CMB ANOMALIES AND THE HUBBLE TENSION

Assessing the consistency of CMB Observations to probe new physics

COSMOVERSE AT LISBON

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ACKNOWLEDGEMENTS

PRESENTATION BASED ON:

Di Valentino, **WG** et. al
2209.12872

Di Valentino, **WG** et. al
2209.14054

WG et. al
2210.09018

WG et. al
2305.15378

WG - 2305.16919
‘CMB Anomalies and the Hubble Tension’

Invited chapter for the edited book "Hubble Constant Tension"
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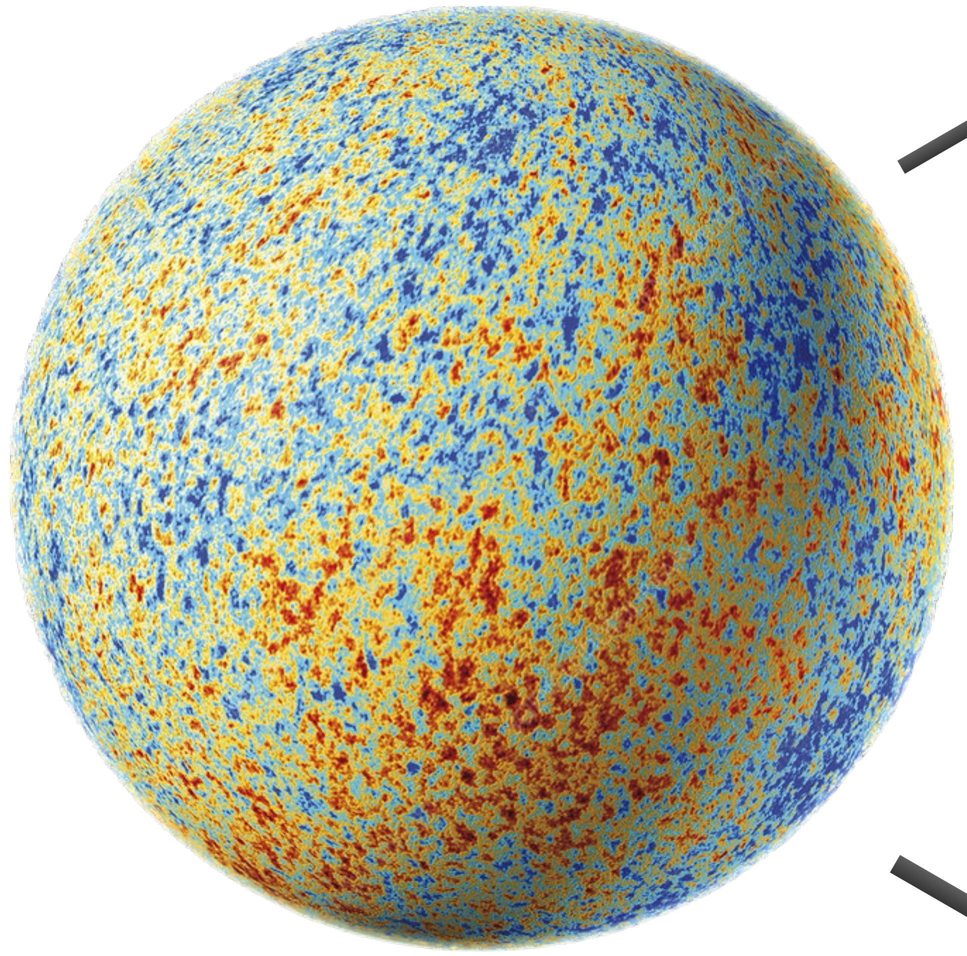
Eleonora Di Valentino (University of Sheffield)

Olga Mena (University of Valencia)

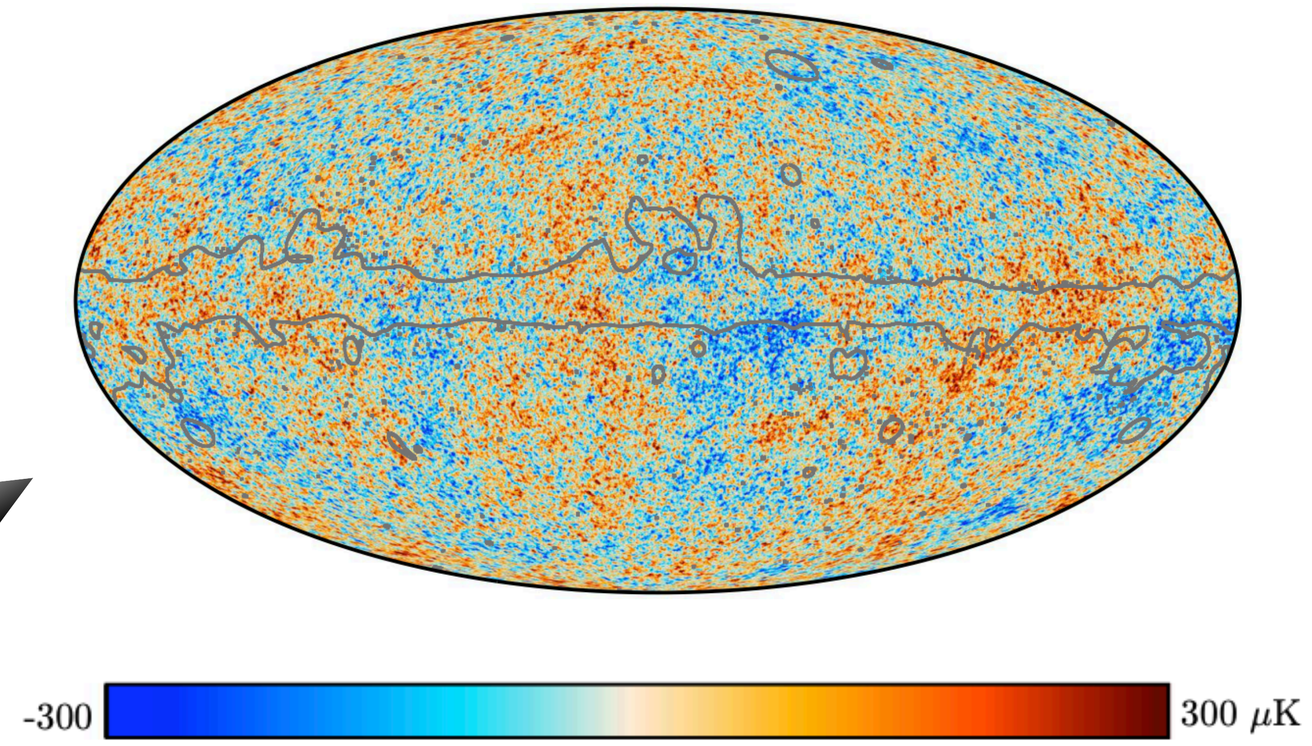
Alessandro Melchiorri (Sapienza, University of Rome)
...

