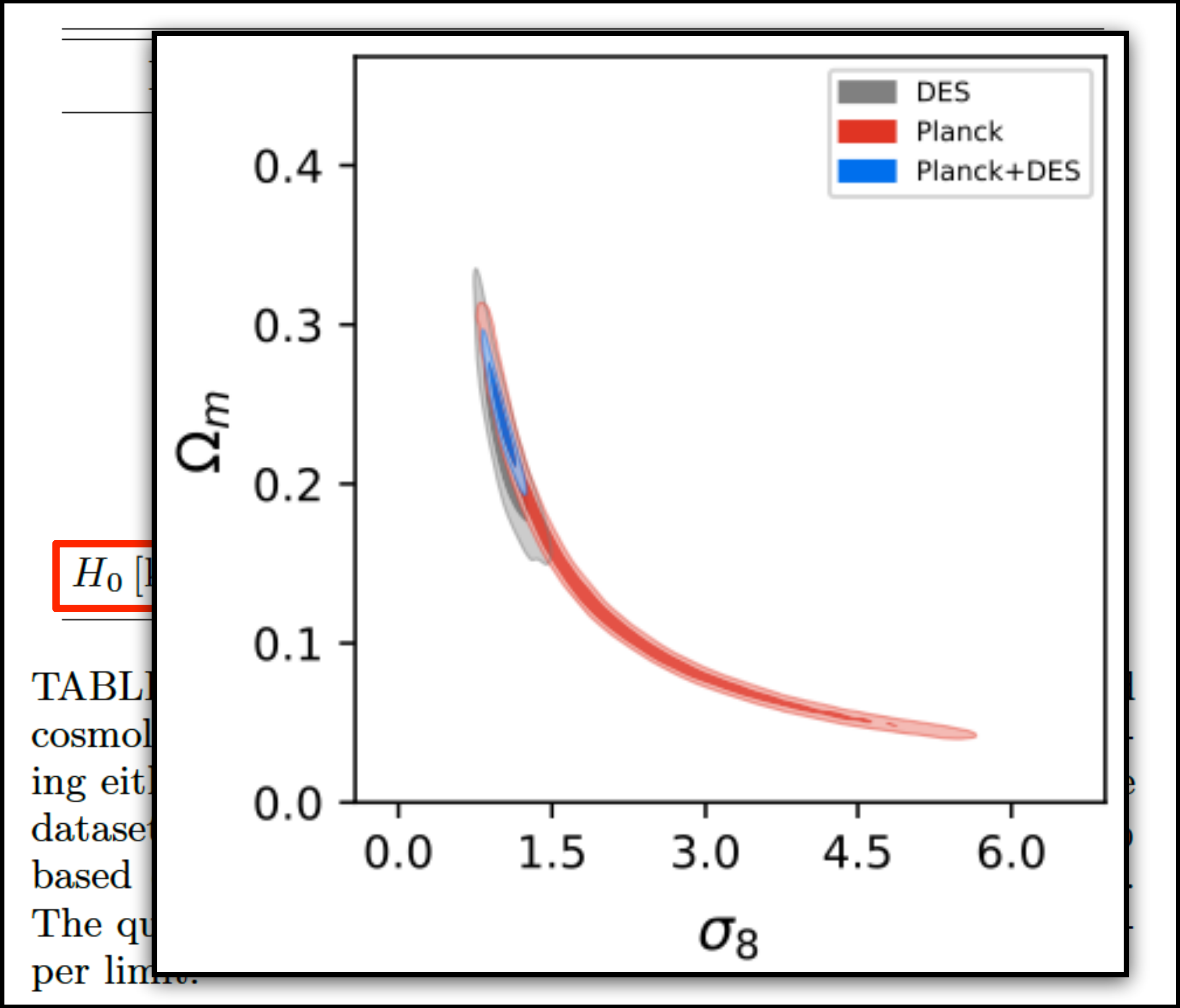
The reason is that once a coupling is switched on and

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)



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

Bayes factor

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

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

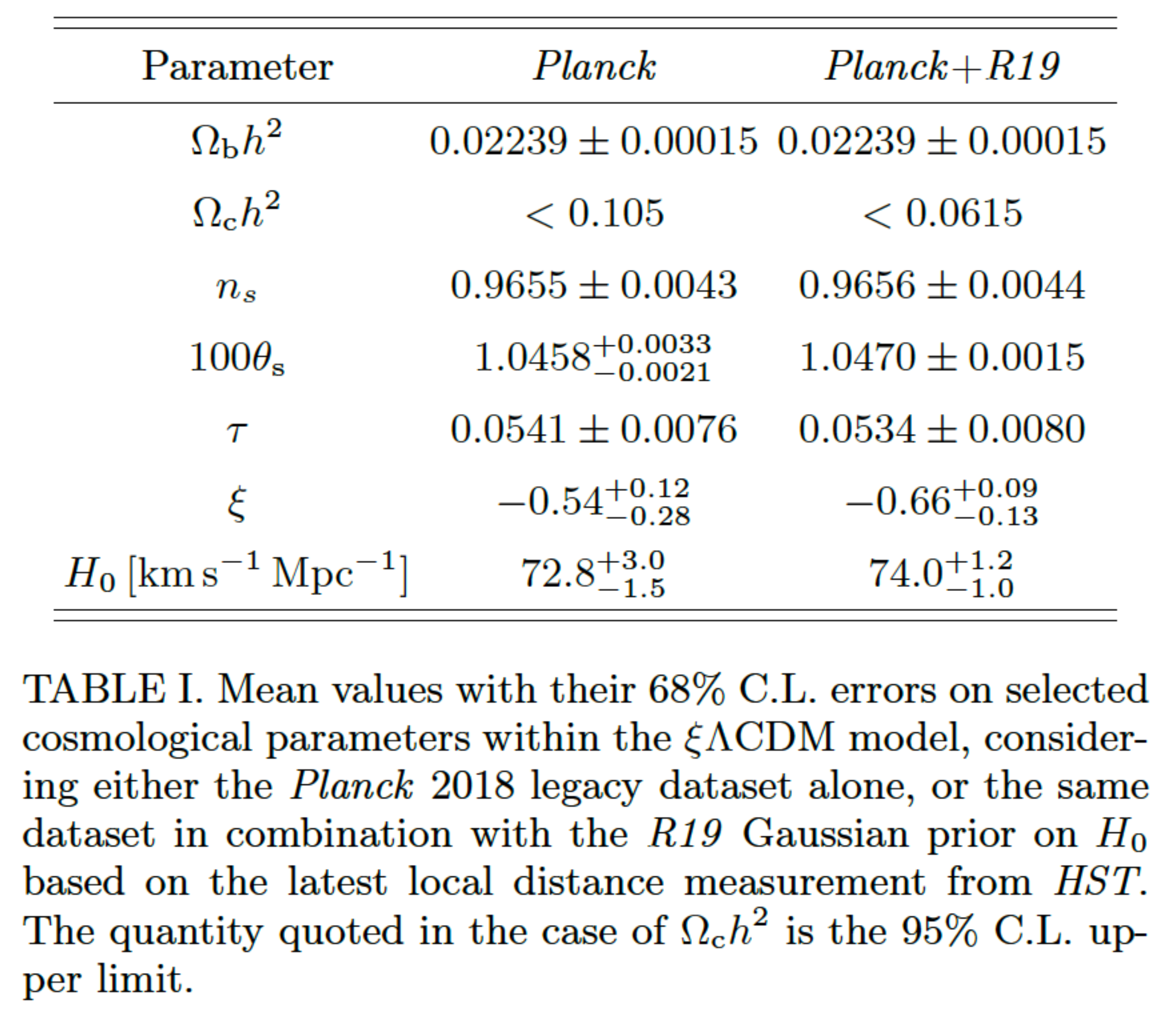
Given two competing models M_0 and M_1 it is useful to consider the ratio of the likelihood probability (the Bayes factor):

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

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

IDE can solve the H0 tension

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



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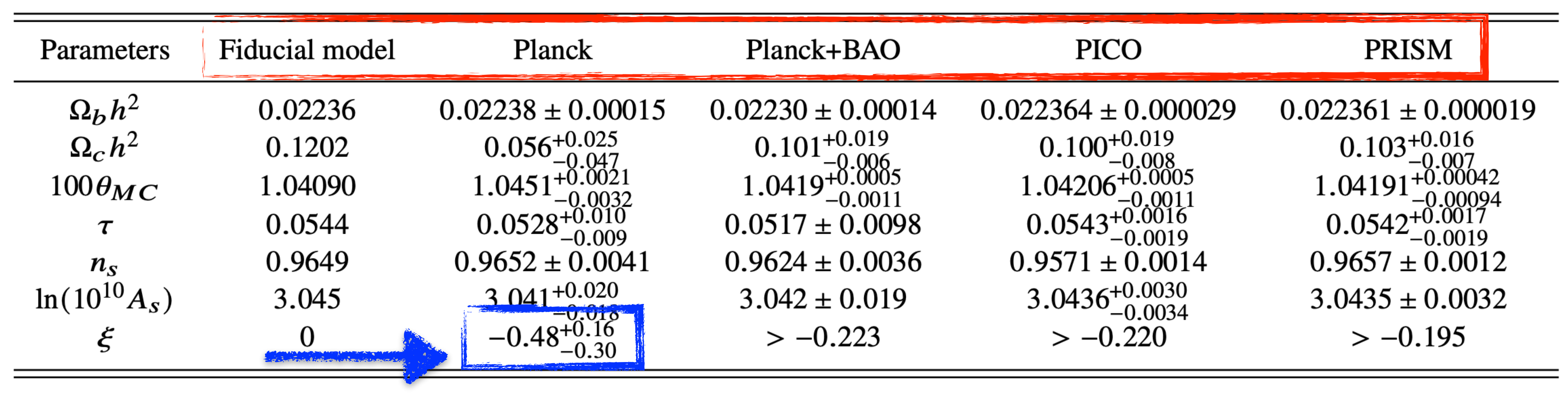
$100\theta_s$	$1.0458^{+0.0033}_{-0.0021}$	1.0470 ± 0.0015
τ	0.0541 ± 0.0076	0.0534 ± 0.0080
ξ	$-0.54^{+0.12}_{-0.28}$	$-0.66^{+0.09}_{-0.13}$
$H_0\,[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$	$72.8^{+3.0}_{-1.5}$	$74.0^{+1.2}_{-1.0}$

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

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

fake IDE detection

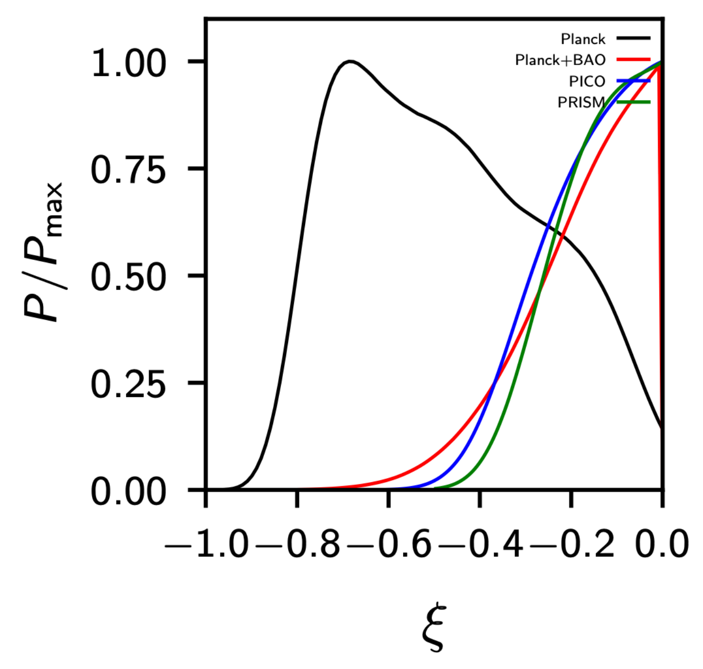


Parameters	Fiducial model	Planck	Planck+BAO	PICO	PRISM
$\Omega_b h^2$	0.02236	0.02238 ± 0.00015	0.02230 ± 0.00014	0.022364 ± 0.000029	0.022361 ± 0.000019
$\Omega_c h^2$	0.1202	$0.056^{+0.025}_{-0.047}$	$0.101^{+0.019}_{-0.006}$	$0.100^{+0.019}_{-0.008}$	$0.103^{+0.016}_{-0.007}$
$100\theta_{MC}$	1.04090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

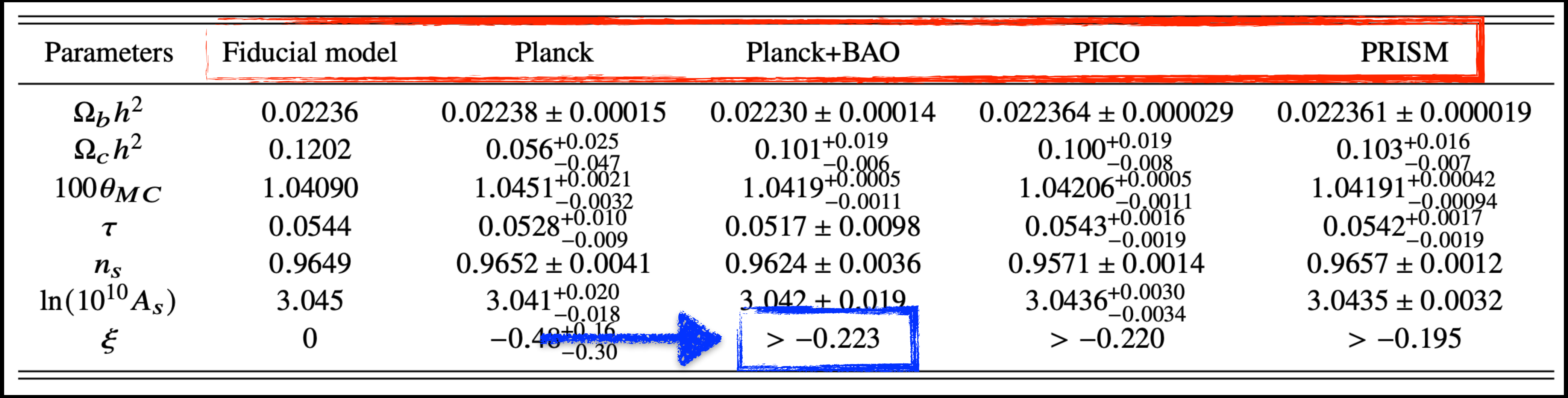
For a mock Planck-like experiment, due to the strong correlation present between the standard and the exotic physics parameters, there is a dangerous detection at more than 3σ for a coupling between dark matter and dark energy different from zero, even if the fiducial model has ξ =0:

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



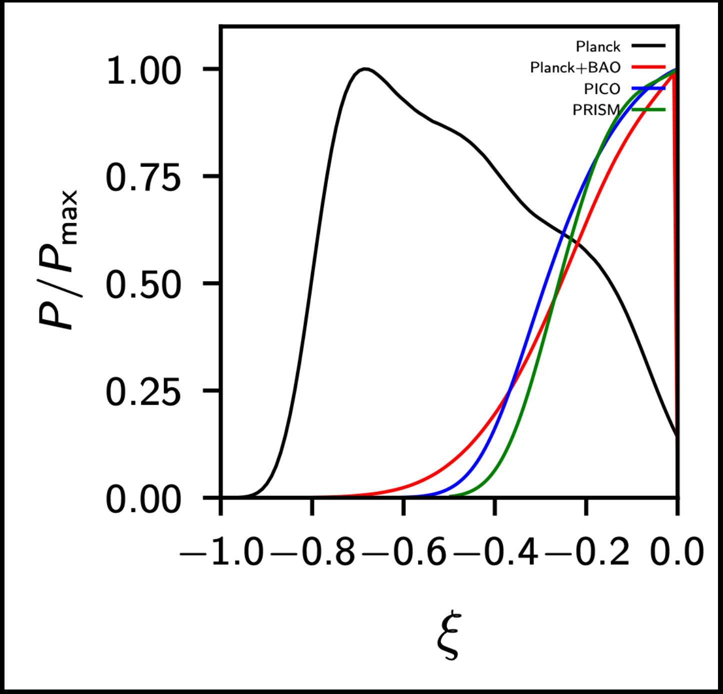
Mock experiments

fake IDE detection



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

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

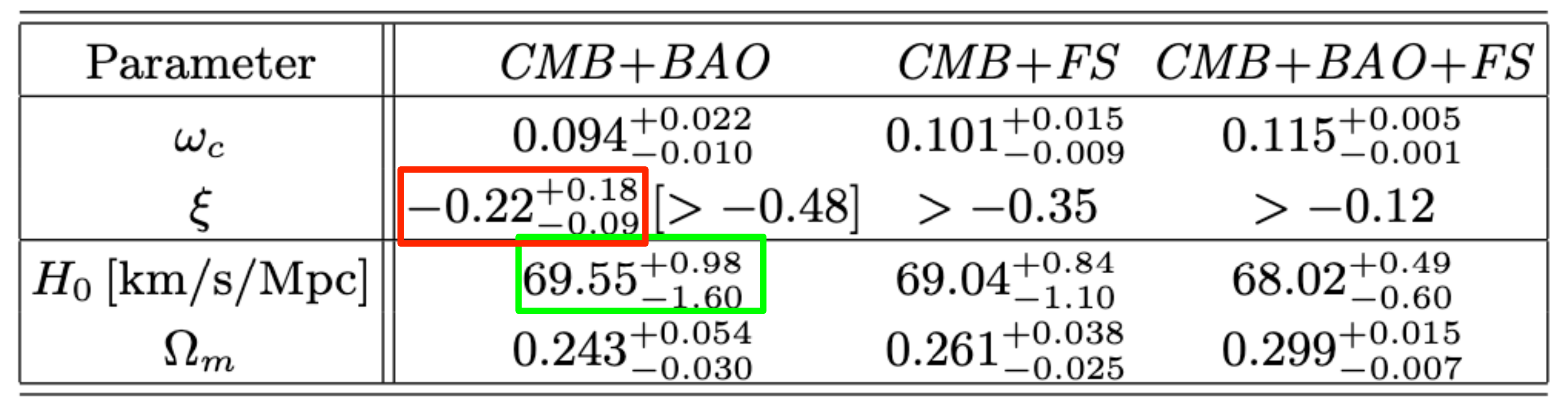


The inclusion of mock BAO data,
a mock dataset built using the same fiducial
cosmological model than that of the CMB,
helps in breaking the degeneracy,
providing a lower limit for the coupling ξ
in perfect agreement with zero.