1 CMB Anomalies: a brief multi-experiment overview

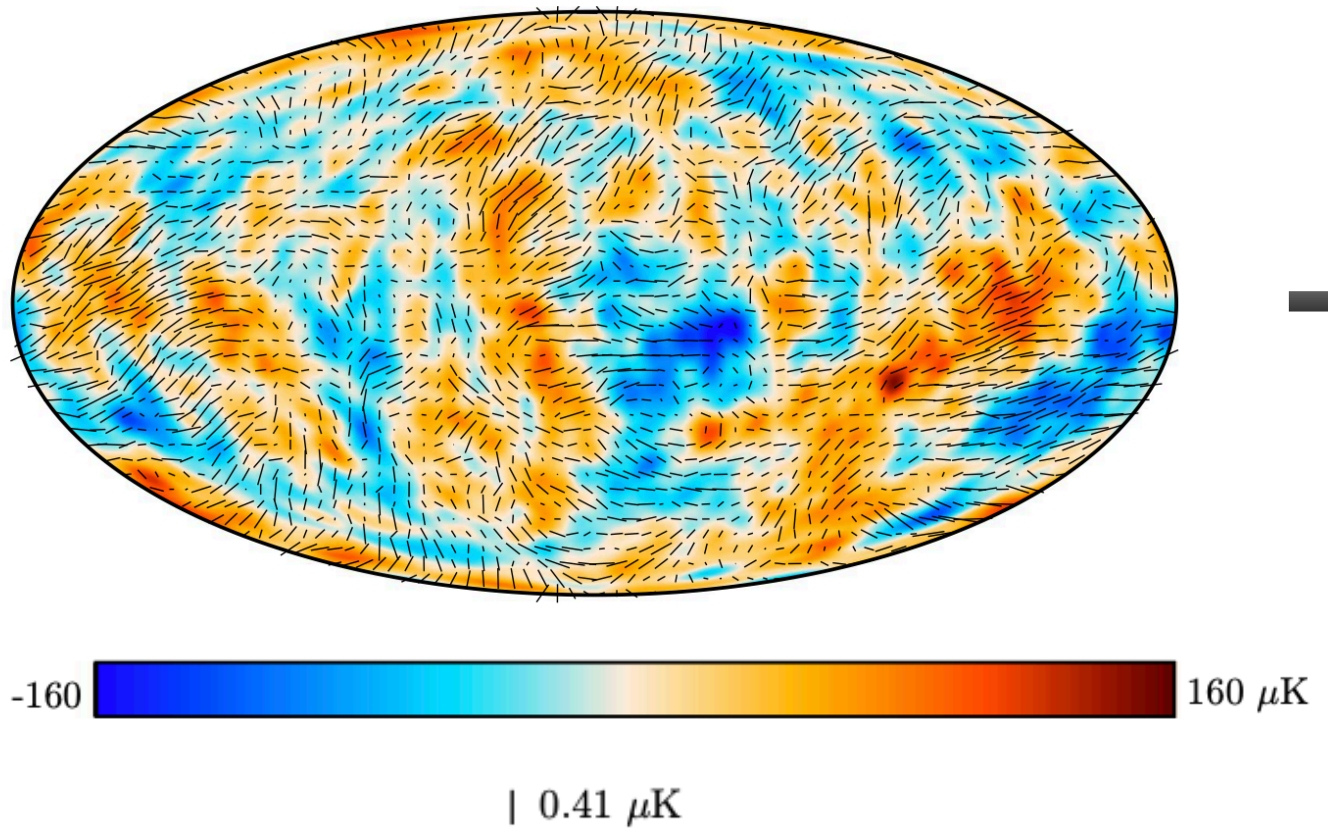
Relic Photons from the Big Bang

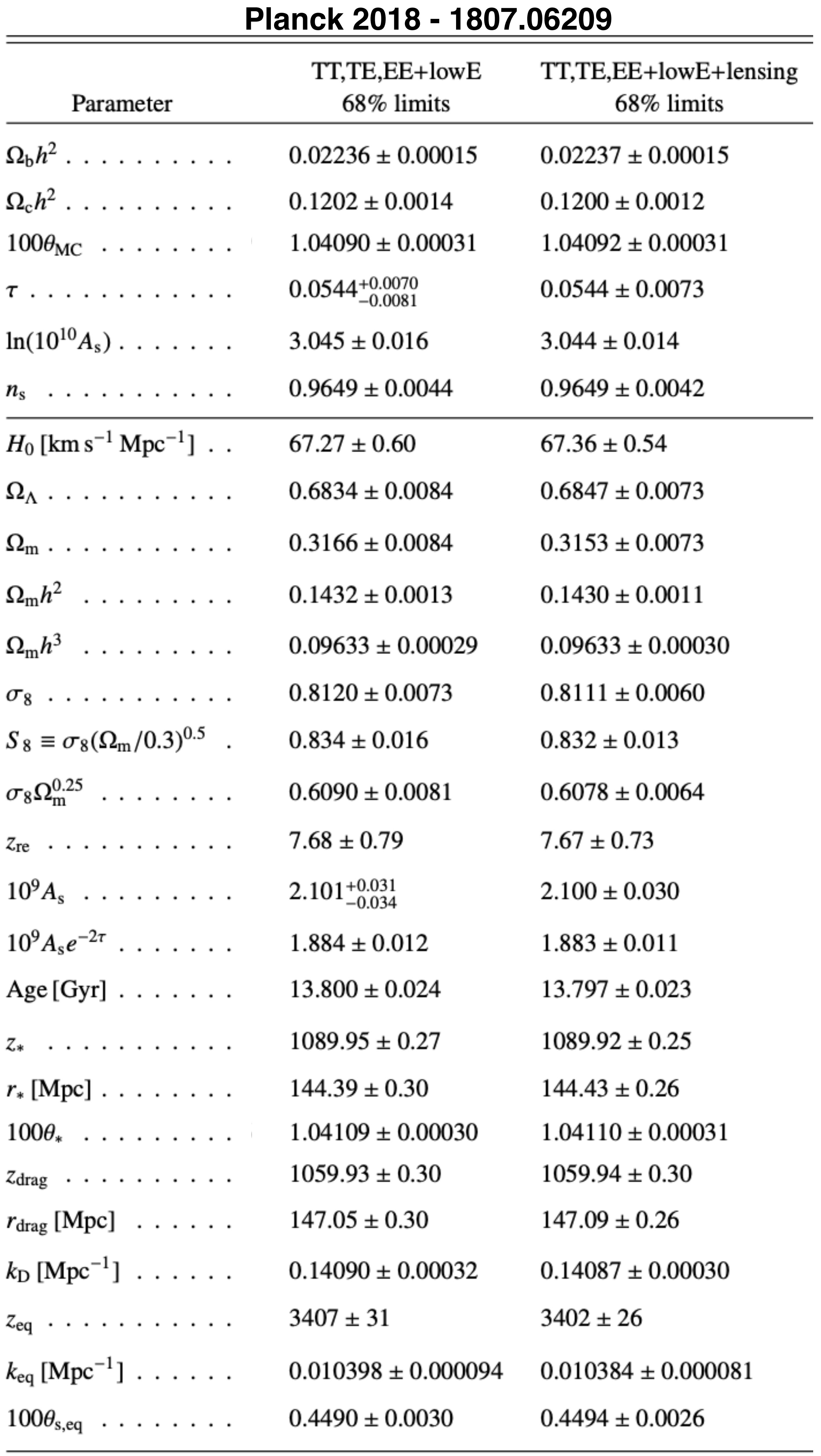


Temperature anisotropies



Polarization





Planck 2018 - 1807.06209

Parameter	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits
$\Omega_b h^2$	0.02236 ± 0.00015	0.02237 ± 0.00015
$\Omega_c h^2$	0.1202 ± 0.0014	0.1200 ± 0.0012
$100\theta_{MC}$	1.04090 ± 0.00031	1.04092 ± 0.00031
τ	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.045 ± 0.016	3.044 ± 0.014
n_s	0.9649 ± 0.0044	0.9649 ± 0.0042
H_0 [km s^{-1} Mpc^{-1}] . .	67.27 ± 0.60	67.36 ± 0.54
Ω_Λ	0.6834 ± 0.0084	0.6847 ± 0.0073
Ω_m	0.3166 ± 0.0084	0.3153 ± 0.0073
$\Omega_m h^2$	0.1432 ± 0.0013	0.1430 ± 0.0011
$\Omega_m h^3$	0.09633 ± 0.00029	0.09633 ± 0.00030
σ_8	0.8120 ± 0.0073	0.8111 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$.	0.834 ± 0.016	0.832 ± 0.013
$\sigma_8 \Omega_m^{0.25}$	0.6090 ± 0.0081	0.6078 ± 0.0064
z_{re}	7.68 ± 0.79	7.67 ± 0.73
$10^9 A_s$	$2.101^{+0.031}_{-0.034}$	2.100 ± 0.030
$10^9 A_s e^{-2\tau}$	1.884 ± 0.012	1.883 ± 0.011
Age [Gyr]	13.800 ± 0.024	13.797 ± 0.023
z_*	1089.95 ± 0.27	1089.92 ± 0.25
r_* [Mpc]	144.39 ± 0.30	144.43 ± 0.26
$100\theta_*$	1.04109 ± 0.00030	1.04110 ± 0.00031
z_{drag}	1059.93 ± 0.30	1059.94 ± 0.30
r_{drag} [Mpc]	147.05 ± 0.30	147.09 ± 0.26
k_D [Mpc^{-1}]	0.14090 ± 0.00032	0.14087 ± 0.00030
z_{eq}	3407 ± 31	3402 ± 26
k_{eq} [Mpc^{-1}]	0.010398 ± 0.000094	0.010384 ± 0.000081
$100\theta_{s,eq}$	0.4490 ± 0.0030	0.4494 ± 0.0026

① CMB ANOMALIES: A BRIEF MULTI-EXPERIMENT OVERVIEW

CMB VS CMB-INDEPENDENT PROBES

In the last years, some tensions between CMB and CMB-independent observations are emerging at different statistical levels

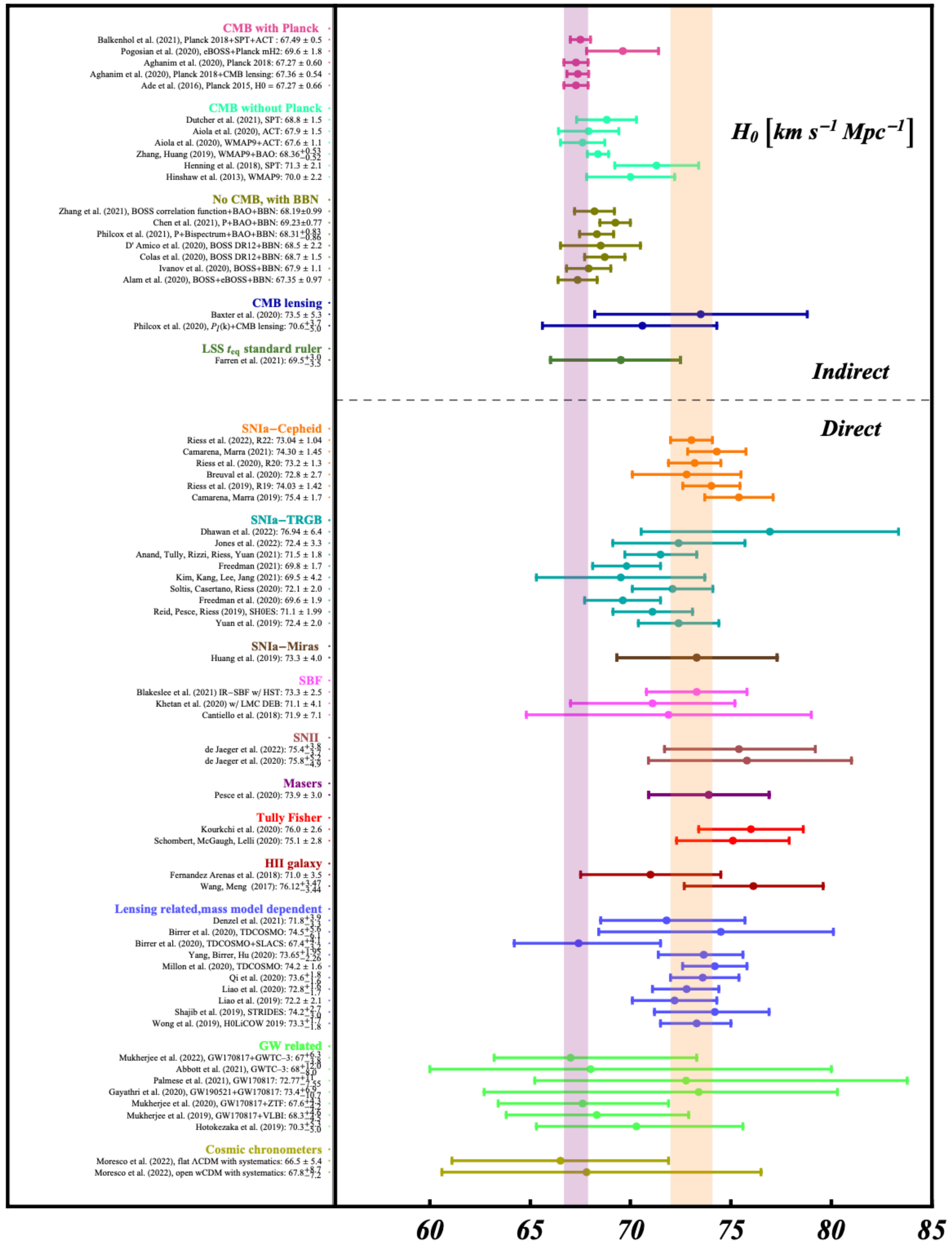
HUBBLE TENSION

The widely known tension between the value of the Hubble parameter as directly measured by using local distance ladder measurements of Type Ia supernova and the value inferred by CMB observations reached the level of 5 standard deviations

S8 AND SIGMA8

Other disagreements involve the value of matter clustering parameters (such as S8 and sigma8) as measured by Weak Lensing surveys (DES and Kids) and inferred by CMB observations

Snowmass - 2203.06142



68% CL constraint on the Hubble parameter from different cosmological probes

❶ CMB ANOMALIES: A BRIEF MULTI-EXPERIMENT OVERVIEW

CMB ANOMALIES

CMB observations have achieved sub-percent accuracy.

While this is a blessing, it also represents a challenge: as precision increases, any deviations or anomalies may become more statistically significant and point to tensions in our understanding of the Universe

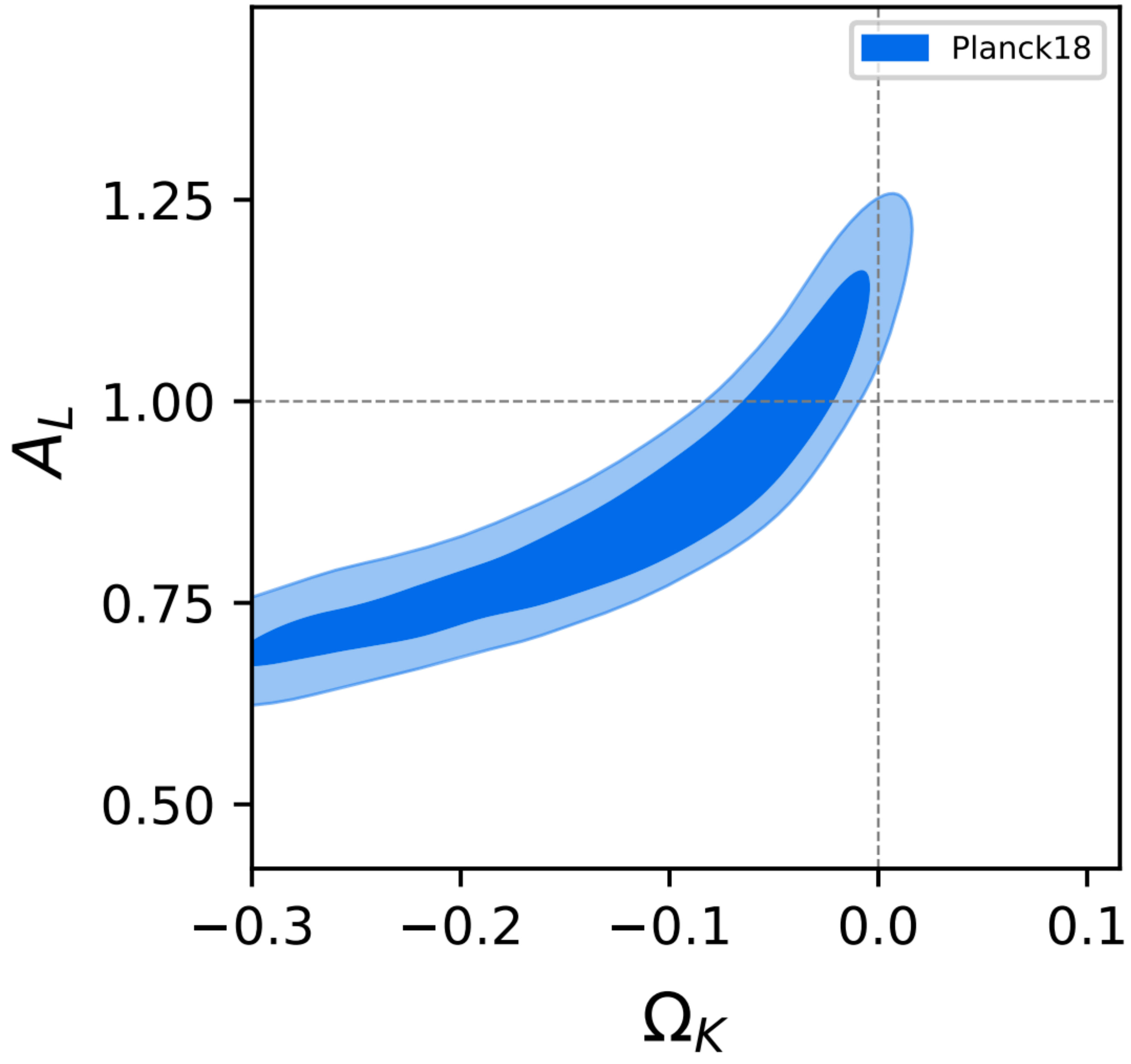
PLANCK

One notable example is the **higher lensing amplitude at about 2.8σ** observed in the Planck data.

Since more lensing is expected with more Cold Dark Matter (CDM), the lensing anomaly immediately recasts a preference for a closed Universe, which in turn helps to explain other large-scale anomalies in the data, such as the deficit of amplitude in the quadrupole and octupole modes.

Consequently, the final **Planck indication for a closed Universe** becomes very significant, **reaching the level of 3.4 standard deviations**

E. Di Valentino *et al,* - 1911.02087



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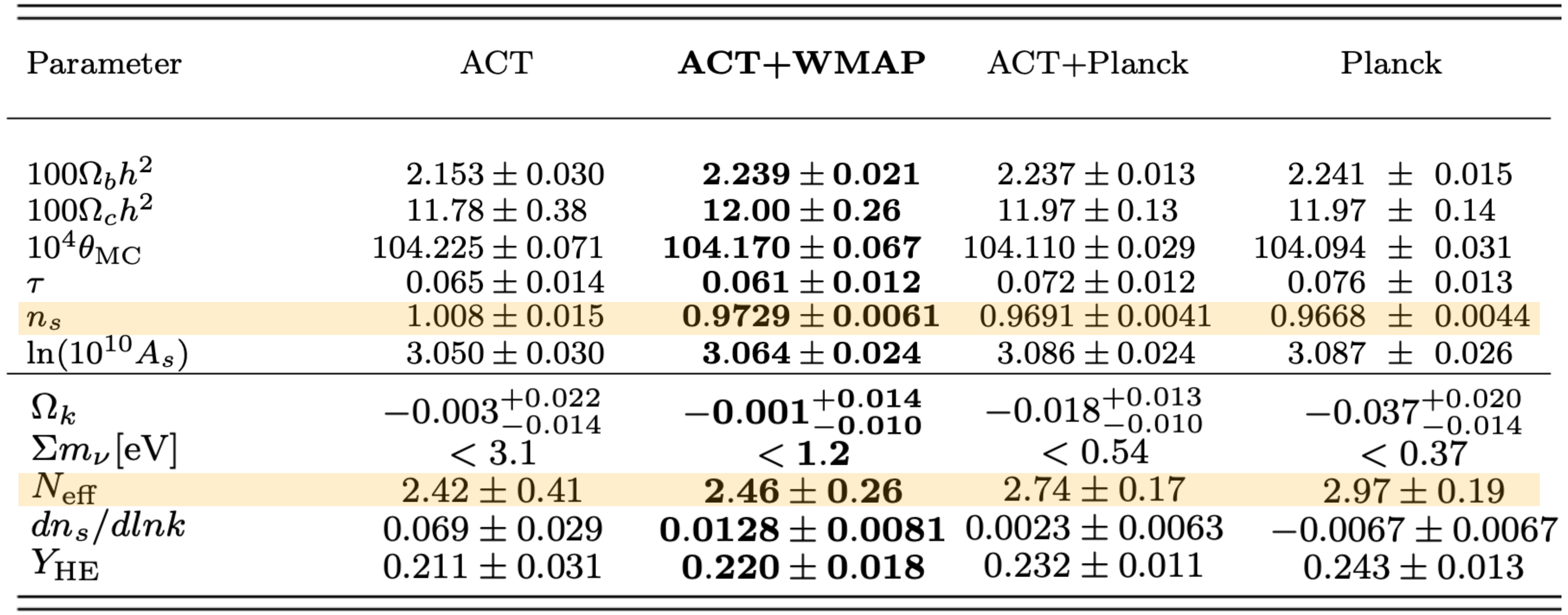
ACT

ACT (and SPT) data have provided full support for a spatially flat Universe and a lensing amplitude consistent with ΛCDM

However, the same ACT data have revealed other relevant deviations from the standard cosmological model:

- Preference for a unitary **spectral index** of primordial perturbations (in tension with Planck at 99.3% CL)
- A smaller **effective number of relativistic degrees of freedom** in the early Universe (in tension with the SM at ~2.5 standard deviations)
- An indication in favour of **Early Dark Energy** at 3 standard deviations