Mock experiments

IDE can solve the H0 tension

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

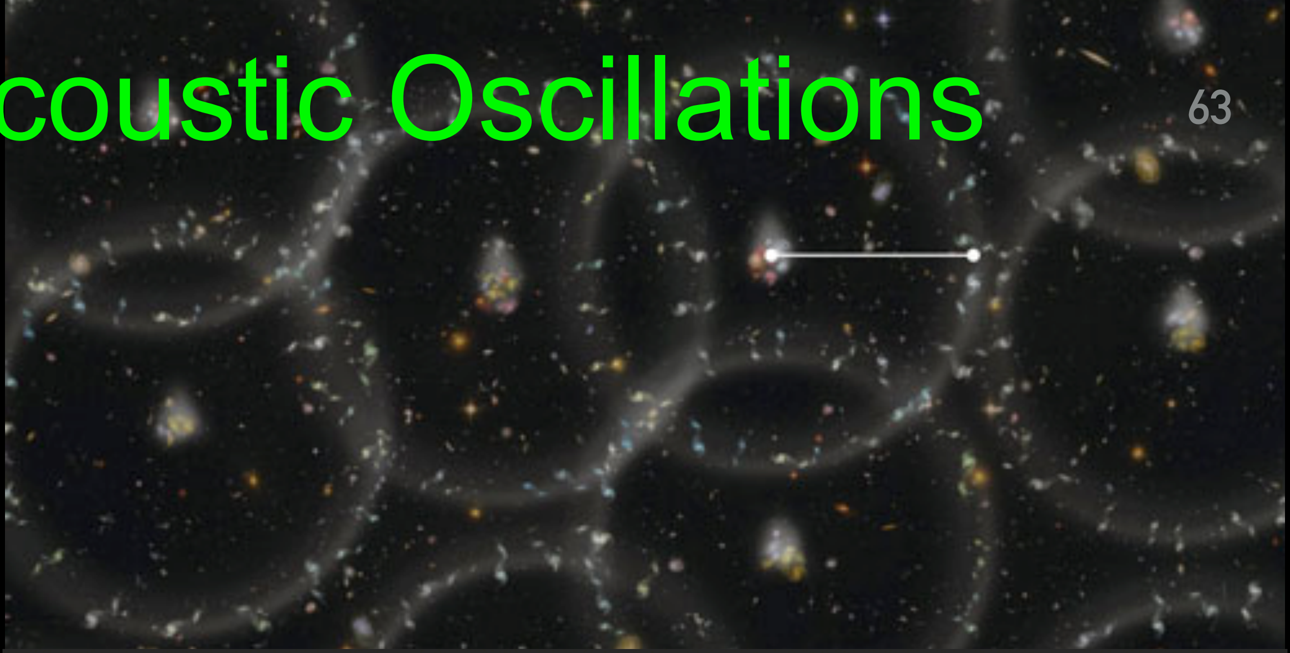
Nunes, Vagnozzi, Kumar, Di Valentino, and Mena, *Phys.Rev.D* 105 (2022) 12, 123506

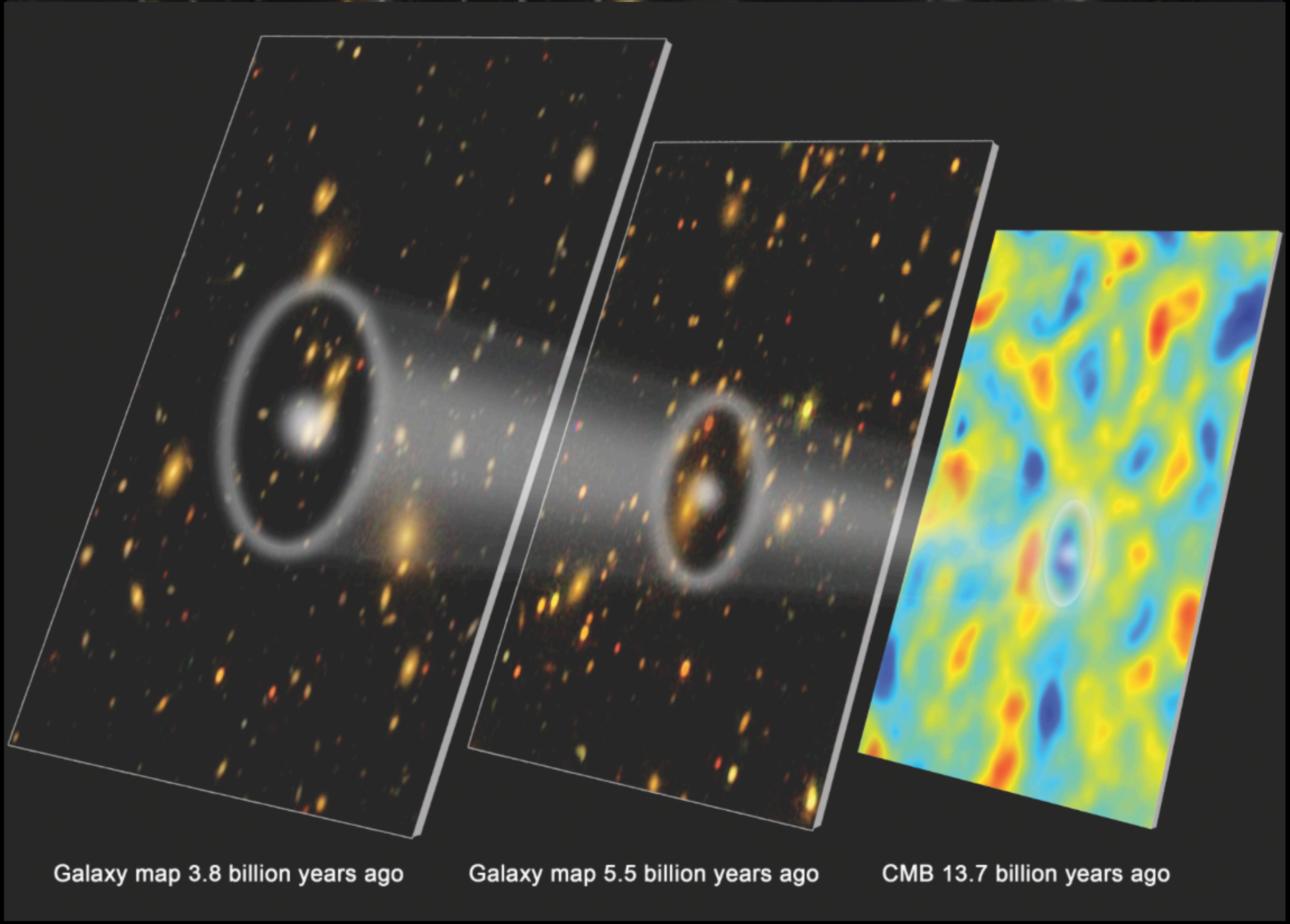
The addition of low-redshift measurements, as BAO data, still hints to the presence of a coupling, albeit at a lower statistical significance. Also for this data sets the Hubble constant values is larger than that obtained in the case of a pure ΛCDM scenario, enough to bring the H0 tension at 2.1σ with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

Baryon Acoustic Oscillations

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.

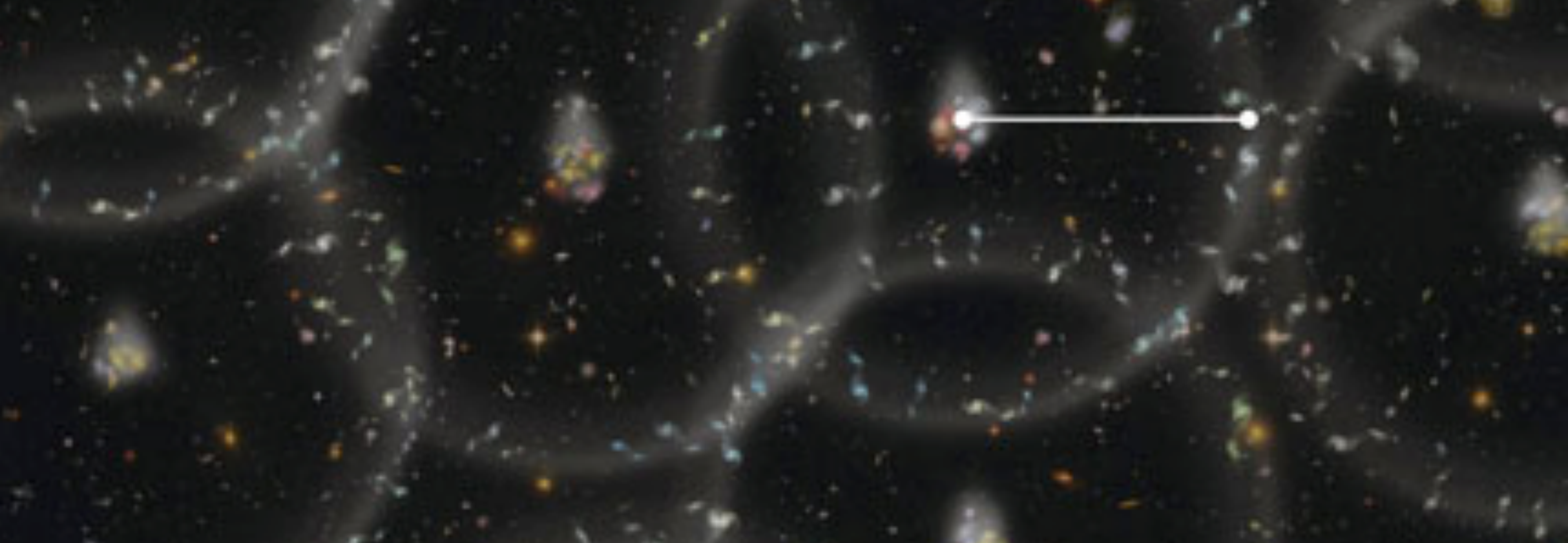
Since the data reduction process leading to these measurements involves making certain assumptions about the fiducial cosmology, this makes BAO measurements dependent on the cosmological model being used.





Baryon Acoustic Oscillations

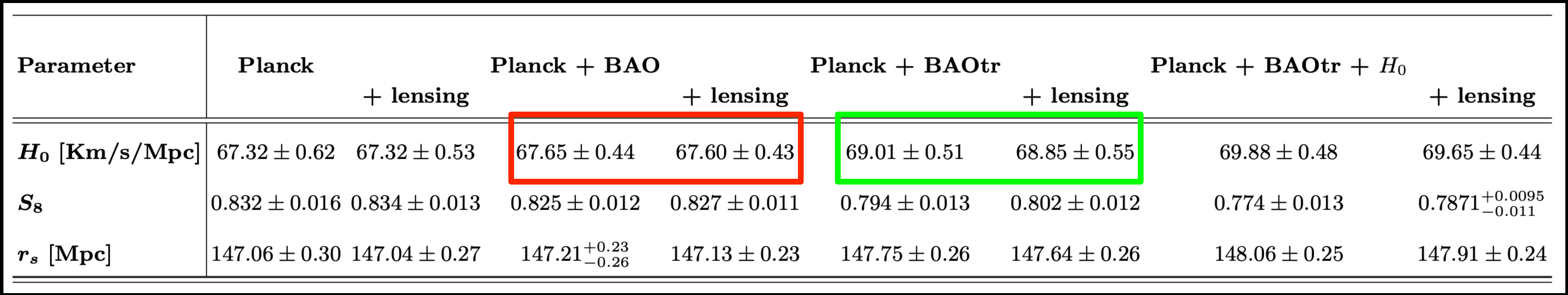
In other words, could the tension between Planck+BAO and SH0ES be due to a statistical fluctuation in this case?



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 (Nunes et al. arXiv:2002.09293) that are less model dependent because they are obtained working on spherical shells with redshift thickness Δz and only considering their angular distribution.

IDE can solve the H0 tension

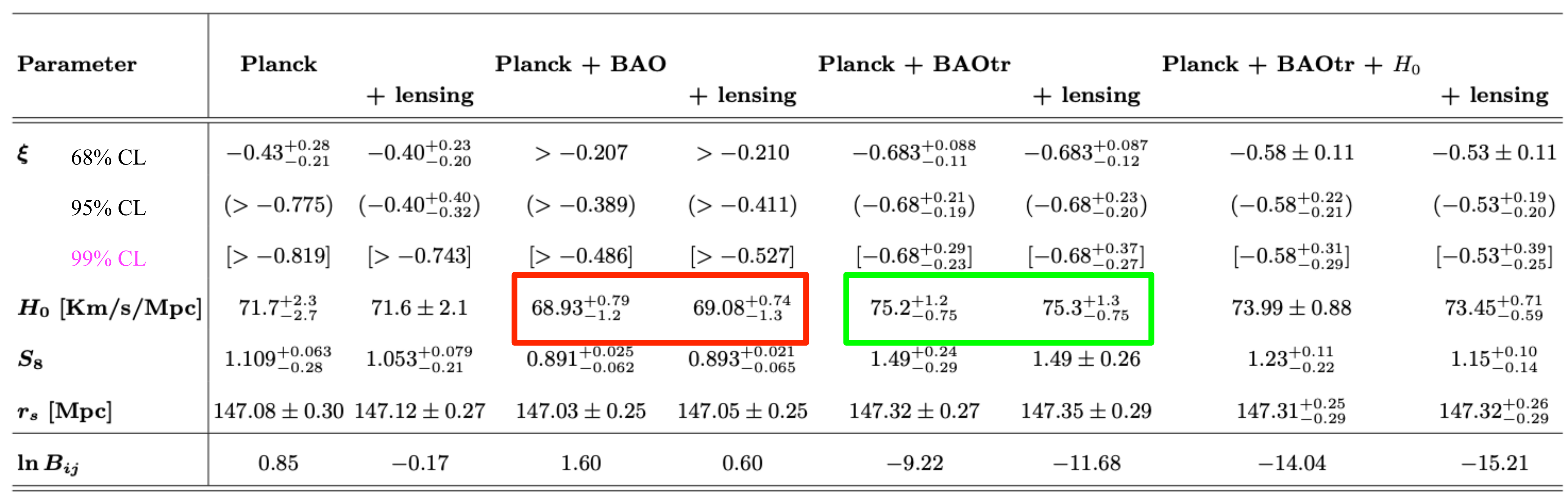


Parameter	**Planck**		**Planck + BAO**		**Planck + BAOtr**		**Planck + BAOtr + H_0**	
		+ lensing		**+ lensing**		**+ lensing**		**+ lensing**
H_0 **[Km/s/Mpc]**	67.32 ± 0.62	67.32 ± 0.53	67.65 ± 0.44	67.60 ± 0.43	69.01 ± 0.51	68.85 ± 0.55	69.88 ± 0.48	69.65 ± 0.44
S_8	0.832 ± 0.016	0.834 ± 0.013	0.825 ± 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 ΛCDM,
and the 2D BAO measurements, less model dependent,
shows almost the same results for the ΛCDM scenario.

Bernui, Di Valentino, Giarè, Kumar, and Nunes, *Phys.Rev.D* 107 (2023) 10, 103531

IDE can solve the H0 tension



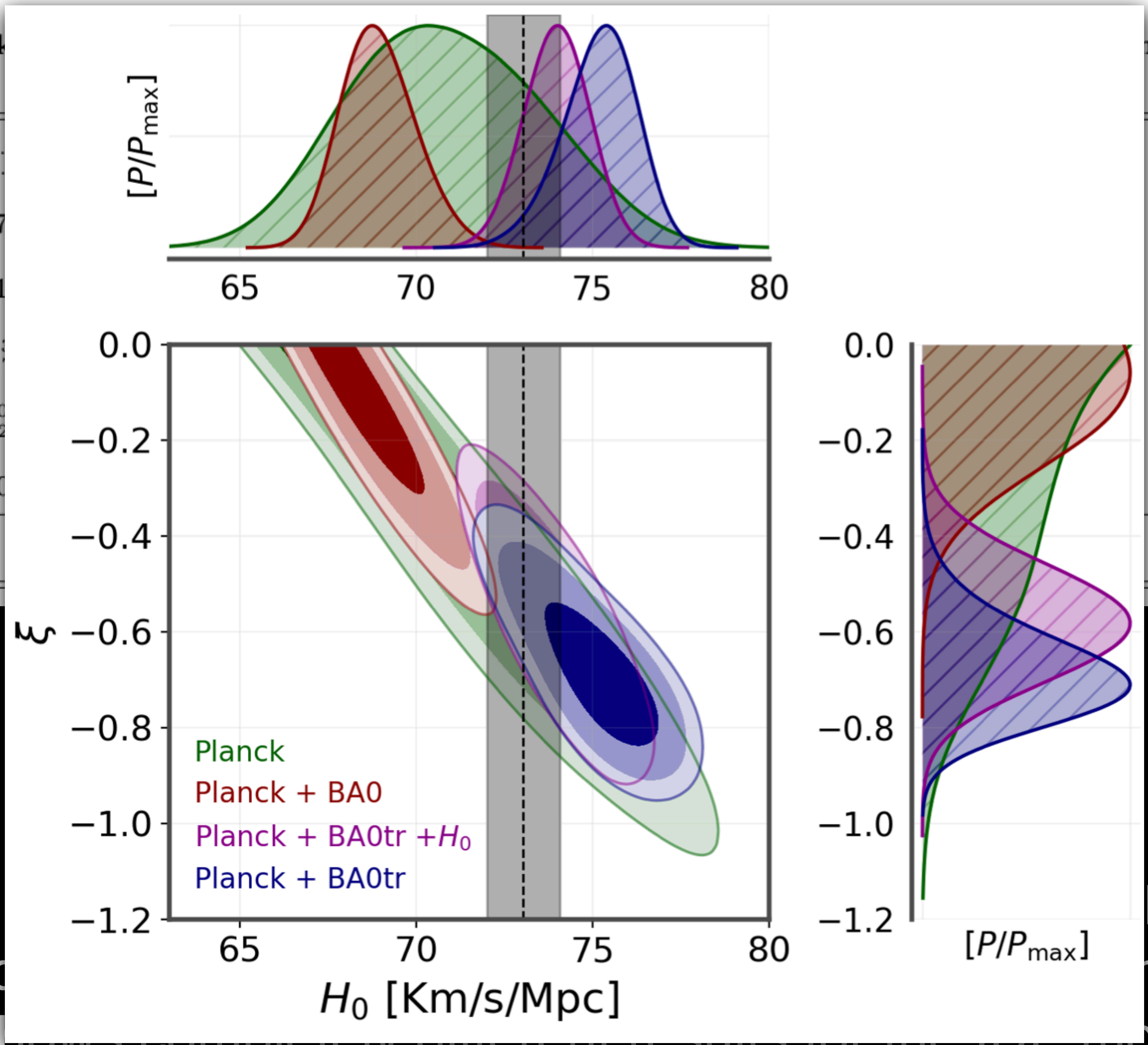
Parameter	**Planck**		**Planck + BAO**		**Planck + BAOtr**		**Planck + BAOtr + H_0**	
		+ lensing		**+ lensing**		**+ lensing**		**+ lensing**
ξ 68% CL	$-0.43^{+0.28}_{-0.21}$	$-0.40^{+0.23}_{-0.20}$	> -0.207	> -0.210	$-0.683^{+0.088}_{-0.11}$	$-0.683^{+0.087}_{-0.12}$	-0.58 ± 0.11	-0.53 ± 0.11
95% CL	(> -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 ΛCDM,
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 H0 tension with SH0ES.

Bernui, Di Valentino, Giarè, Kumar, and Nunes, *Phys.Rev.D* 107 (2023) 10, 103531

IDE can solve the H0 tension

Parameter		Planc	ck + BAOtr + H_0	+ lensing
ξ	68% CL	$-0.43^{+0.}_{-0.}$	-0.58 ± 0.11	-0.53 ± 0.11
	95% CL	$(> -0.77$	$(-0.58^{+0.22}_{-0.21})$	$(-0.53^{+0.19}_{-0.20})$
	99% CL	$[> -0.81$	$[-0.58^{+0.31}_{-0.29}]$	$[-0.53^{+0.39}_{-0.25}]$
H_0 [Km/s/Mpc]		$71.7^{+2.}_{-2.}$	73.99 ± 0.88	$73.45^{+0.71}_{-0.59}$
S_8		$1.109^{+0.0}_{-0.2}$	$1.23^{+0.11}_{-0.22}$	$1.15^{+0.10}_{-0.14}$
r_s [Mpc]		147.08 ± 0	$147.31^{+0.25}_{-0.29}$	$147.32^{+0.26}_{-0.29}$
$\ln B_{ij}$		0.85	-14.04	-15.21



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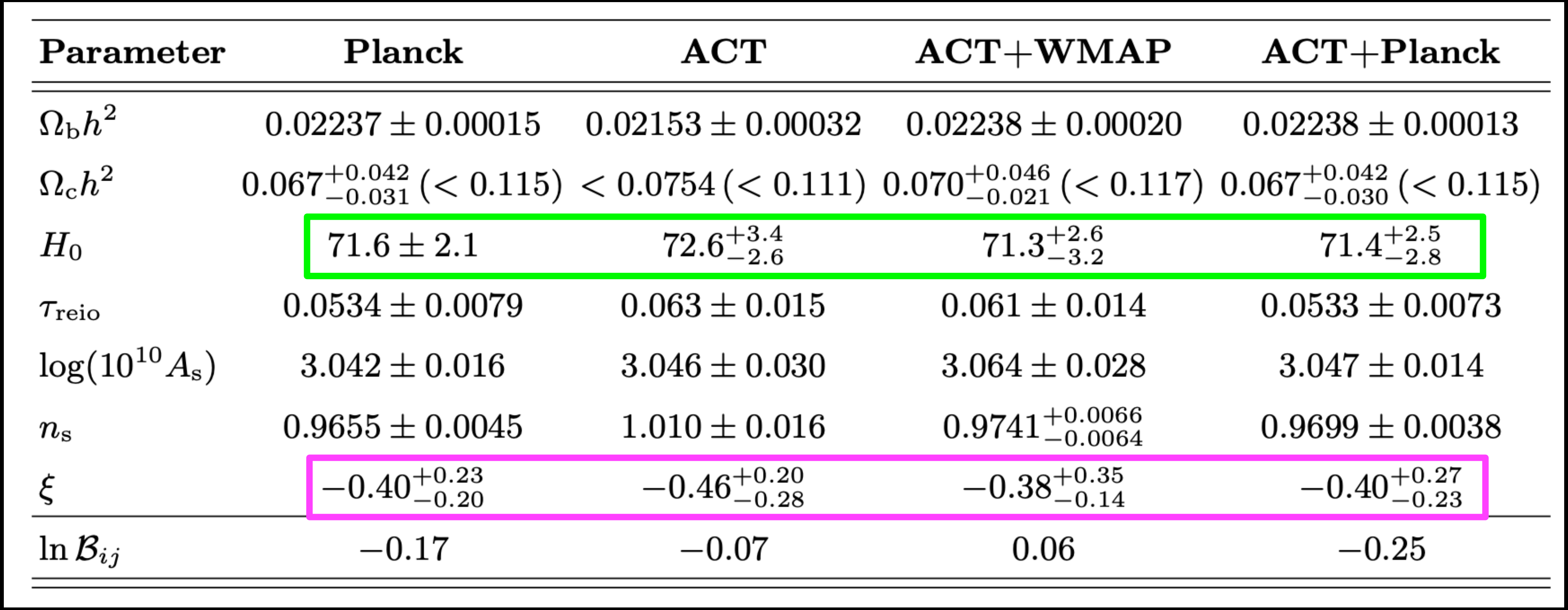
There is a strong evidence for the coupling at more than 99% CL, solving at the same time the H0 tension with SH0ES.

Bernui, Di Valentino, Giarè, Kumar, and Nunes, *Phys.Rev.D* 107 (2023) 10, 103531

IDE from ACT can solve the H0 tension



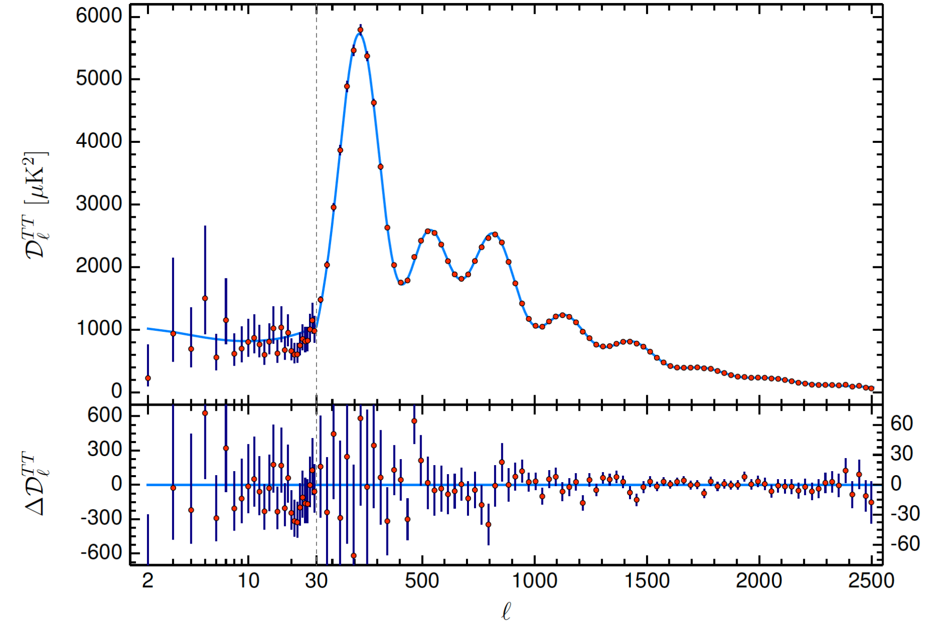
Parameter	**Planck**	**ACT**	**ACT+WMAP**	**ACT+Planck**
$\Omega_\mathrm{b}h^2$	0.02237 ± 0.00015	0.02153 ± 0.00032	0.02238 ± 0.00020	0.02238 ± 0.00013
$\Omega_\mathrm{c}h^2$	$0.067^{+0.042}_{-0.031}\,(< 0.115)$	$< 0.0754\,(< 0.111)$	$0.070^{+0.046}_{-0.021}\,(< 0.117)$	$0.067^{+0.042}_{-0.030}\,(< 0.115)$
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
$\log(10^{10}A_\mathrm{s})$	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.

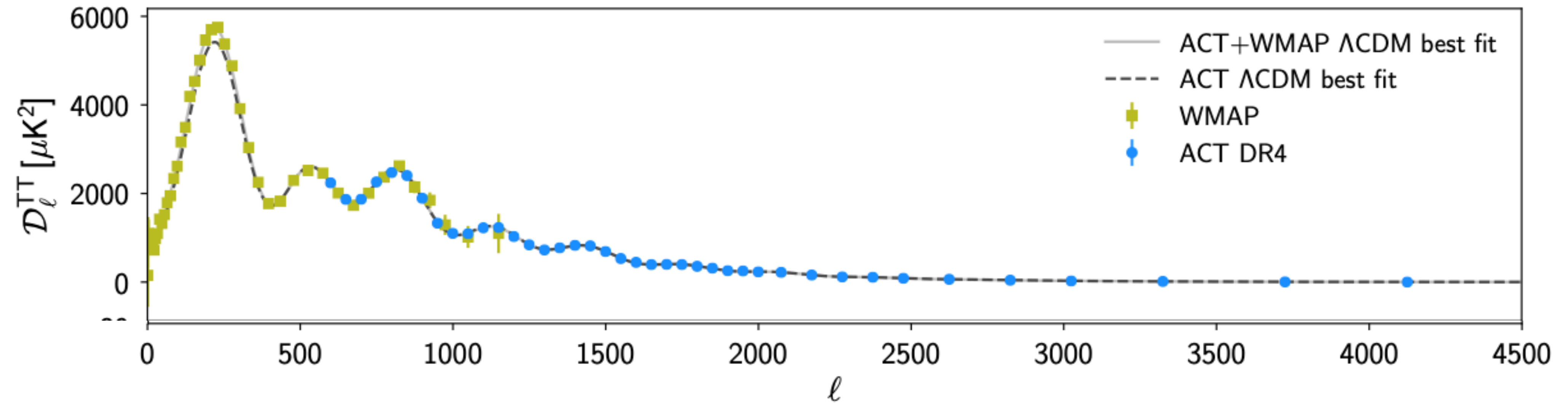
IDE from ACT can solve the H0 tension

Parameter	Planck	ACT	ACT+WMAP	ACT+Planck
$\Omega_\mathrm{b}h^2$	0.02237 ± 0.00015	0.02153 ± 0.00032	0.02238 ± 0.00020	0.02238 ± 0.00013
$\Omega_\mathrm{c}h^2$	$0.067^{+0.}_{-0.}$		.7)	$0.067^{+0.042}_{-0.030}$ (< 0.115)
H_0	71.			$71.4^{+2.5}_{-2.8}$
τ_reio	0.053			0.0533 ± 0.0073
$\log(10^{10}A_\mathrm{s})$	3.04			3.047 ± 0.014
n_s	0.965			0.9699 ± 0.0038
ξ	−0.			$-0.40^{+0.27}_{-0.23}$
$\ln \mathcal{B}_{ij}$	-			-0.25