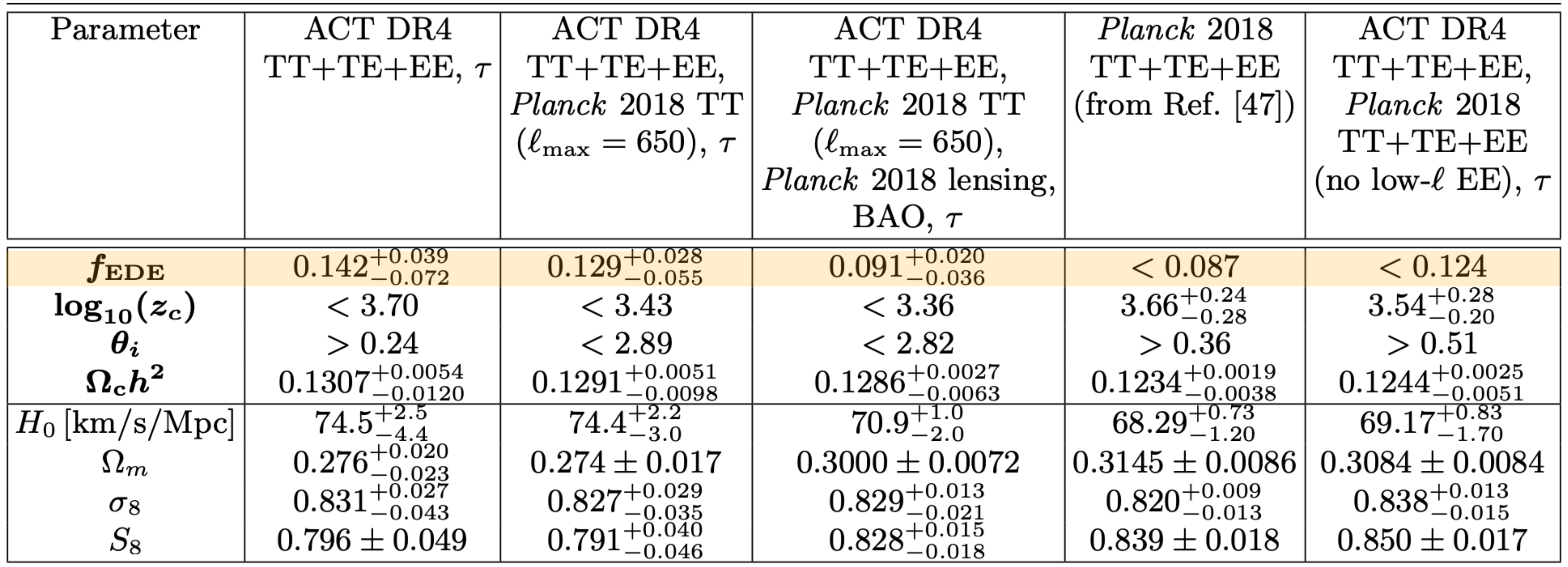
ACT-DR4 - 2007.07288



Parameter	ACT	**ACT+WMAP**	ACT+Planck	Planck
$100\Omega_b h^2$	2.153 ± 0.030	$\mathbf{2.239 \pm 0.021}$	2.237 ± 0.013	2.241 ± 0.015
$100\Omega_c h^2$	11.78 ± 0.38	$\mathbf{12.00 \pm 0.26}$	11.97 ± 0.13	11.97 ± 0.14
$10^4\theta_{\rm MC}$	104.225 ± 0.071	$\mathbf{104.170 \pm 0.067}$	104.110 ± 0.029	104.094 ± 0.031
τ	0.065 ± 0.014	$\mathbf{0.061 \pm 0.012}$	0.072 ± 0.012	0.076 ± 0.013
n_s	1.008 ± 0.015	$\mathbf{0.9729 \pm 0.0061}$	0.9691 ± 0.0041	0.9668 ± 0.0044
$\ln(10^{10} A_s)$	3.050 ± 0.030	$\mathbf{3.064 \pm 0.024}$	3.086 ± 0.024	3.087 ± 0.026
Ω_k	$-0.003^{+0.022}_{-0.014}$	$\mathbf{-0.001^{+0.014}_{-0.010}}$	$-0.018^{+0.013}_{-0.010}$	$-0.037^{+0.020}_{-0.014}$
$\Sigma m_\nu[\rm eV]$	< 3.1	$\mathbf{< 1.2}$	< 0.54	< 0.37
$N_{\rm eff}$	2.42 ± 0.41	$\mathbf{2.46 \pm 0.26}$	2.74 ± 0.17	2.97 ± 0.19
$dn_s/dlnk$	0.069 ± 0.029	$\mathbf{0.0128 \pm 0.0081}$	0.0023 ± 0.0063	-0.0067 ± 0.0067
$Y_{\rm HE}$	0.211 ± 0.031	$\mathbf{0.220 \pm 0.018}$	0.232 ± 0.011	0.243 ± 0.013

J. Colin Hill *et al,* - 2109.04451

Constraints on EDE ($n = 3$)



Parameter	ACT DR4 TT+TE+EE, τ	ACT DR4 TT+TE+EE, *Planck* 2018 TT ($\ell_{\rm max} = 650$), τ	ACT DR4 TT+TE+EE, *Planck* 2018 TT ($\ell_{\rm max} = 650$), *Planck* 2018 lensing, BAO, τ	*Planck* 2018 TT+TE+EE (from Ref. [47])	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	$3.66^{+0.24}_{-0.28}$	$3.54^{+0.28}_{-0.20}$
$\boldsymbol{\theta_i}$	> 0.24	< 2.89	< 2.82	> 0.36	> 0.51
$\boldsymbol{\Omega_c h^2}$	$0.1307^{+0.0054}_{-0.0120}$	$0.1291^{+0.0051}_{-0.0098}$	$0.1286^{+0.0027}_{-0.0063}$	$0.1234^{+0.0019}_{-0.0038}$	$0.1244^{+0.0025}_{-0.0051}$
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

② Global Consistency of CMB experiments

Evaluating the global consistency

What makes CMB anomalies difficult to interpret ***individually*** is that different experiments often point in discordant directions, and none of the most relevant deviations can be cross-validated through independent probes.

Accurate statistical methods have been developed to quantify the ***global*** agreement between experiments under a given model of cosmology

W. Handley and P. Lemos, - 2007.08496

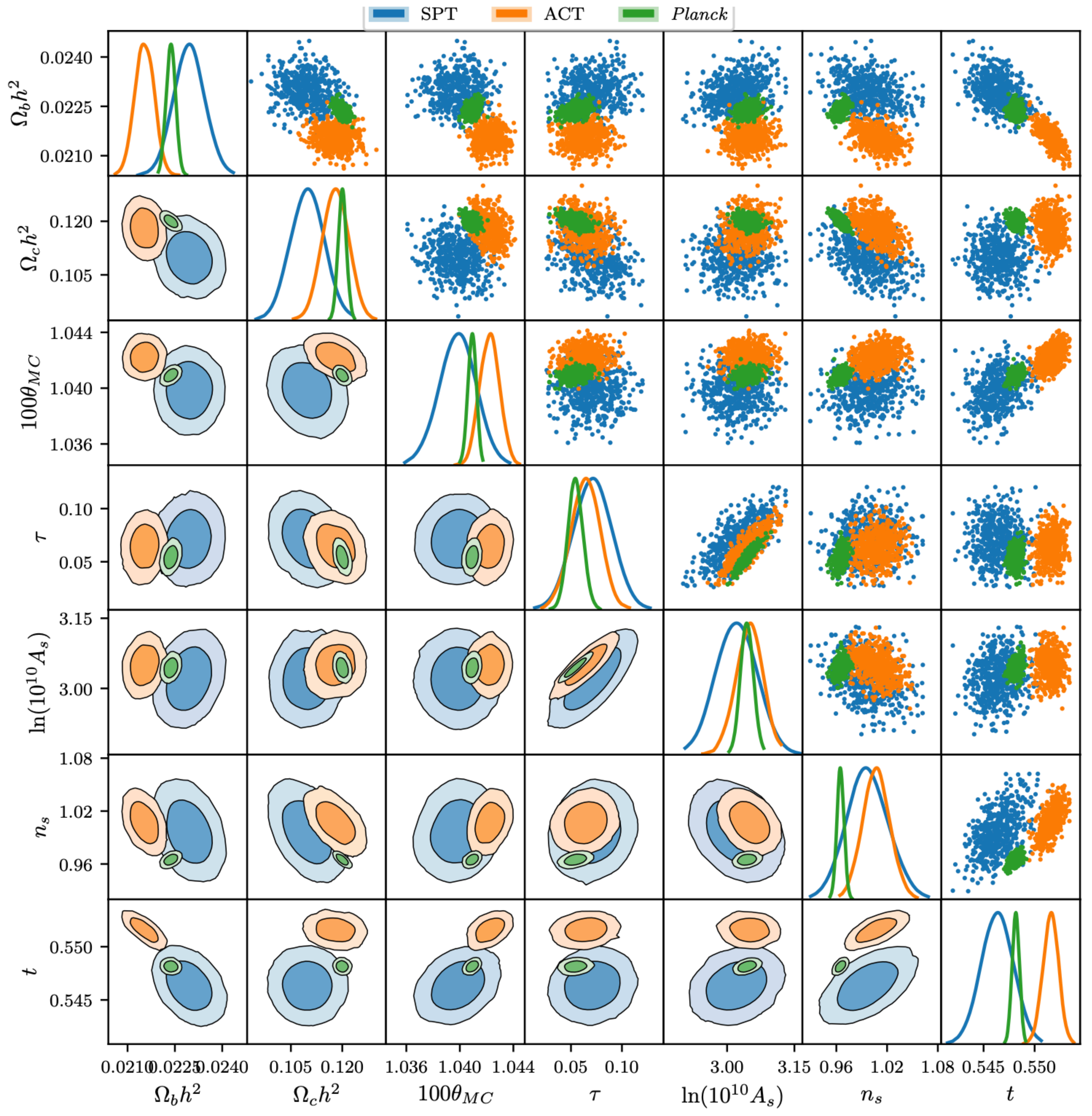
Dataset combination	χ^2	p	tension	$\log S$
ACT vs *Planck*	17.2	0.86%	2.63σ	-5.60
ACT vs SPT	15.4	1.77%	2.37σ	-4.68
Planck vs SPT	9.1	16.82%	1.38σ	-1.55
ACT vs *Planck*+SPT	18.4	0.52%	2.79σ	-6.22

Rerum cognoscere causas

Important to acquire a clear understanding of the **limitations of current data** and the **uncertainties in the cosmological model.**

This becomes a crucial need in relation to the **Hubble tension** as many proposed solutions call for a new paradigm shift in cosmology while relying almost entirely on the resilience of such observations.

W. Handley and P. Lemos, - 2007.08496



② Global Consistency of CMB experiments

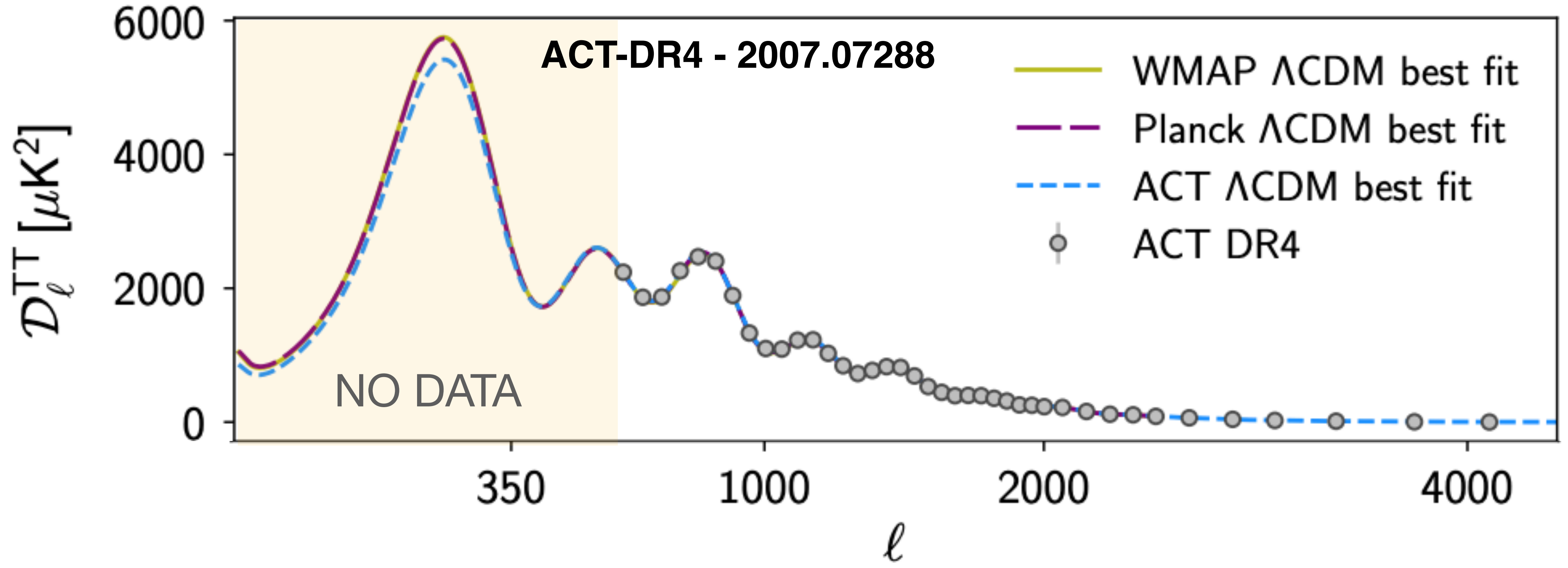
The limitations of current data

Assuming a ΛCDM cosmology, the main source of tension between ACT and Planck arises from the measurements of the **scalar spectral index** and the **baryon energy density**

If we believe these differences to emerge from limitations in the data, a logical step is to identify which (missing) part of the dataset is responsible for the discrepancy

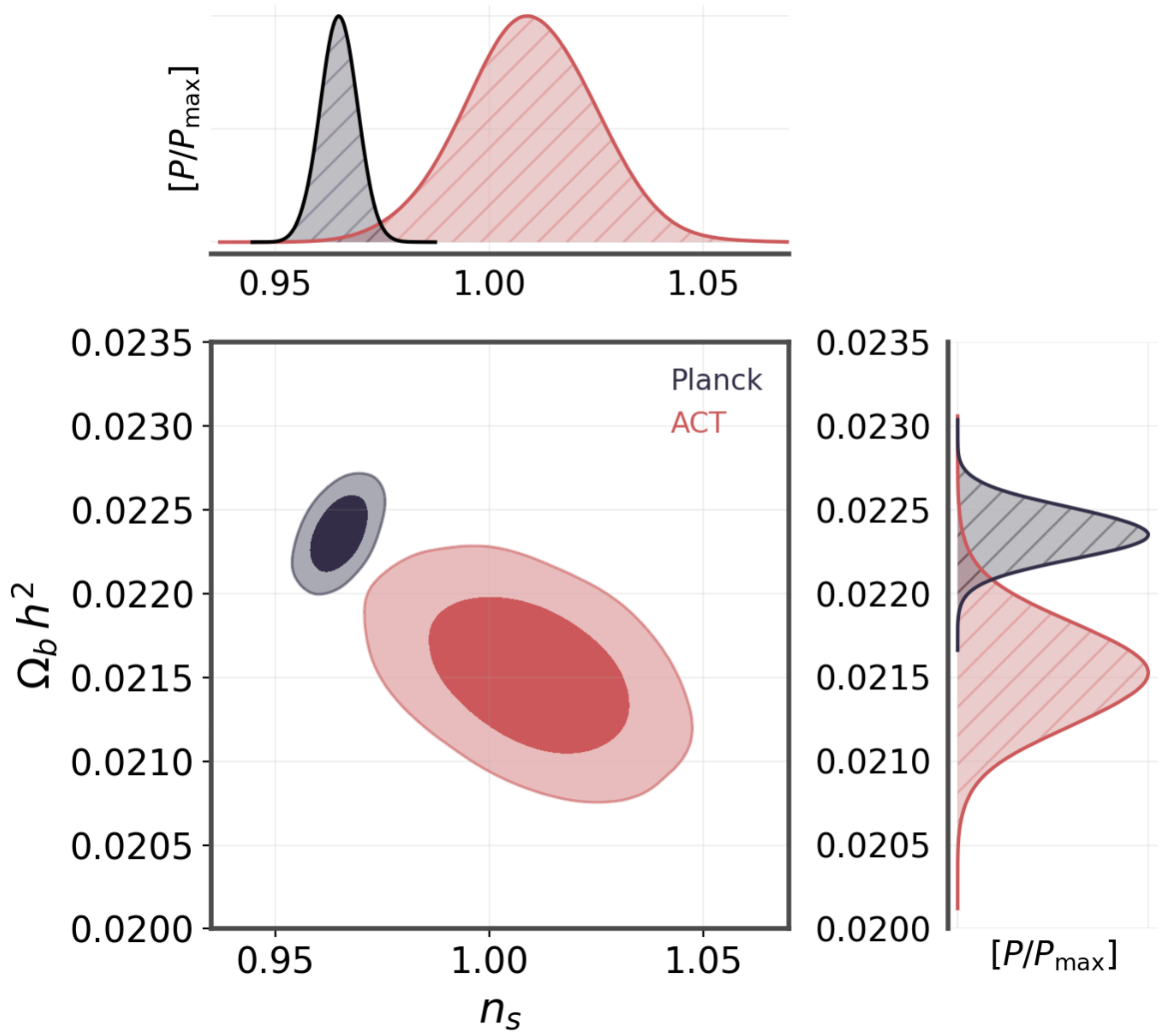
ACT Temperature data

In the **absence of data around the first two acoustic peaks**, there is a strong degeneracy between $\Omega_b h^2$ and n_s as a lower value of the former can be mimicked by a larger value of the latter



ACT-DR4 - 2007.07288

WG *et al,* - 2210.09018



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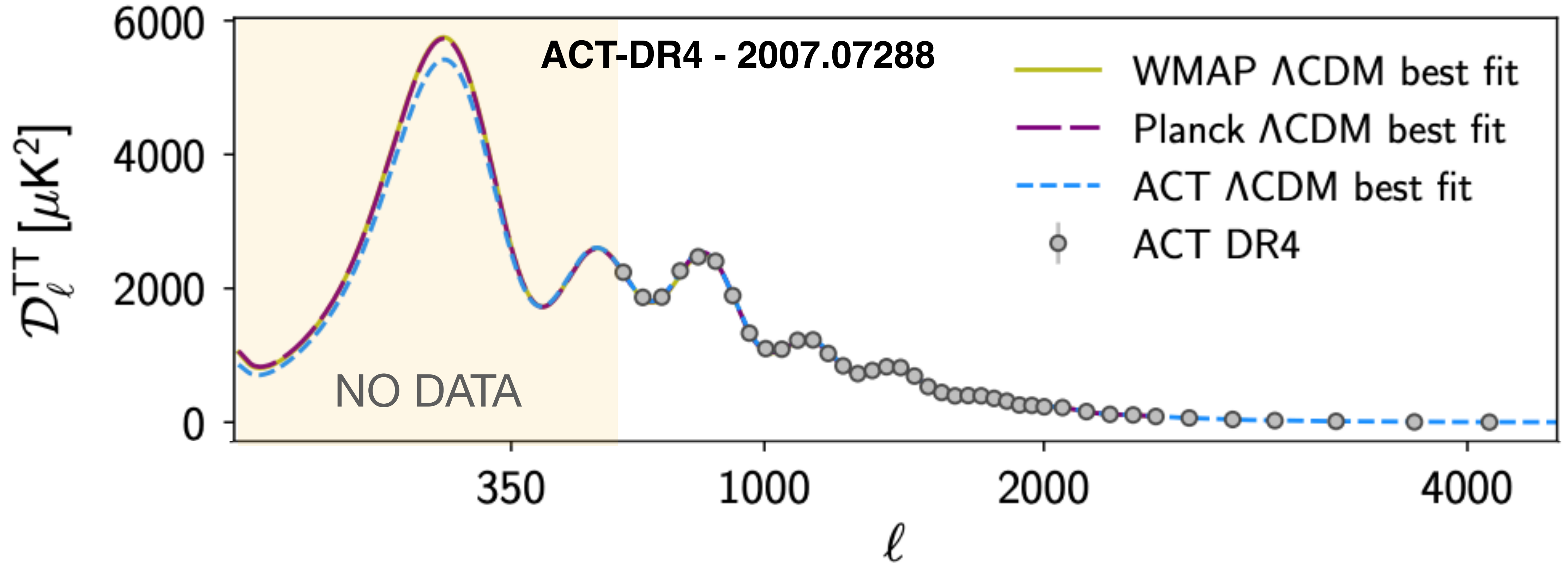
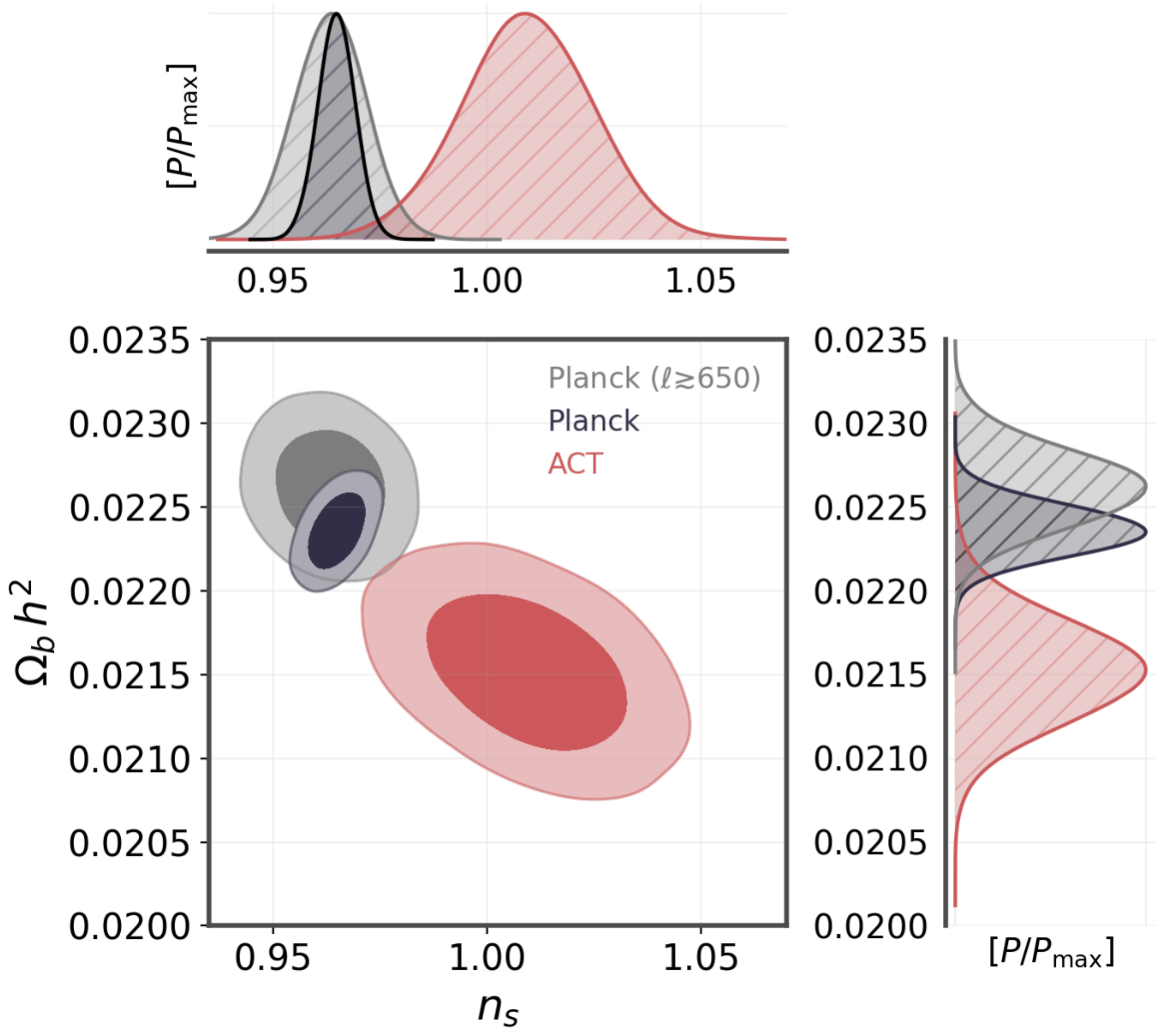