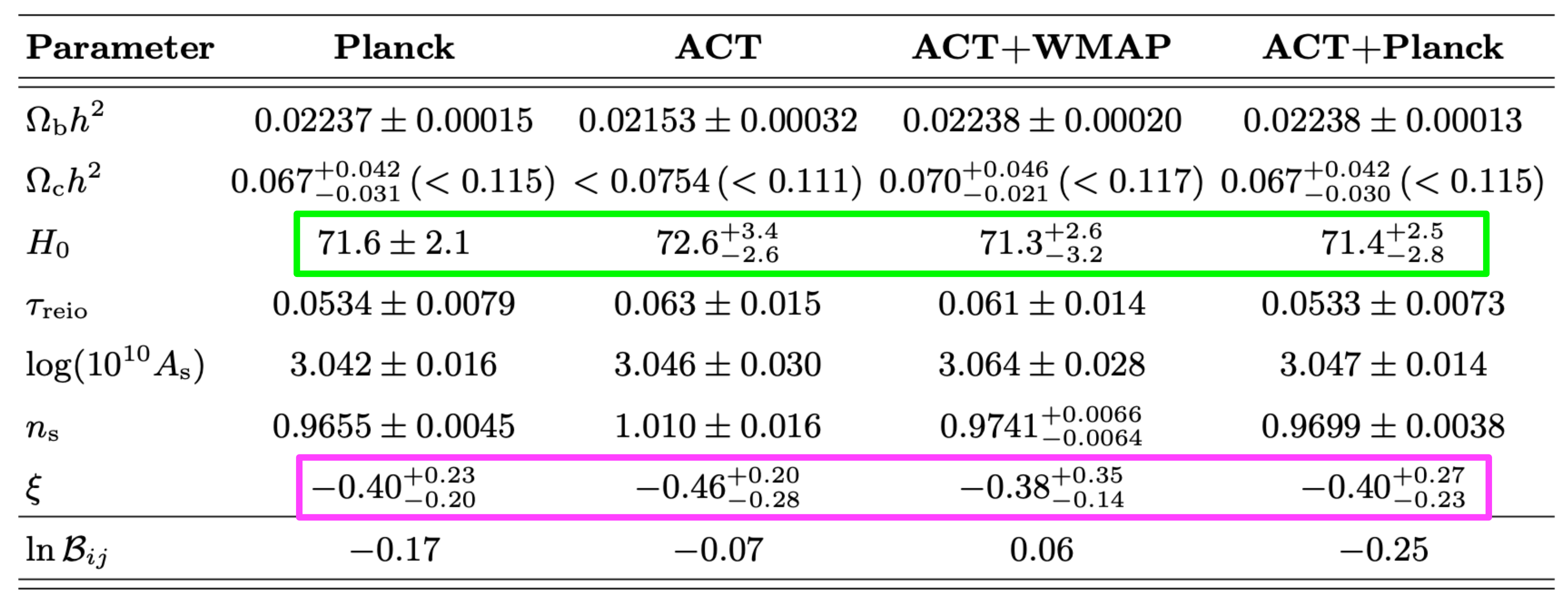


Zha

3) 032



IDE from ACT can solve the H0 tension

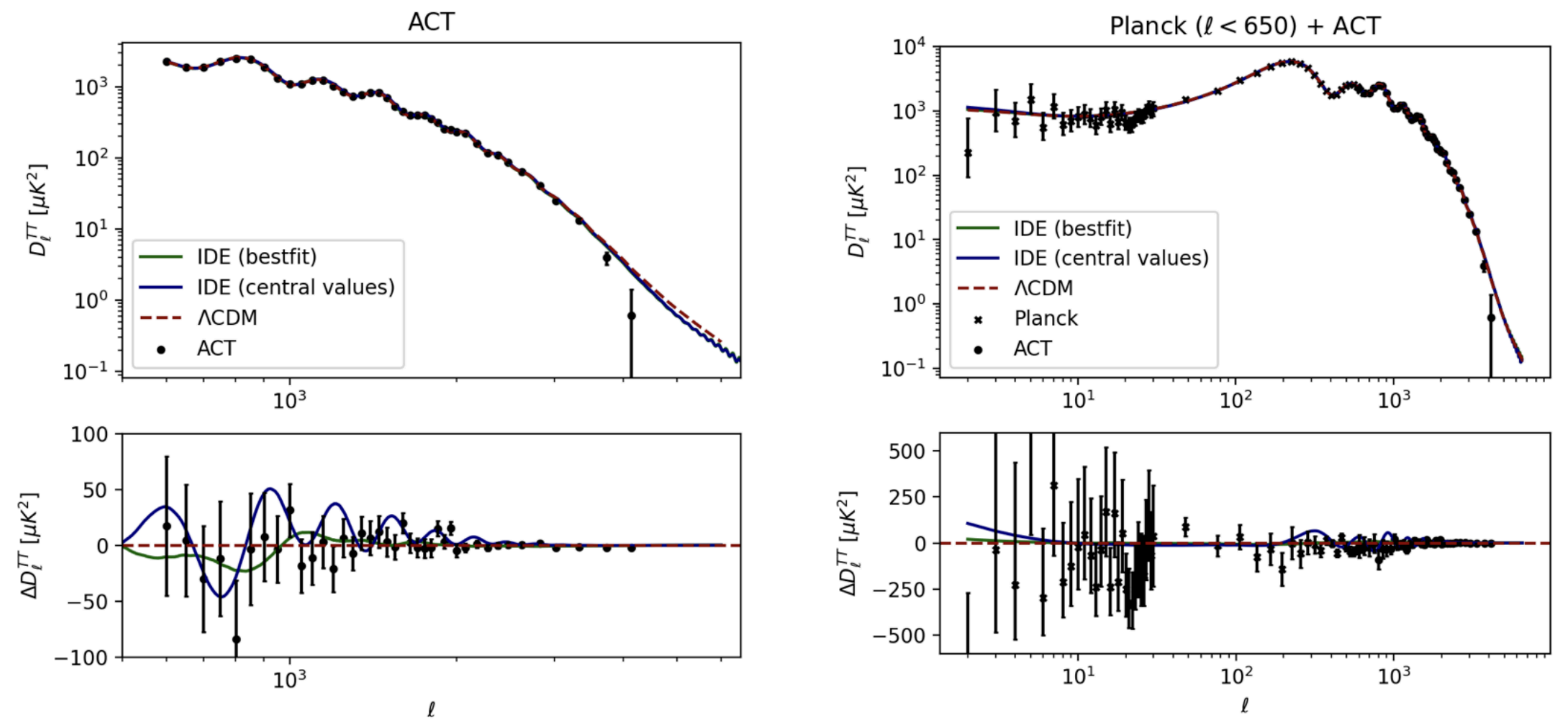


Parameter	Planck	ACT	ACT+WMAP	ACT+Planck
$\Omega_b h^2$	0.02237 ± 0.00015	0.02153 ± 0.00032	0.02238 ± 0.00020	0.02238 ± 0.00013
$\Omega_c h^2$	$0.067^{+0.042}_{-0.031}\,(< 0.115)$	$< 0.0754\,(< 0.111)$	$0.070^{+0.046}_{-0.021}\,(< 0.117)$	$0.067^{+0.042}_{-0.030}\,(< 0.115)$
H_0	71.6 ± 2.1	$72.6^{+3.4}_{-2.6}$	$71.3^{+2.6}_{-3.2}$	$71.4^{+2.5}_{-2.8}$
$\tau_{\rm reio}$	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 H0 consistent
with the local distance ladder measurements.

IDE from ACT can solve the H0 tension



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.

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

A_L : a failed consistency check

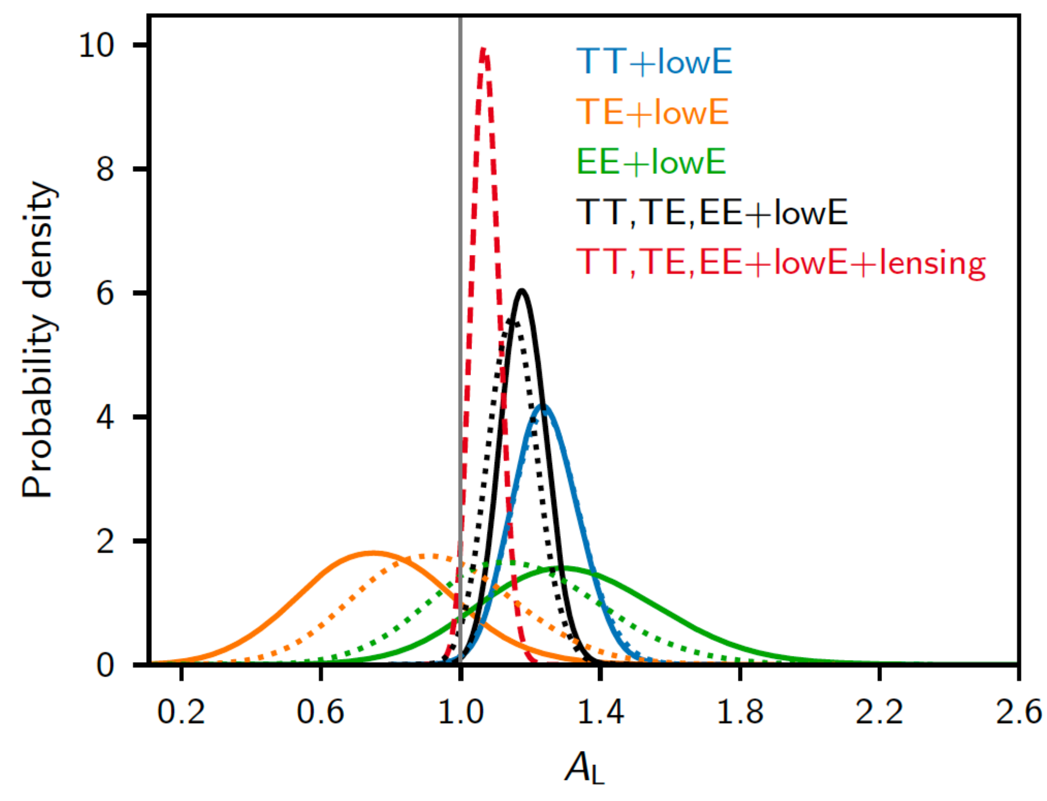
The Planck lensing-reconstruction power spectrum is consistent with the amplitude expected for ΛCDM models that fit the CMB spectra, so the Planck lensing measurement is compatible with AL = 1.

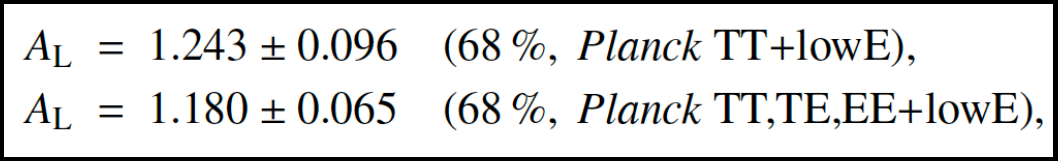
However, the distributions of AL inferred from the CMB power spectra alone indicate a preference for AL > 1.

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

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

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

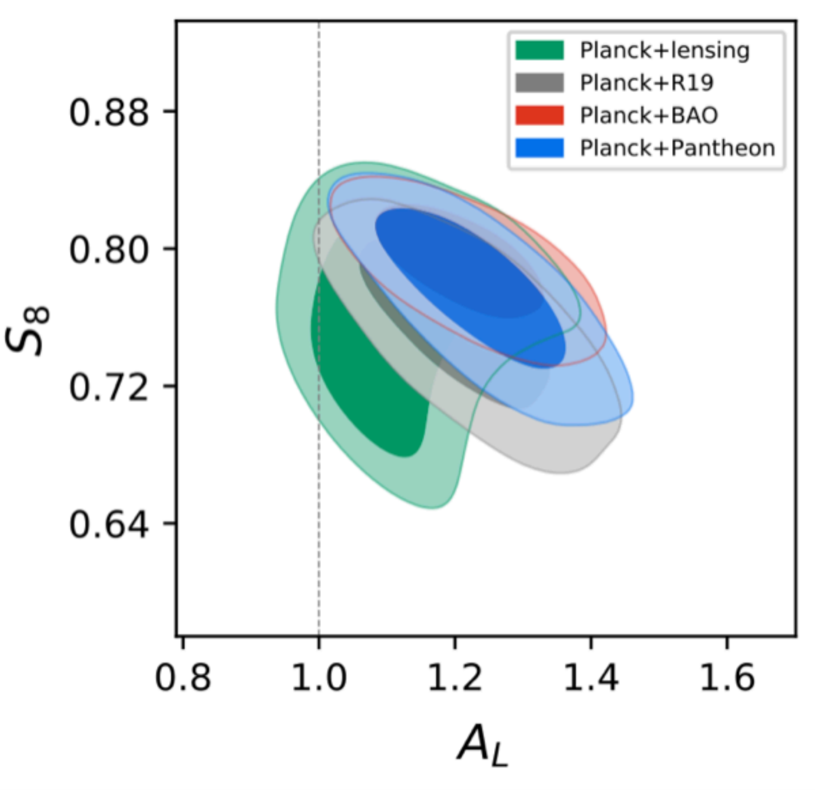




$$A_L = 1.243 \pm 0.096 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT{+}lowE}),$$

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

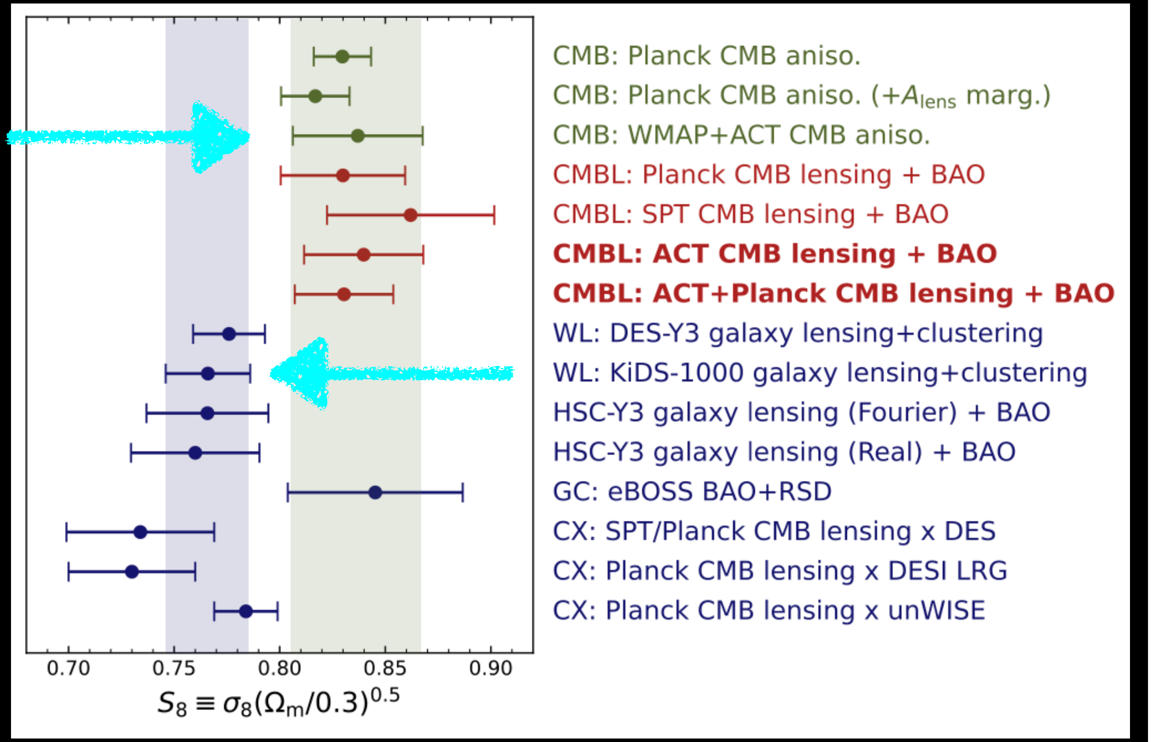
A_L can explain the S8 tension



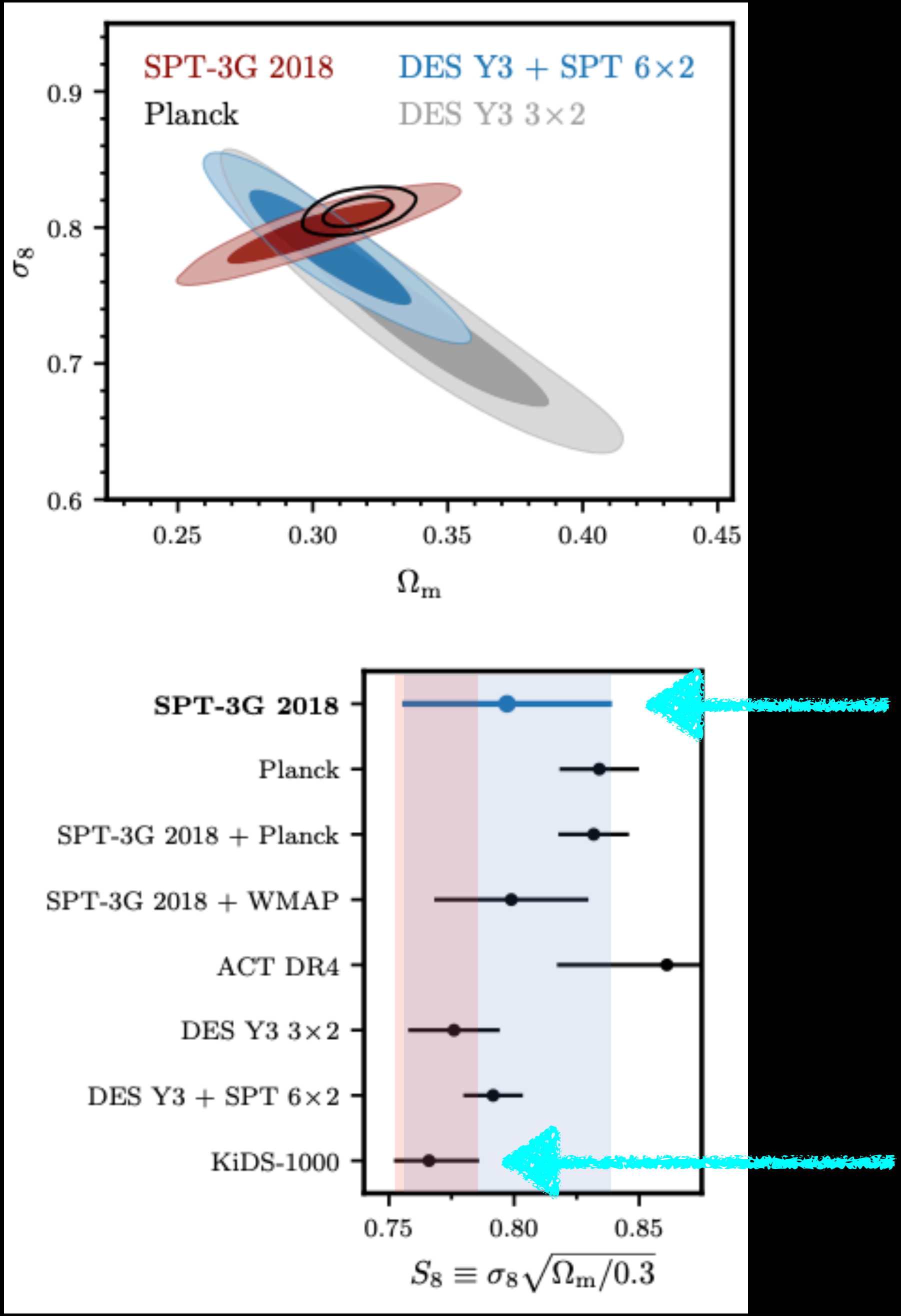
Di Valentino, Melchiorri and Silk, JCAP 2001 (2020) no.01, 013

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

Alternative CMB are not in significant tension

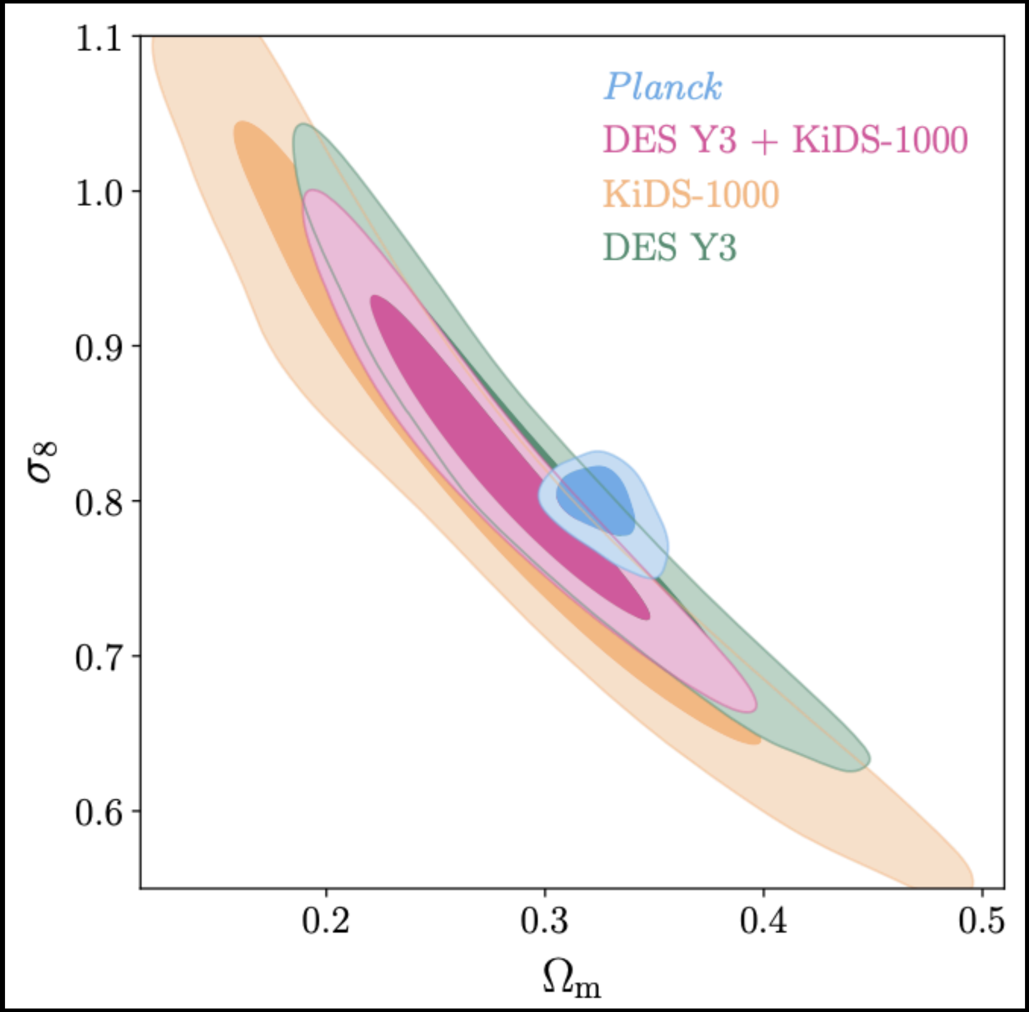


ACT collaboration, arXiv:2304.05203



SPT-3G collaboration, arXiv:2212.05642

DES Y3 + KiDS-1000



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

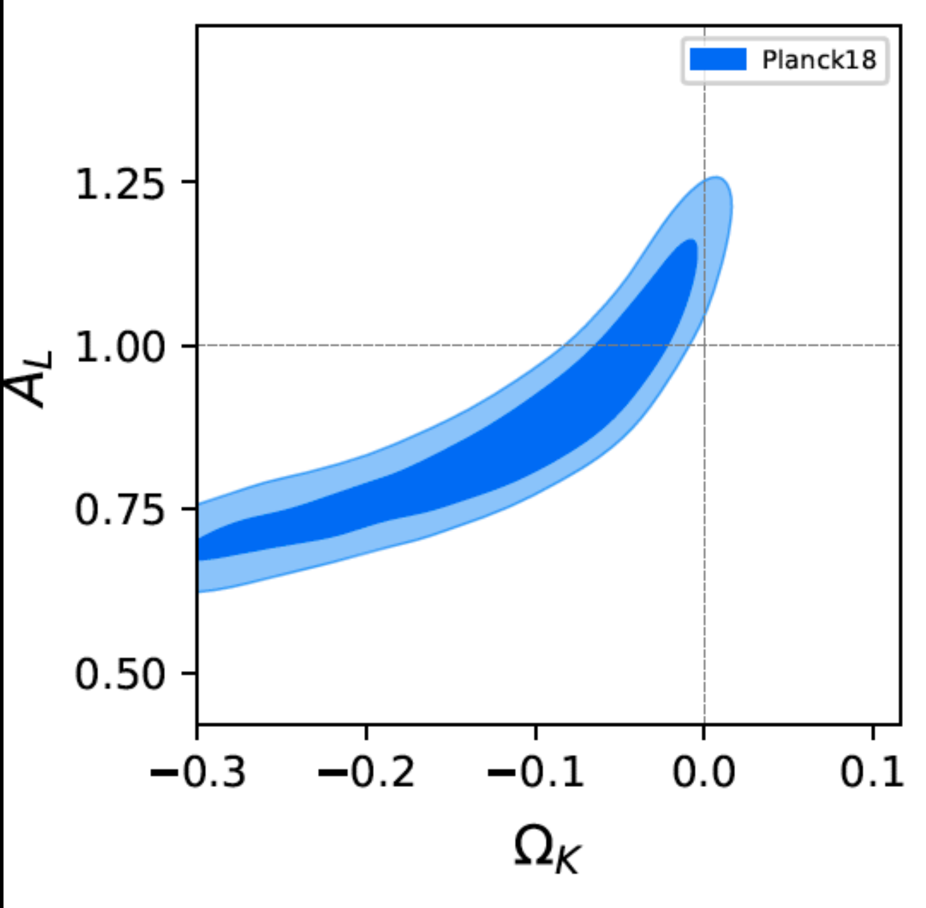
There is no more S8 tension, showing now an agreement at about 1.7σ between Planck assuming ΛCDM and this combined analysis.

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

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

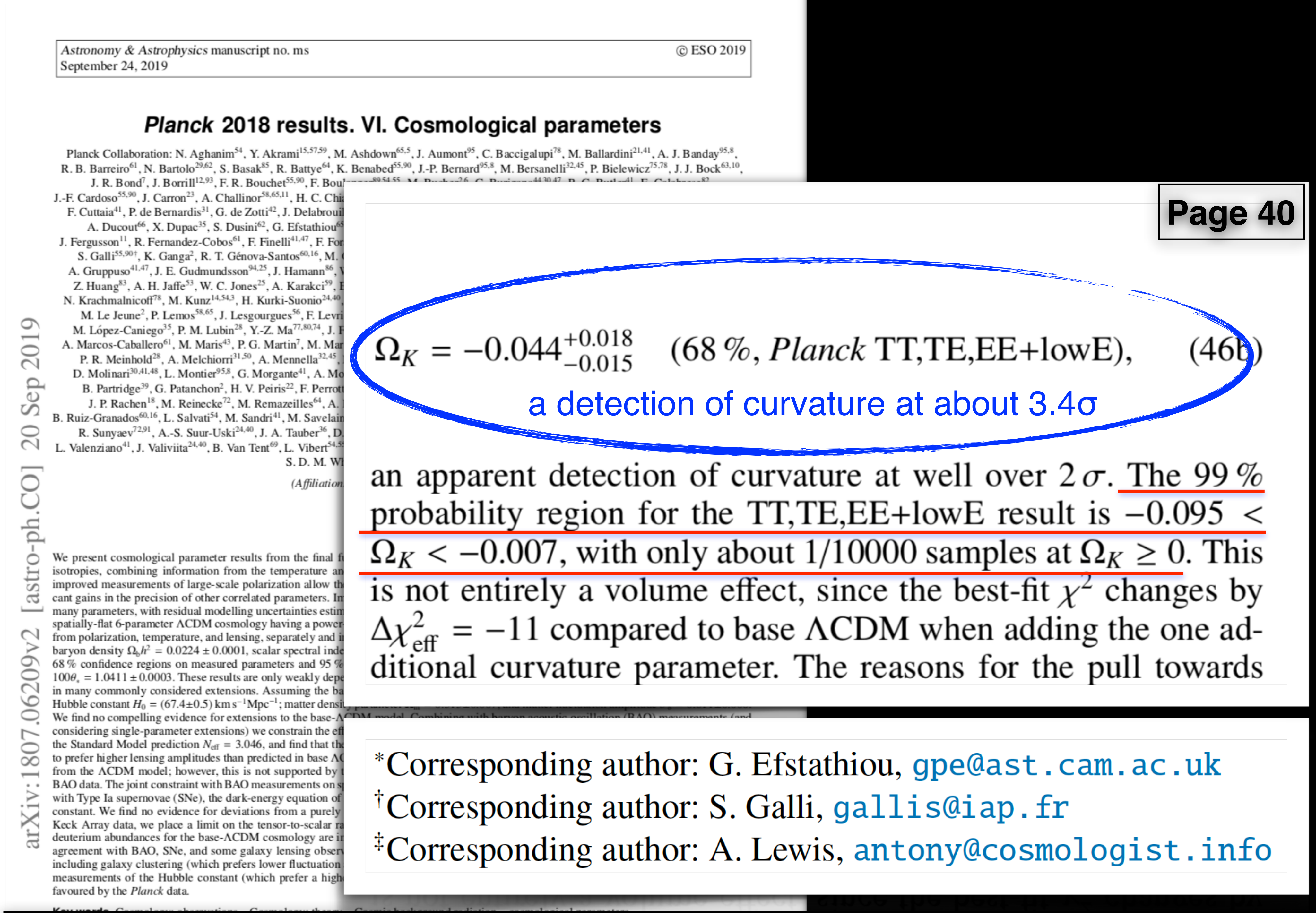
But…
assuming General Relativity,
is there a physical explanation
for A_L?

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 AL 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.



Astronomy & Astrophysics manuscript no. ms
September 24, 2019

Planck 2018 results. VI. Cosmological parameters

Planck Collaboration: N. Aghanim[54], Y. Akrami[15,57,59], M. Ashdown[65,5], J. Aumont[95], C. Baccigalupi[78], M. Ballardini[21,41], A. J. Banday[95,8],
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We present cosmological parameter results from the final f
isotropies, combining information from the temperature an
improved measurements of large-scale polarization allow th
cant gains in the precision of other correlated parameters. In
many parameters, with residual modelling uncertainties estim
spatially-flat 6-parameter ΛCDM cosmology having a power
from polarization, temperature, and lensing, separately and i
baryon density $\Omega_b h^2 = 0.0224 \pm 0.0001$, scalar spectral inde
68 % confidence regions on measured parameters and 95 %
$100\theta_* = 1.0411 \pm 0.0003$. These results are only weakly depe
in many commonly considered extensions. Assuming the ba
Hubble constant $H_0 = (67.4 \pm 0.5)\,\mathrm{km\,s^{-1}Mpc^{-1}}$; matter densit
We find no compelling evidence for extensions to the base-ΛCDM model. Combining with baryon acoustic oscillation (BAO) measurements (and
considering single-parameter extensions) we constrain the eff
the Standard Model prediction $N_{\rm eff} = 3.046$, and find that th
to prefer higher lensing amplitudes than predicted in base Λ
from the ΛCDM model; however, this is not supported by t
BAO data. The joint constraint with BAO measurements on s
with Type Ia supernovae (SNe), the dark-energy equation of
constant. We find no evidence for deviations from a purely
Keck Array data, we place a limit on the tensor-to-scalar ra
deuterium abundances for the base-ΛCDM cosmology are i
agreement with BAO, SNe, and some galaxy lensing obser
including galaxy clustering (which prefers lower fluctuation
measurements of the Hubble constant (which prefer a high
favoured by the *Planck* data.

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

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

a detection of curvature at about 3.4σ

an apparent detection of curvature at well over 2 σ. 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 $\Delta\chi^2_{\rm eff} = -11$ compared to base ΛCDM when adding the one additional curvature parameter. The reasons for the pull towards

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Curvature of the universe

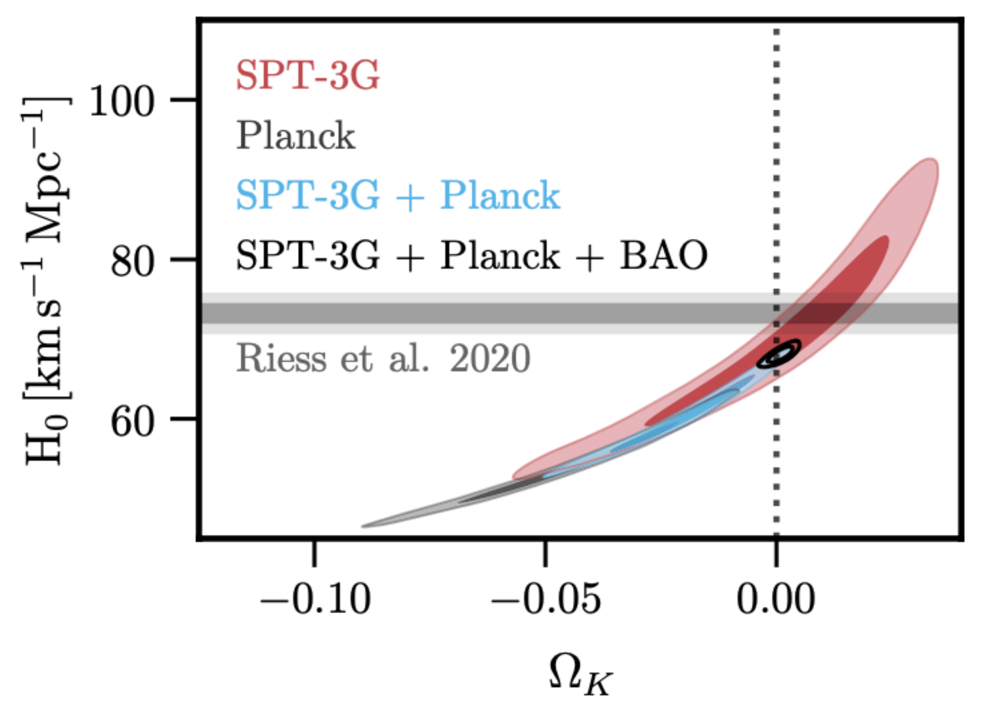
What about the alternative CMB experiments?