WG *et al*, - 2210.09018



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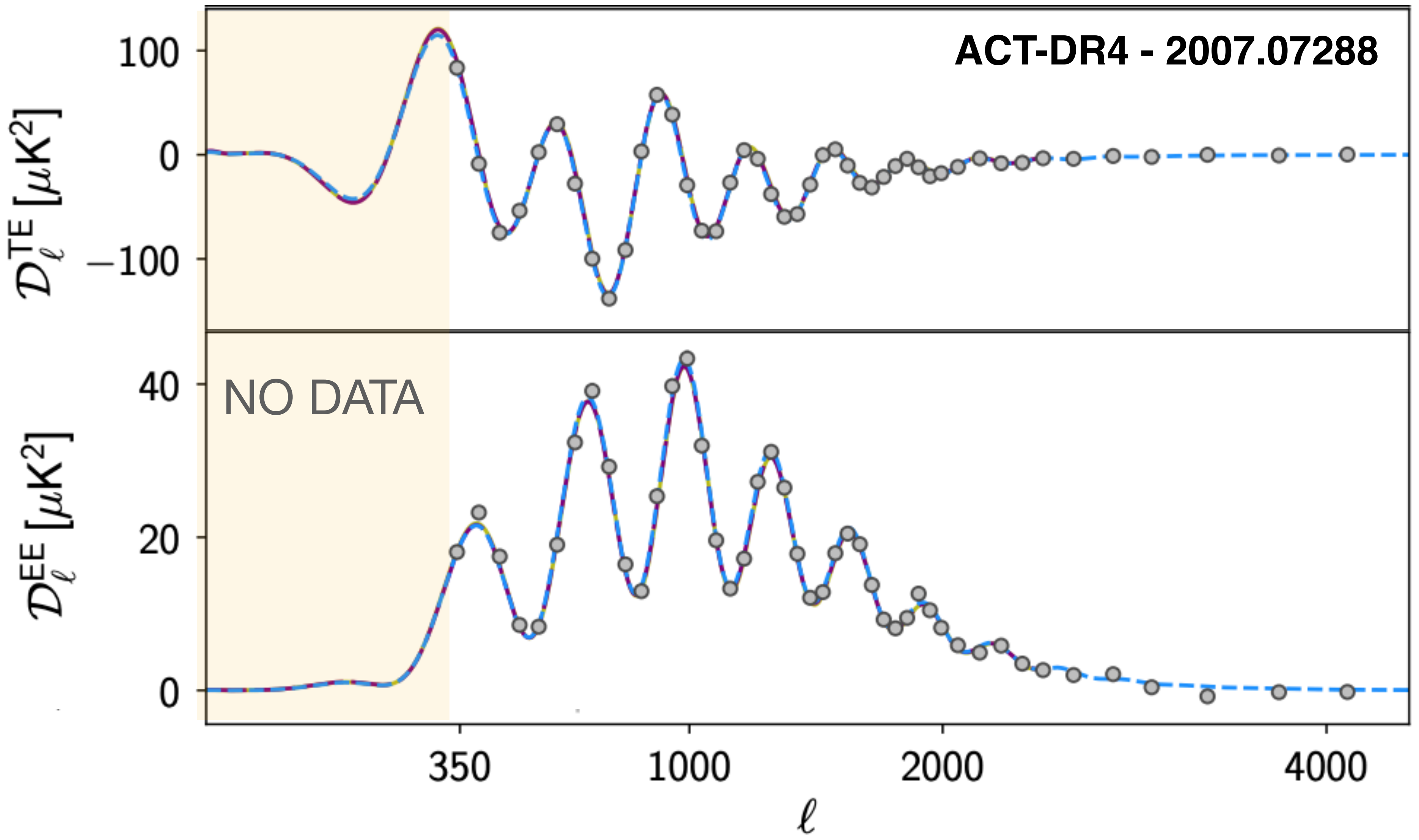
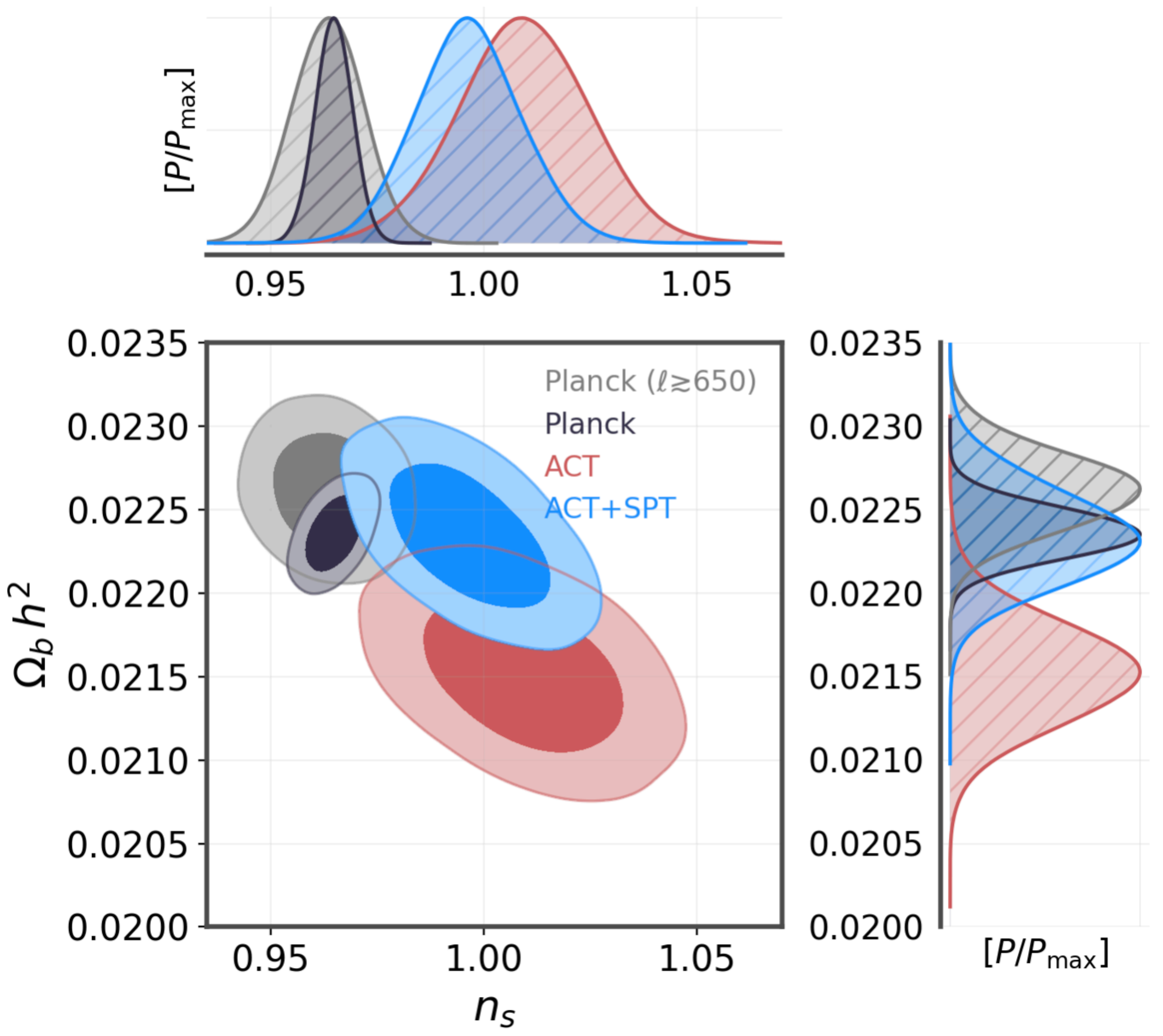
ACT Polarization data

The same for polarization. Is the disagreement coming from TE and/or EE ?



ACT-DR4 - 2007.07288

WG *et al*, - 2210.09018



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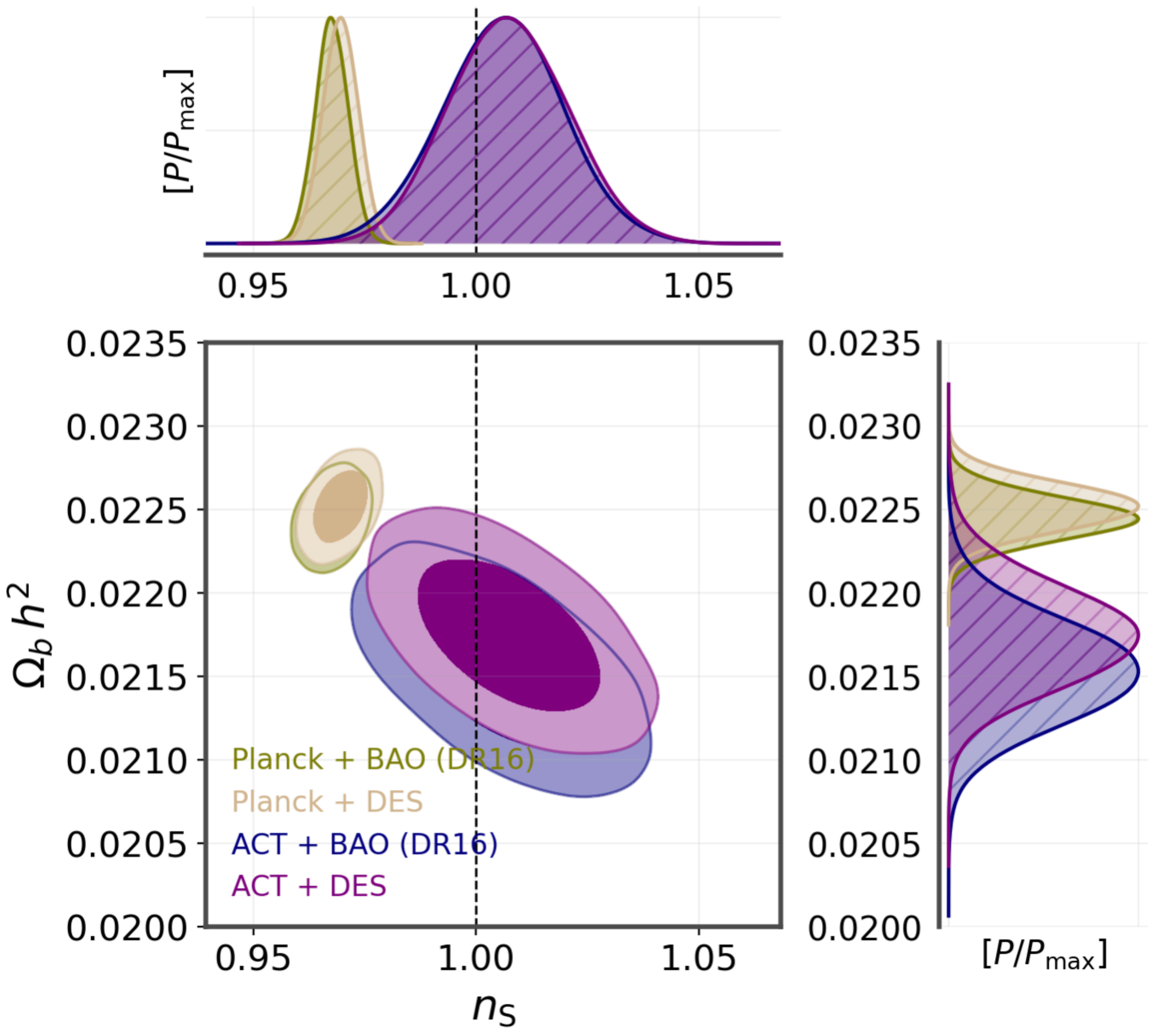
Astrophysical Data

Yet another possibility is to break the geometrical degeneracy among cosmological parameters by using astrophysical observations such as

- Baryon Acoustic Oscillation (BAO) and Redshift Space Distortion (RSD)
- Galaxy clustering and cosmic shear observations from DES

In this case, **including local Universe measurements** does not change the results significantly but leads to tighter errors and **increases the difference**



WG *et al,* - 2210.09018

② GLOBAL CONSISTENCY OF CMB EXPERIMENTS

WG - 2305.16919

THE UNKNOWNS OF THE COSMOLOGICAL MODEL

The value of cosmological parameters inferred from the CMB data clearly depends on the cosmological model and its assumptions.

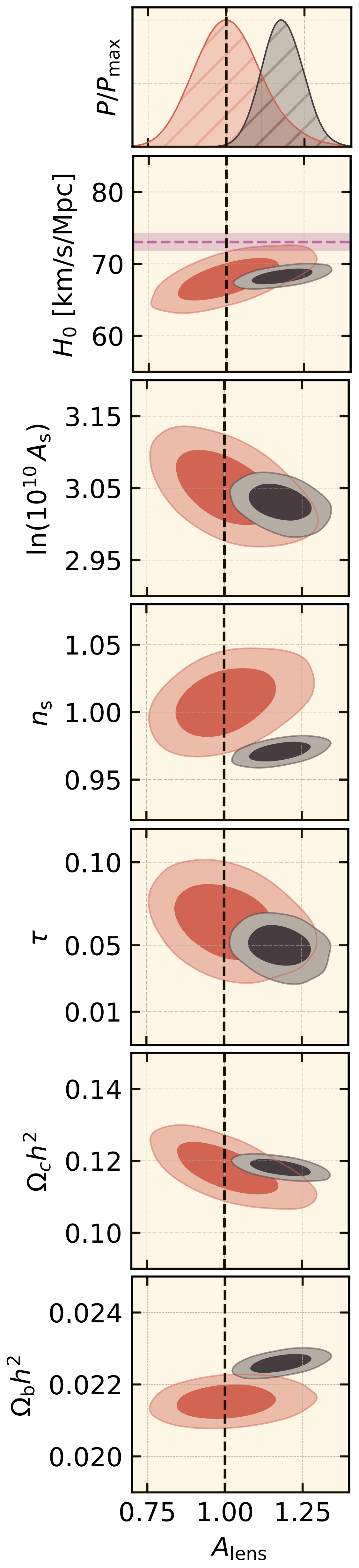
Therefore, a possibility usually explored when finding anomalies in the cosmological parameter values, is to extend the baseline cosmology and study how the results change.

LENSING AMPLITUDE

- **Planck** measures a larger lensing amplitude which is in disagreement at ~ 2.8 standard deviations with ΛCDM ($A_{\rm lens}$=1)

- **ACT** is instead perfectly consistent with $A_{\rm lens}$=1 (despite larger errors)

Planck-2018 vs **ACT-DR4** Constraints on Parameters



2 Global Consistency of CMB experiments

WG - 2305.16919

The Unknowns of the cosmological model

The value of cosmological parameters inferred from the CMB data clearly depends on the cosmological model and its assumptions.

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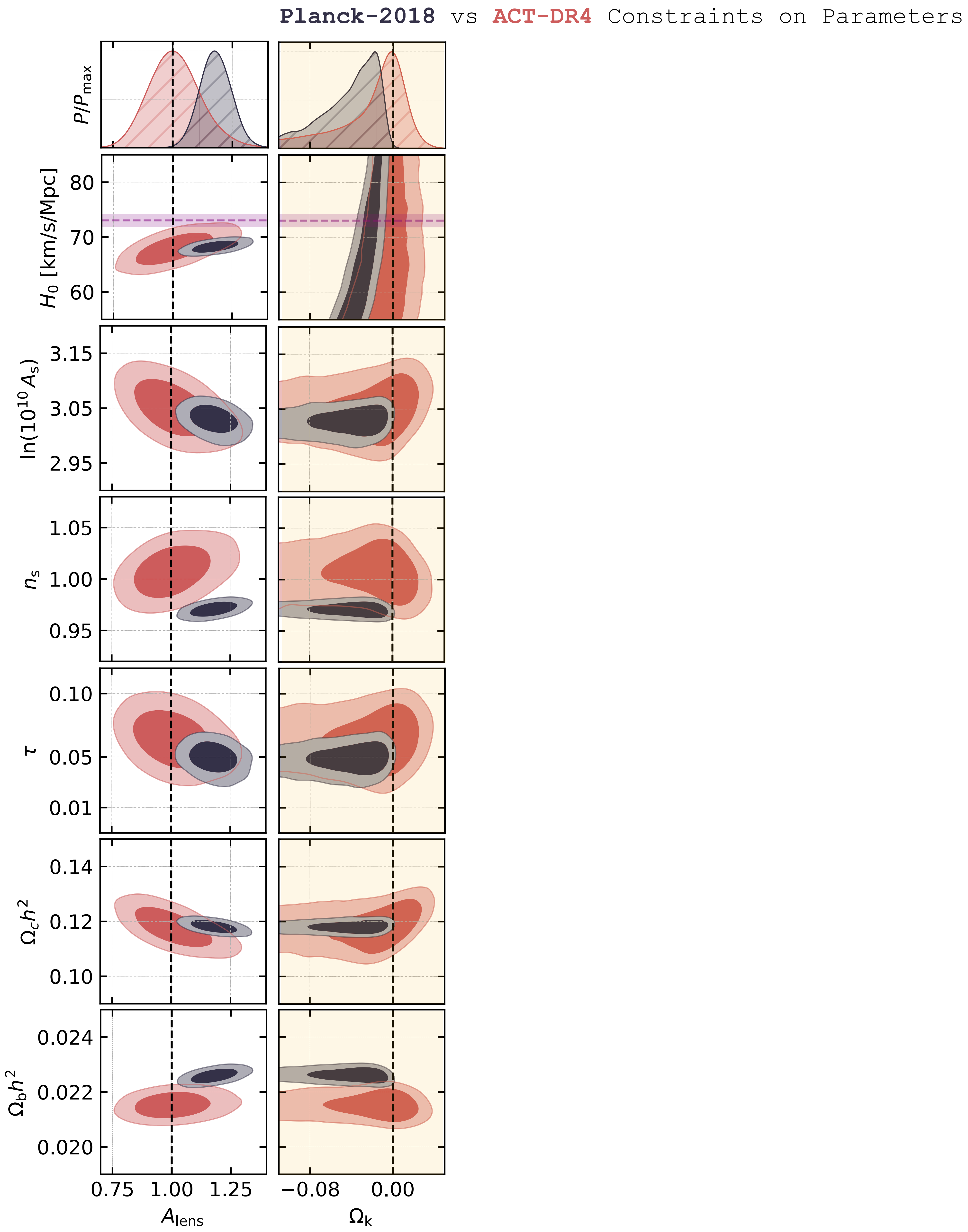
Curvature

- **Planck** gives a ~3.4 standard deviations preference for a closed Universe
- **ACT** is in perfect agreement with spatial flatness (despite larger errors)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WG - 2305.16919