CMB Polarization Measurements with SPTpol

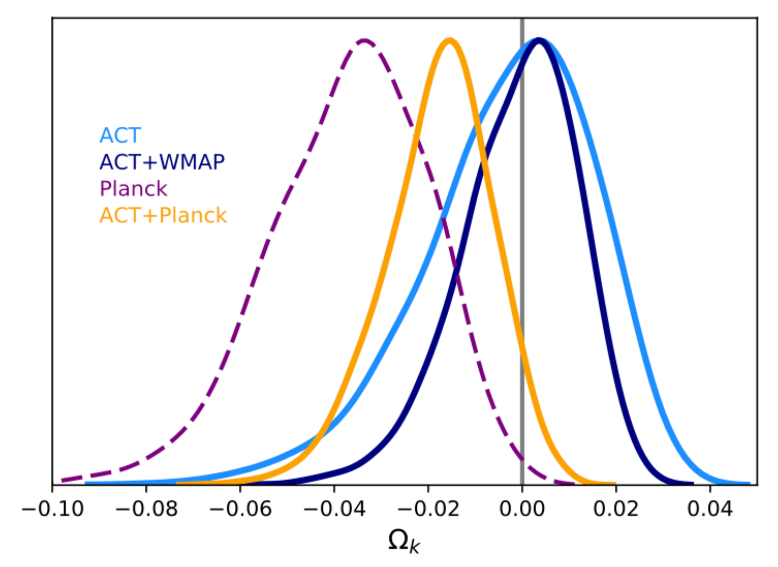
Nicholas Harrington
UC Berkeley

SPT-3G gives at 68% CL:

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



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

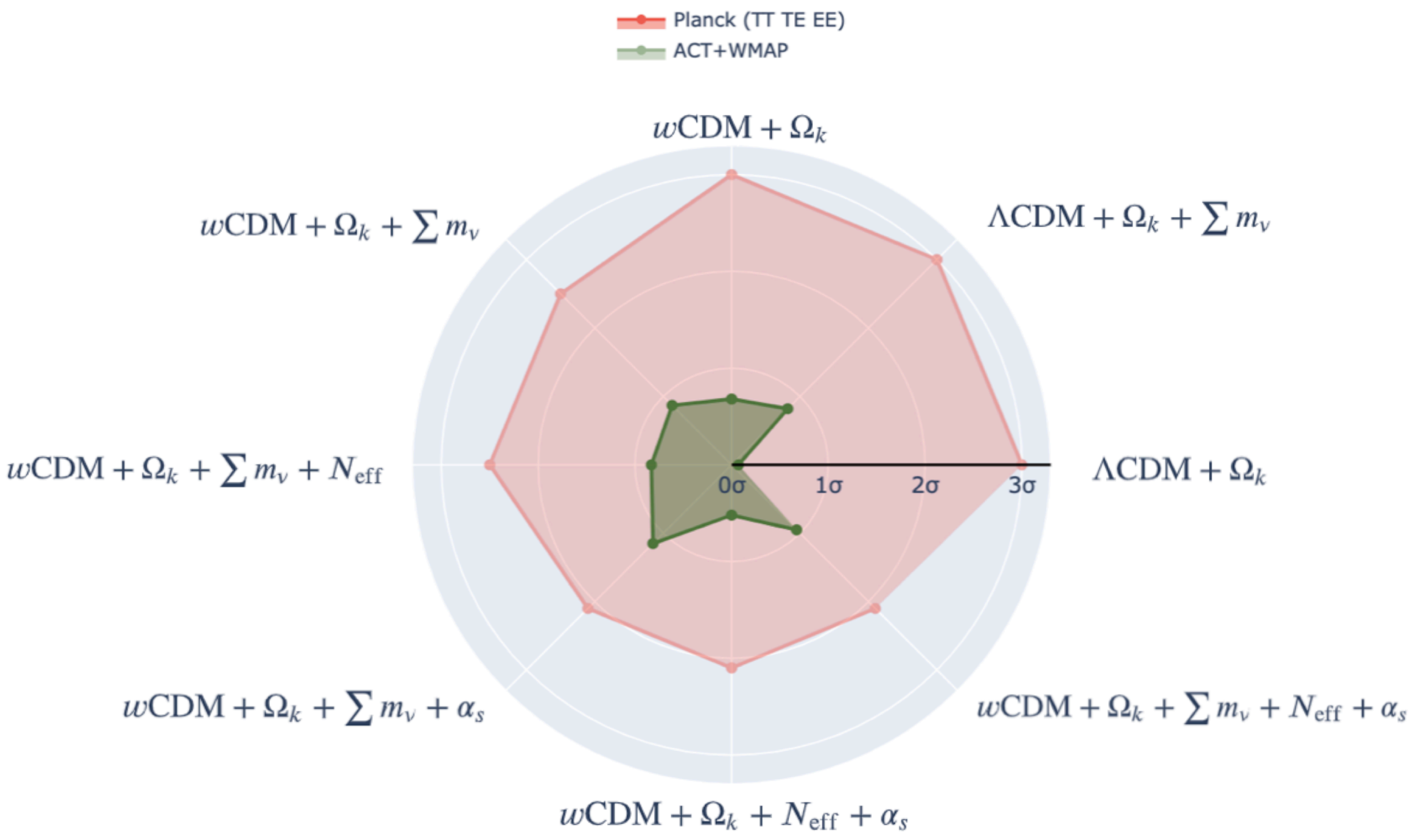


ACT-DR4 + WMAP gives at 68% CL

$\Omega_k = -0.001 \pm 0.012$

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

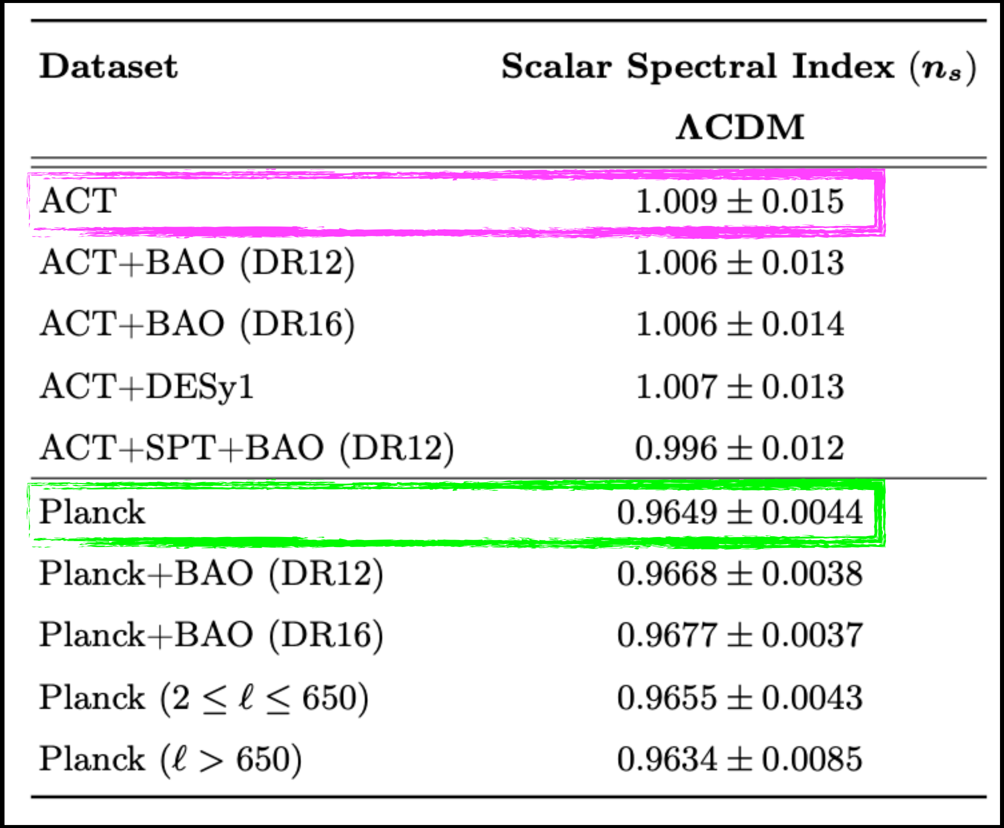
Tension with $\Omega_k = 0$



Di Valentino et al., *Phys.Rev.D* 106 (2022) 10, 103506

And what we see in the simplest ΛCDM+ Ω_k model is robust also in its extensions:
ACT is always in agreement with a flat Universe within 1σ,
while Planck is always preferring a closed universe at the level of 2-3σ.

Inflation: $\Omega_k < 0$ or HZ?

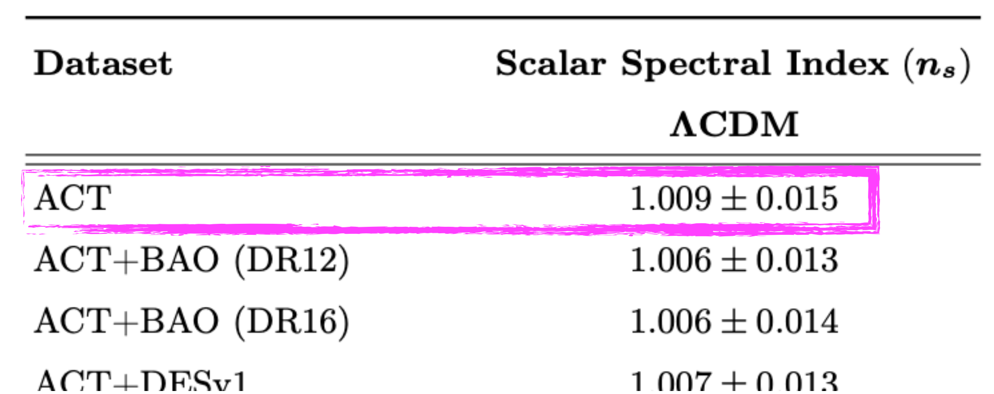


Dataset	Scalar Spectral Index (n_s) ΛCDM
ACT	1.009 ± 0.015
ACT+BAO (DR12)	1.006 ± 0.013
ACT+BAO (DR16)	1.006 ± 0.014
ACT+DESy1	1.007 ± 0.013
ACT+SPT+BAO (DR12)	0.996 ± 0.012
Planck	0.9649 ± 0.0044
Planck+BAO (DR12)	0.9668 ± 0.0038
Planck+BAO (DR16)	0.9677 ± 0.0037
Planck ($2 \leq \ell \leq 650$)	0.9655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

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

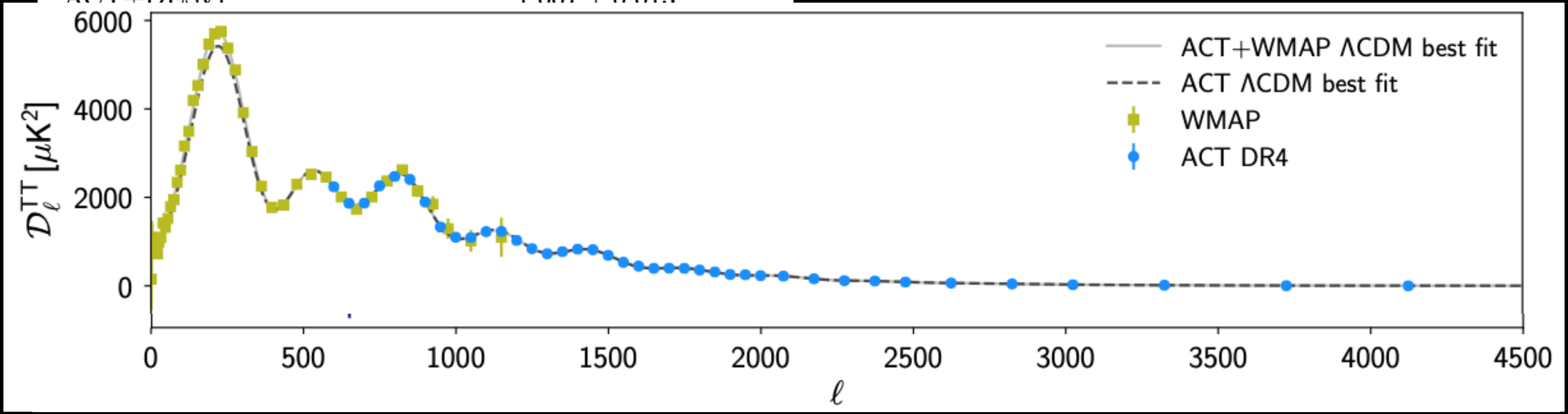
At this point, if Planck seems to disfavour the inflationary prediction for a flat background geometry at more than 3σ, ACT, although in perfect agreement with spatial flatness, shows a preference for a larger spectral index consistent with a Harrison-Zel'dovich scale-invariant spectrum ns=1 of primordial density perturbations introducing a tension with a significance of 2.7σ with the results from the Planck satellite.

Inflation: $\Omega_k < 0$ or HZ?

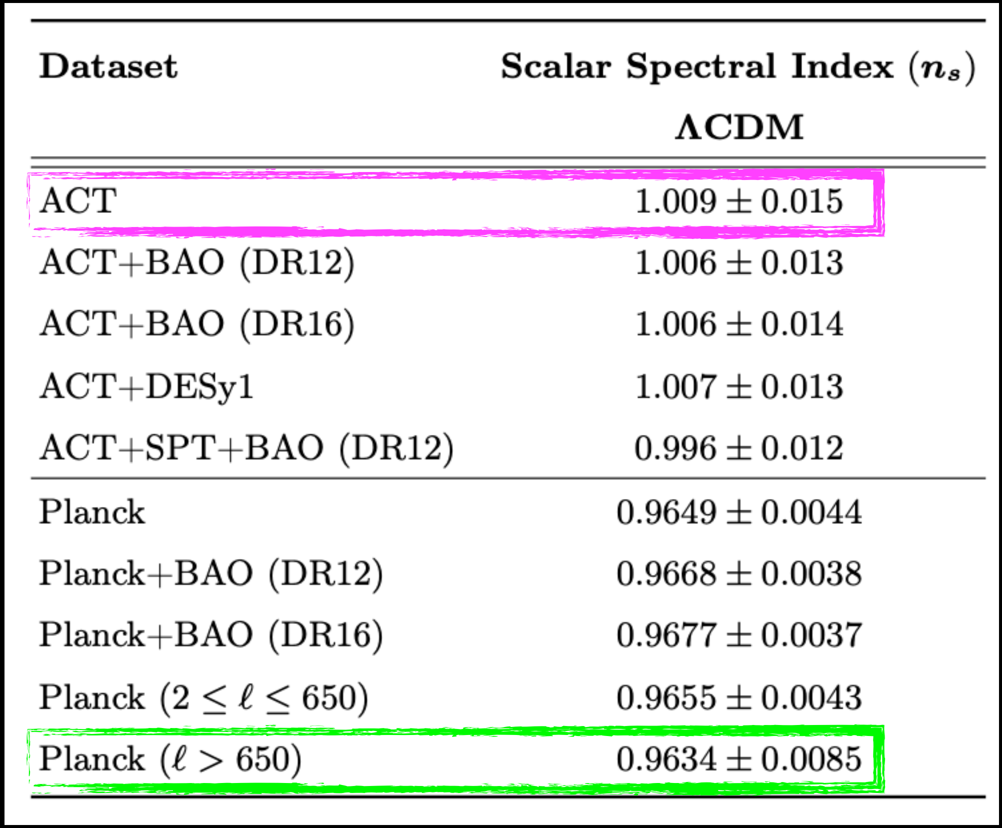


Dataset	Scalar Spectral Index (n_s)
	ΛCDM
ACT	1.009 ± 0.015
ACT+BAO (DR12)	1.006 ± 0.013
ACT+BAO (DR16)	1.006 ± 0.014
ACT+DESy1	1.007 ± 0.013

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.



Inflation: $\Omega_k < 0$ or HZ?



Dataset	**Scalar Spectral Index (n_s)**
	ΛCDM
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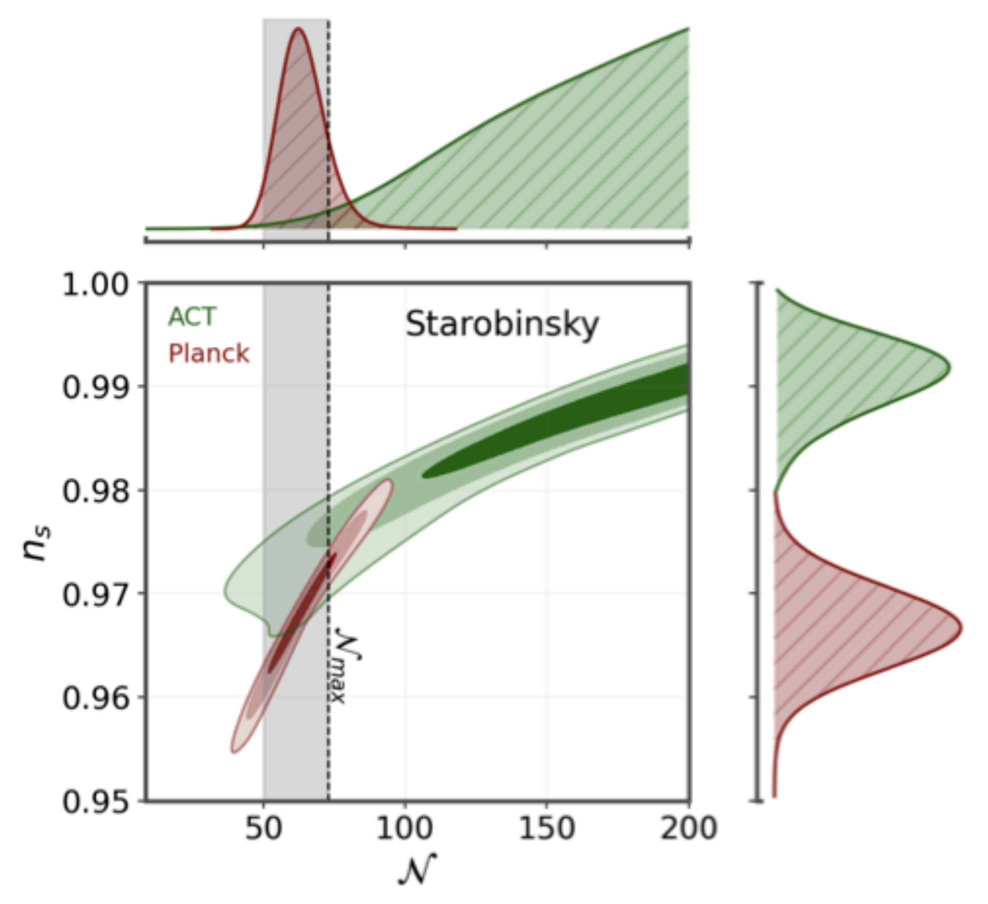
Giarè, Renzi, Mena, Di Valentino, and Melchiorri,
MNRAS 521 (2023) 2, 2911

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 ns, we have performed two separate analyses of the Planck observations, splitting the likelihood into low $2 < l < 650$ and high $l > 650$ 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 ~4.3σ when the information about the first acoustic peak is removed.

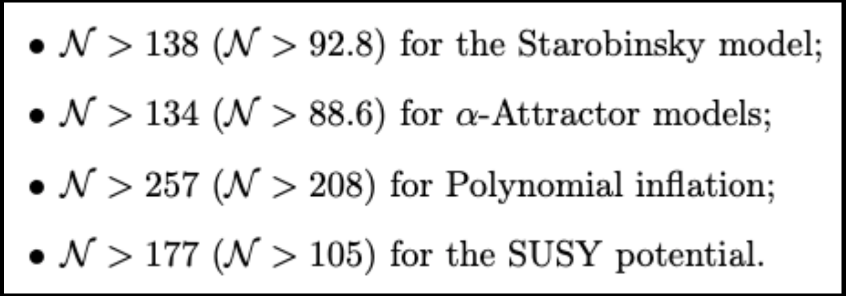


Giarè, Pan, Di Valentino, Yang, de Haro, and Melchiorri, arXiv:2305.15378

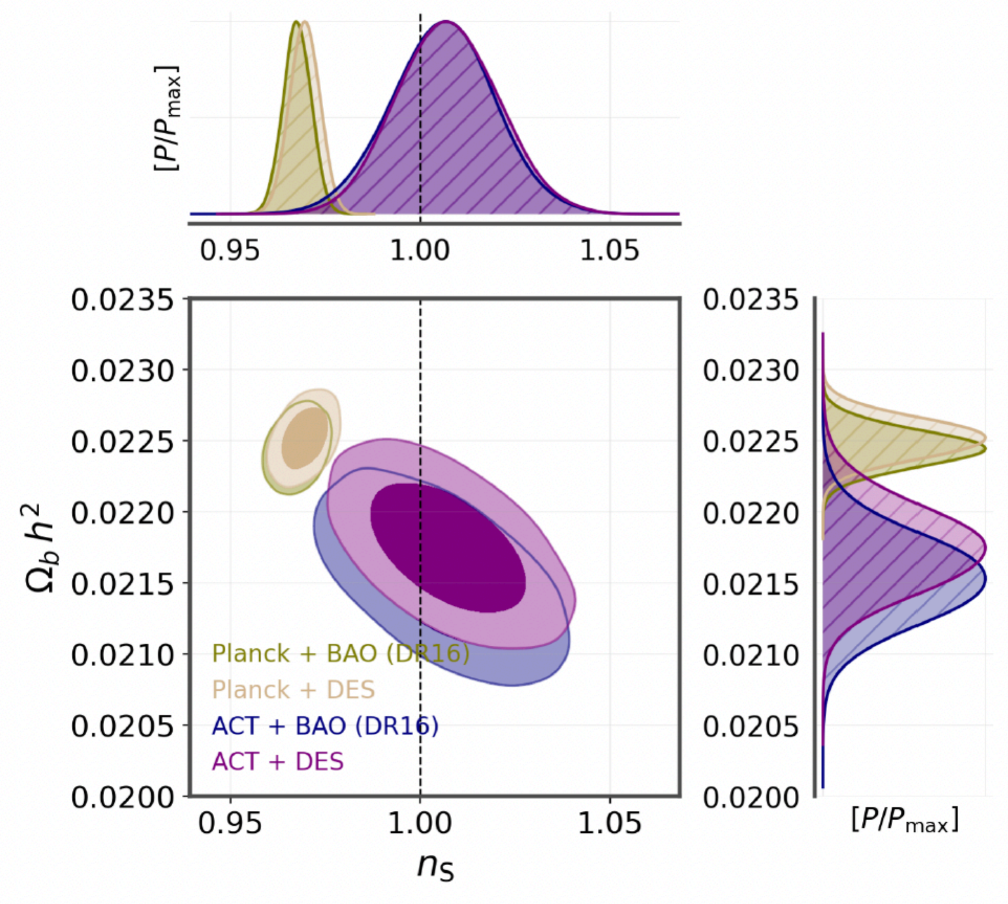
We tested some models of inflation regarded as well - established benchmark scenarios and found out that they are ruled out by ACT at more than 3σ.

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 $N_{efolds} \in [50, N_{max}]$, 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.

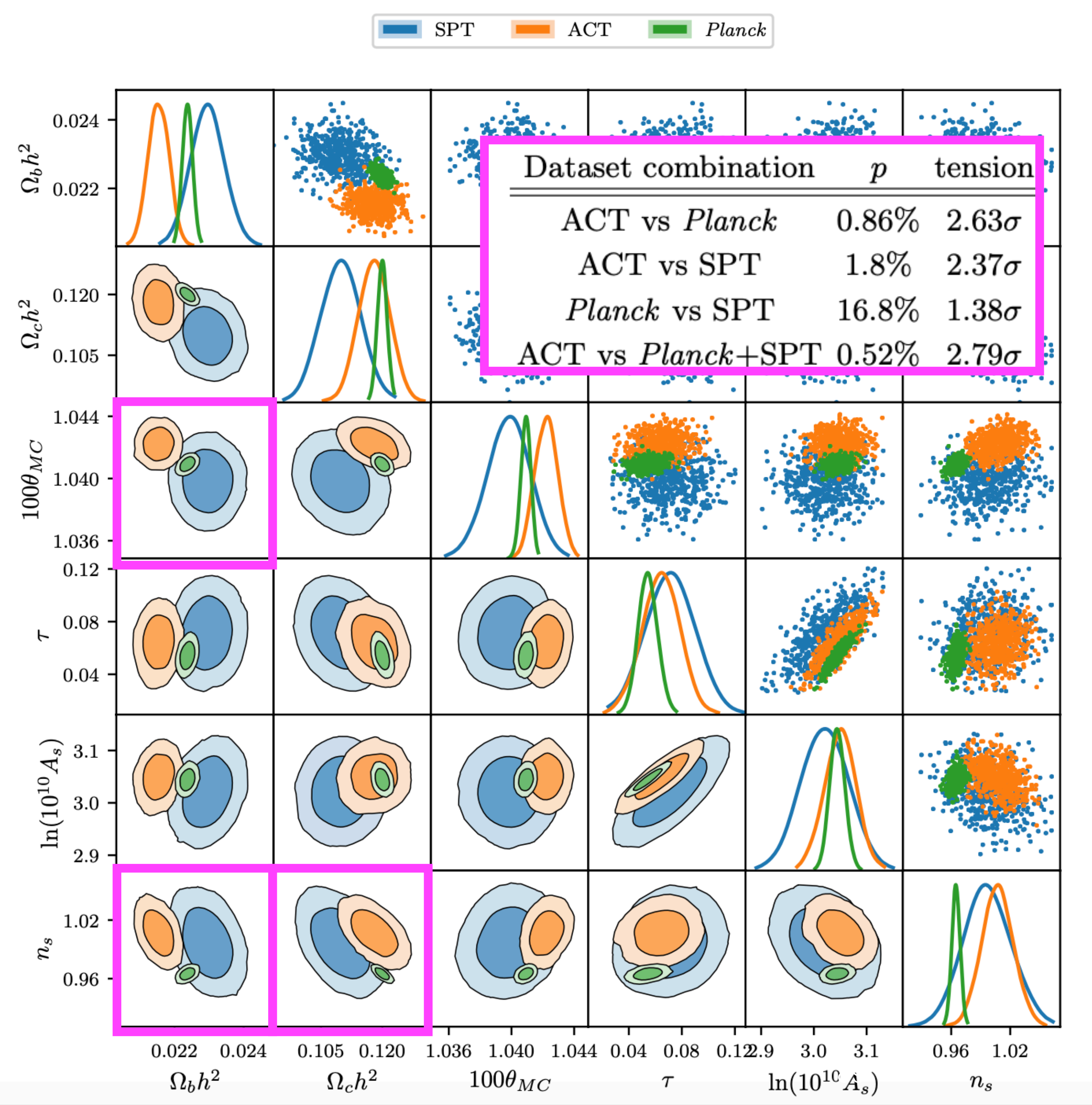


Giarè, Renzi, Mena, Di Valentino, and Melchiorri, MNRAS 521 (2023) 2, 2911

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 $\Omega_b h^2$ - ns degeneracy is opposite for ACT and Planck,
and the disagreement here is significantly exceeding 3σ.

Quantifying global CMB tension

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



Dataset combination	p	tension
ACT vs *Planck*	0.86%	2.63σ
ACT vs SPT	1.8%	2.37σ
Planck vs SPT	16.8%	1.38σ
ACT vs *Planck*+SPT	0.52%	2.79σ

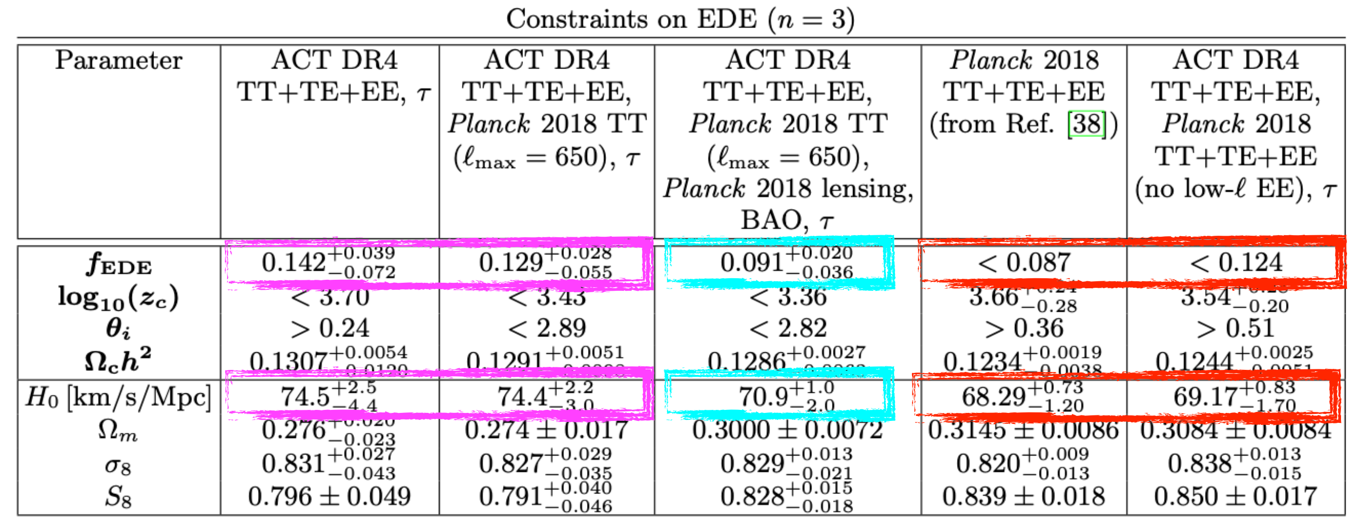
Global tensions between CMB datasets.

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.

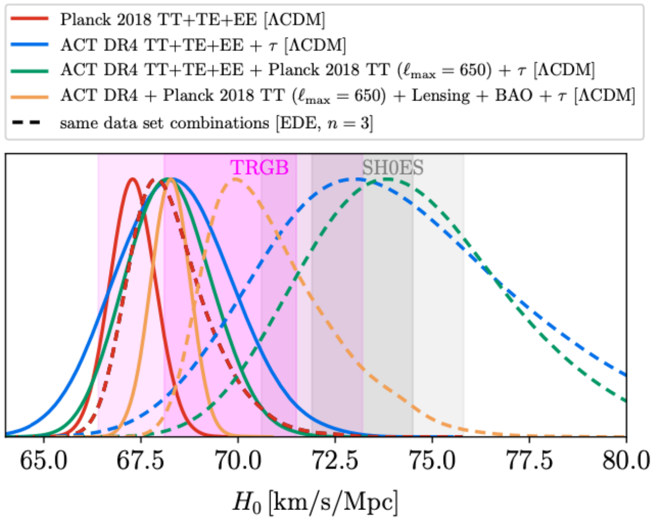
Assuming ΛCDM

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
$\boldsymbol{f_{\rm EDE}}$	$0.142^{+0.039}_{-0.072}$	$0.129^{+0.028}_{-0.055}$	$0.091^{+0.020}_{-0.036}$	< 0.087	< 0.124
$\boldsymbol{\log_{10}(z_c)}$	< 3.70	< 3.43	< 3.36	$3.66^{+0.24}_{-0.28}$	$3.54^{+0.23}_{-0.20}$
$\boldsymbol{\theta_i}$	> 0.24	< 2.89	< 2.82	> 0.36	> 0.51
$\boldsymbol{\Omega_c h^2}$	$0.1307^{+0.0054}_{-0.0120}$	$0.1291^{+0.0051}_{-[illegible]}$	$0.1286^{+0.0027}_{-[illegible]}$	$0.1234^{+0.0019}_{-0.0038}$	$0.1244^{+0.0025}_{-0.0051}$
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 > 3σ, solving completely the Hubble tension. The evidence for EDE > 3σ persists with the inclusion of Planck lensing + BAO data, but shifting H0 towards a lower value. Once the full Planck data are considered, the evidence for EDE disappears and H0 is again in tension with SH0ES.

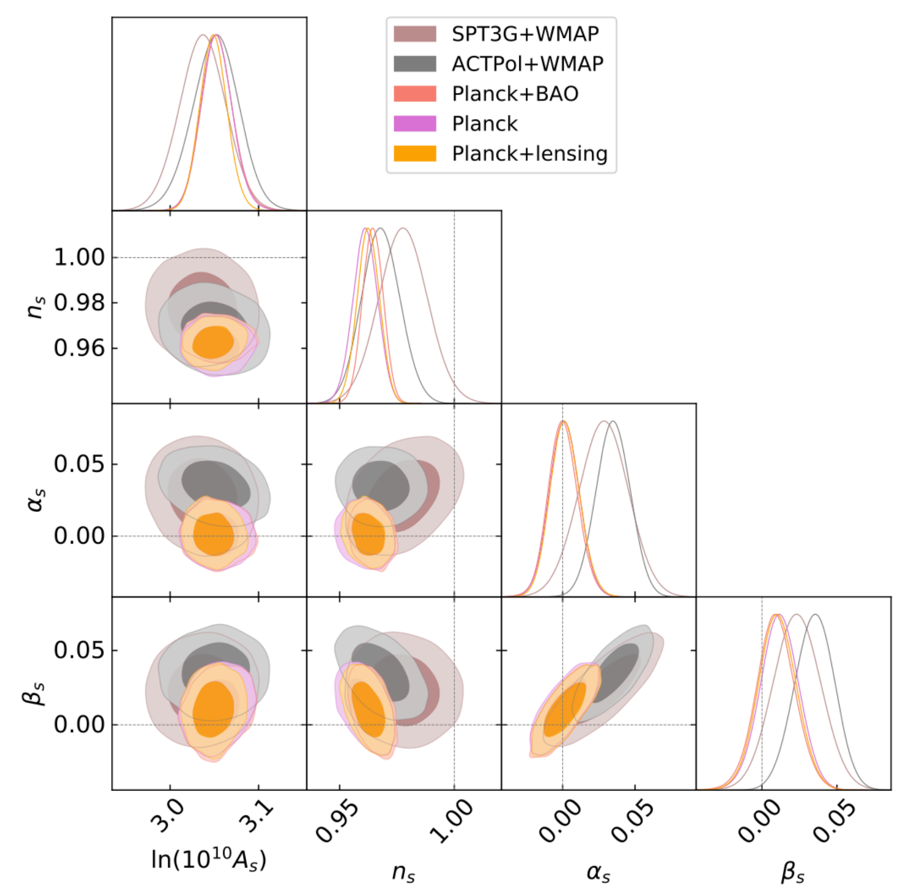
The Planck damping tail is in disagreement with EDE different from zero.

ACT-DR4 vs Planck: α_s and β_s.

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

Parameter	Planck18	ACTPol + WMAP
$\Omega_b h^2$	0.02235 ± 0.00017	0.02195 ± 0.00025
$\Omega_c h^2$	0.1207 ± 0.0015	0.1190 ± 0.0029
		1.04174 ± 0.00066
		0.061 ± 0.013
$\log(10^{10} A_S)$	3.053 ± 0.018	3.051 ± 0.026
n_s	0.9612 ± 0.0054	0.9680 ± 0.0082
α_s	0.001 ± 0.010	0.035 ± 0.012
β_s	0.012 ± 0.013	0.035 ± 0.013

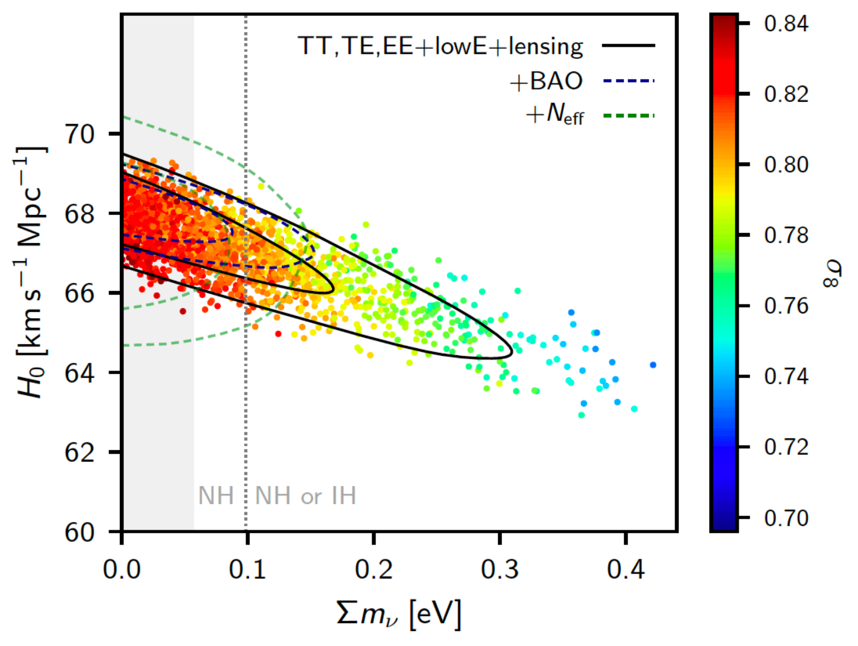
$$\alpha_s \doteq \left[\frac{dn_s}{d\log k}\right]_{k=k_*} \qquad \beta_s \doteq \left[\frac{d\alpha_s}{d\log k}\right]_{k=k_*}$$

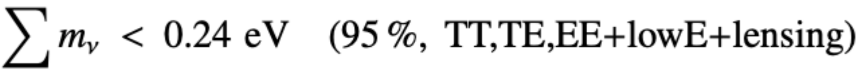


ACT-DR4 and SPT-3G are in agreement one with each other, but in disagreement with Planck, for the value of the running of the scalar spectral index α_s and of the running of the running β_s.

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.

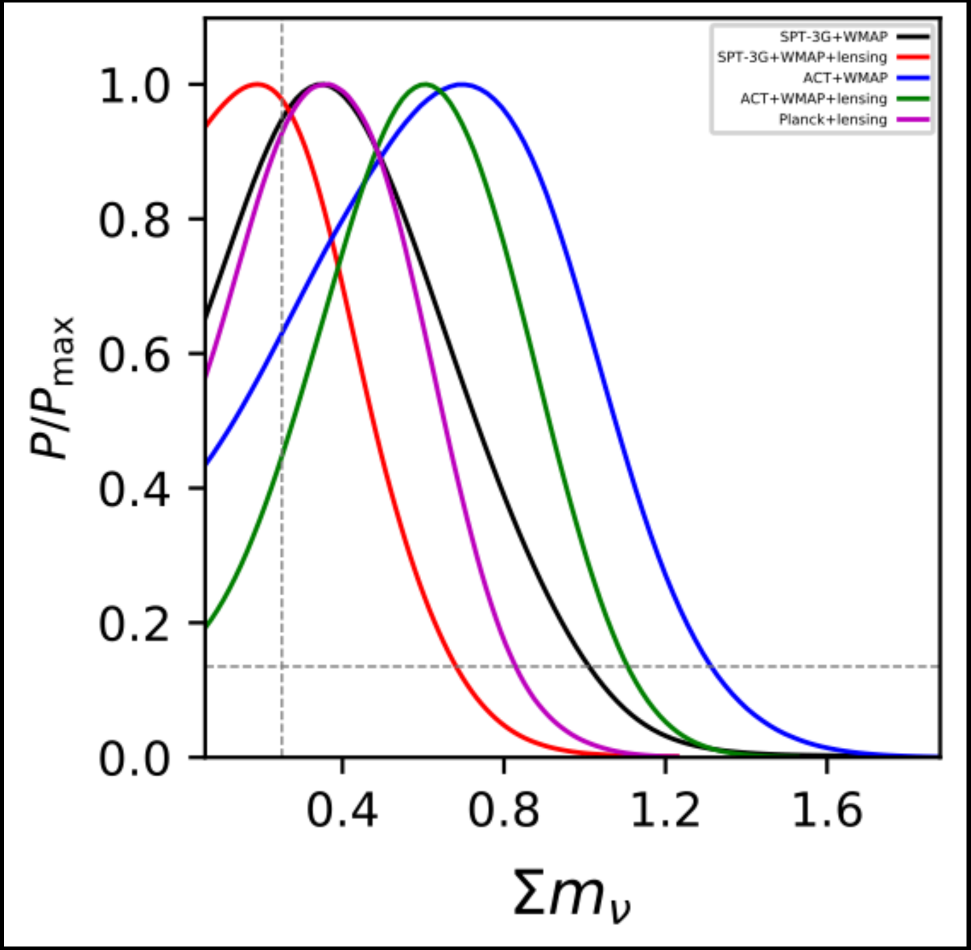
Alternative CMB vs Planck: Σmν





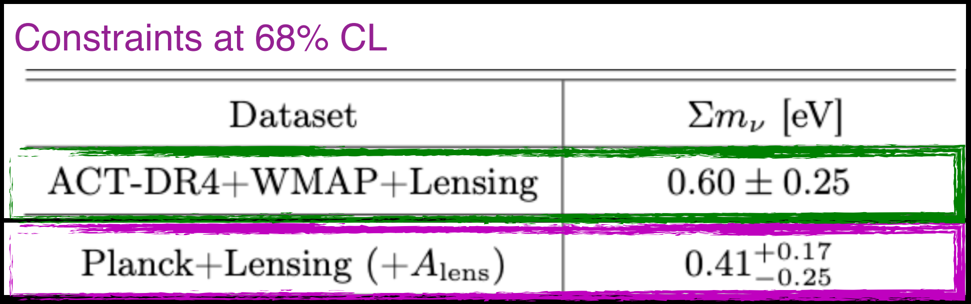
$$\sum m_\nu < 0.24\ \mathrm{eV} \quad (95\,\%,\ \mathrm{TT,TE,EE{+}lowE{+}lensing})$$

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



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

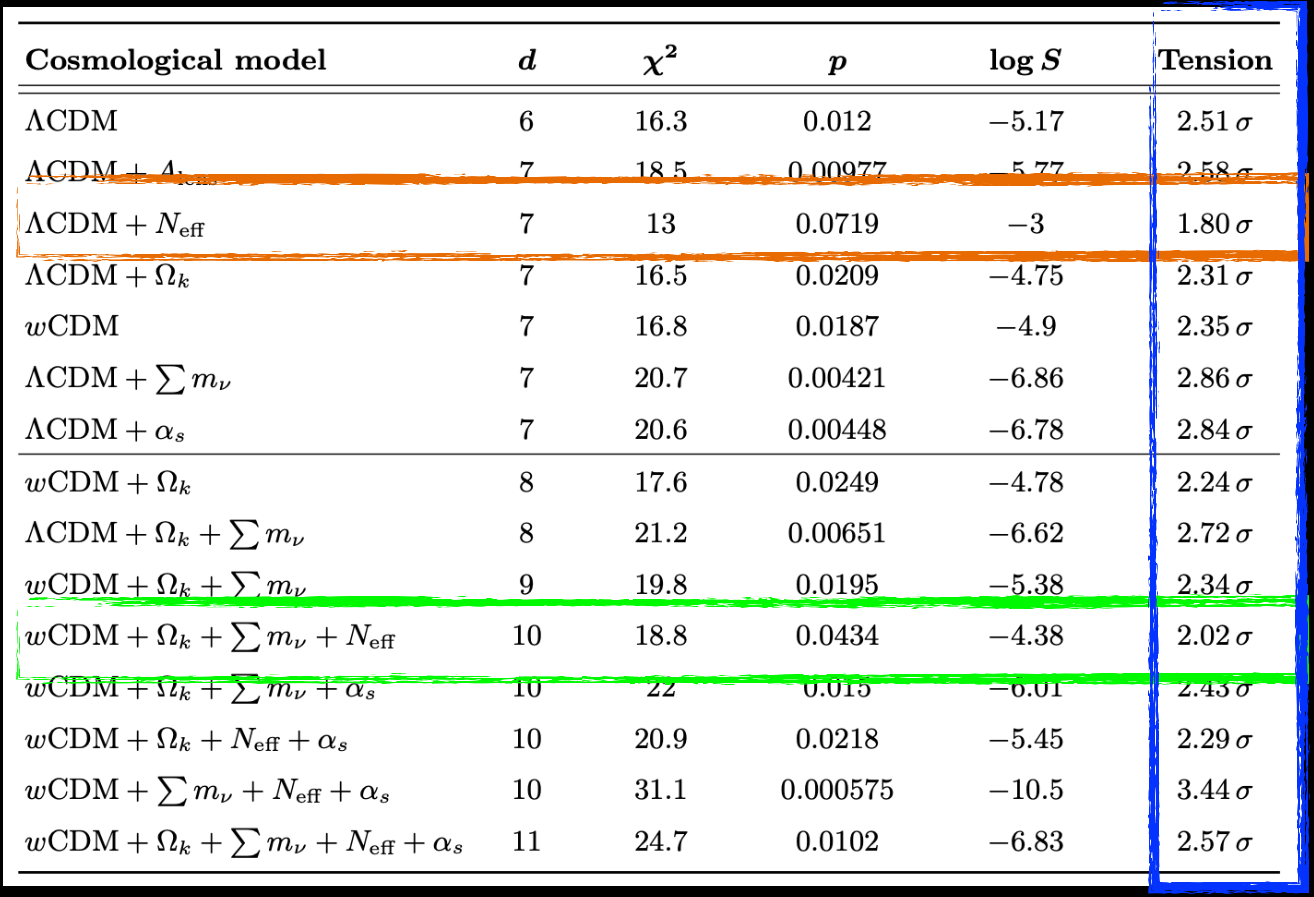
While we have only an upper limit for Planck on the total neutrino mass, ACT-DR4, when combined with WMAP and lensing, prefers a neutrino mass different from zero at more than 95% CL.



Constraints at 68% CL

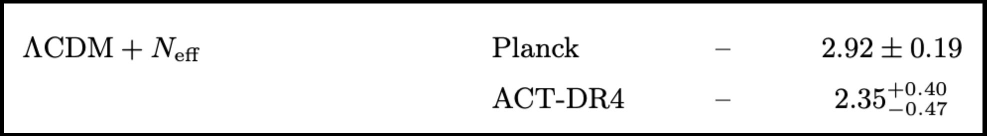
Dataset	Σm_ν [eV]
ACT-DR4+WMAP+Lensing	0.60 ± 0.25
Planck+Lensing ($+A_{\rm lens}$)	$0.41^{+0.17}_{-0.25}$

Quantifying global CMB tension



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

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



$\Lambda\mathrm{CDM} + N_{\mathrm{eff}}$	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 ΛCDM is reduced at the level of 1.8σ when Neff is significantly less than 3.044, while it ranges between 2.3σ and 3.5σ in all the other extended models.

Concluding

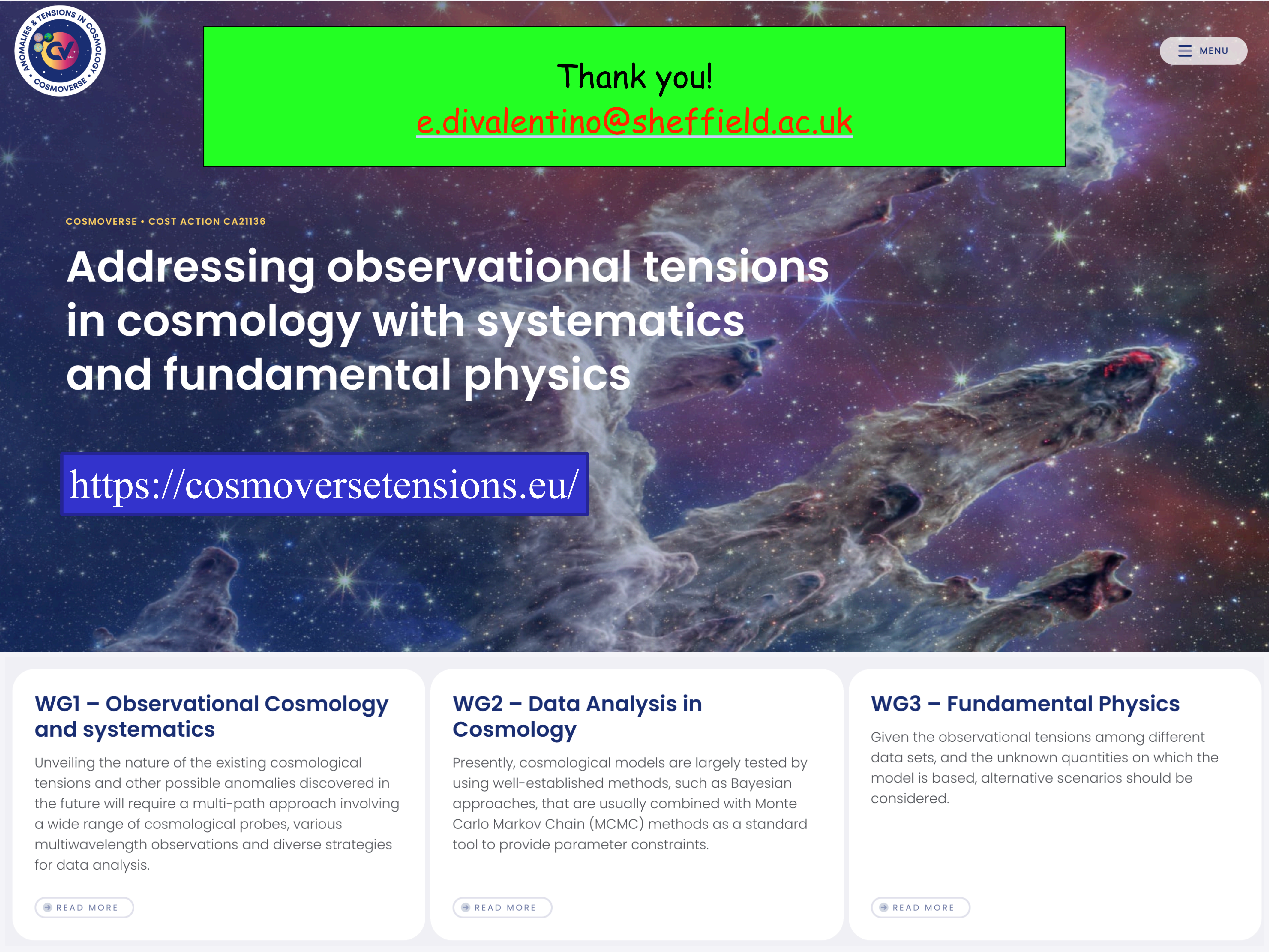
At this point, given the quality of all the analyses at play,
probably these tensions are indicating a problem with the underlying cosmology and our understanding of the Universe,
rather than the presence of systematic effects.

Many models have been proposed to solve the H0 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 S8 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!

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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.

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.

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.