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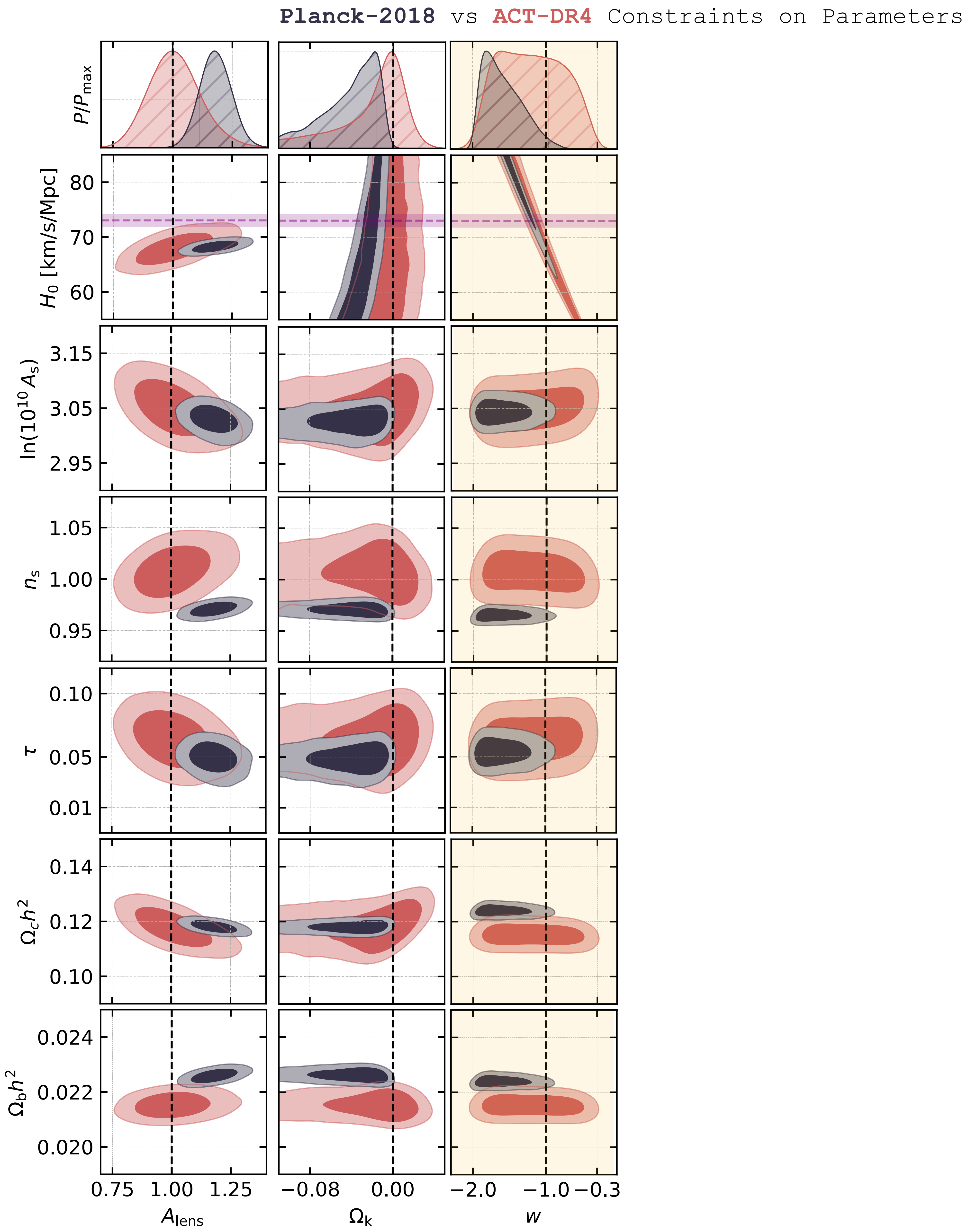
Dark Energy

- **Planck** gives a ~95% CL indication for a phantom equation of state (w<-1)
- **ACT** is in good agreement with the cc value w=-1 (despite larger errors)



Planck-2018 vs **ACT-DR4** Constraints on Parameters

2 GLOBAL CONSISTENCY OF CMB EXPERIMENTS

WG - 2305.16919

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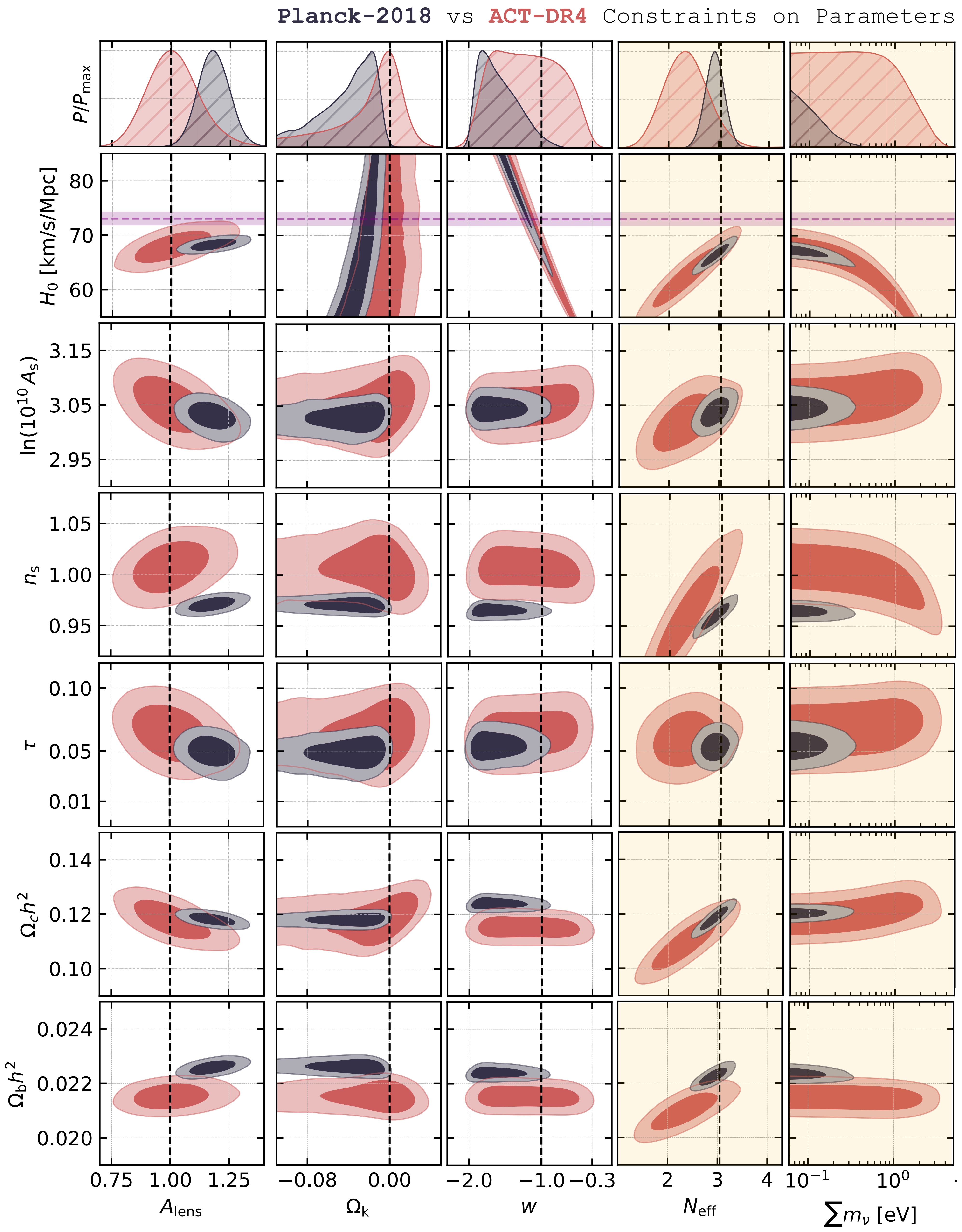
DARK MATTER AND NEUTRINOS

- **Planck** is very constraining on the total neutrino mass, and in perfect agreement with the SM about N_{eff}
- **ACT** is less constraining on the total neutrino mass and in disagreement with the SM about N_{eff} at~2.5 standard deviations



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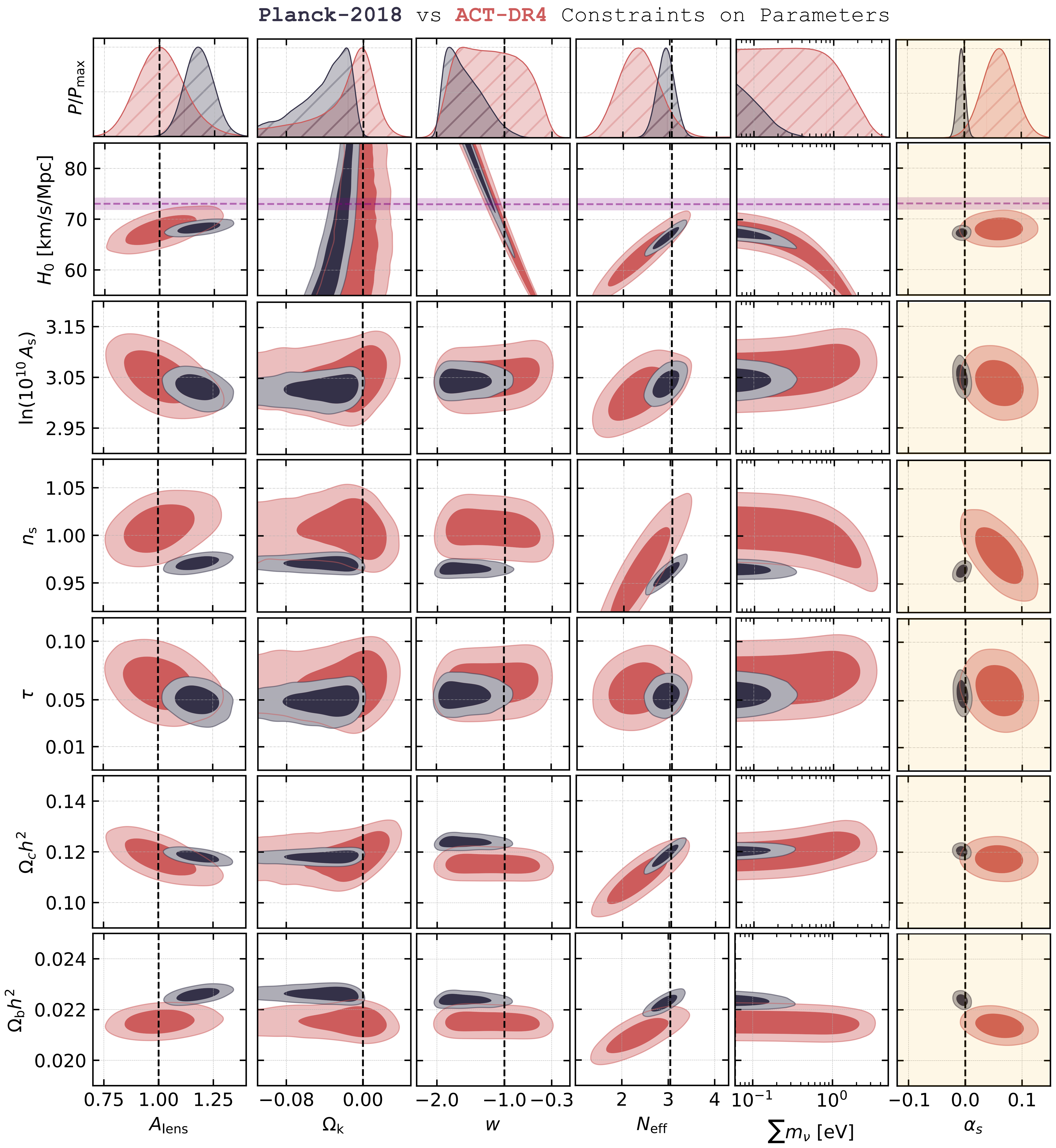
INFLATION

- **Planck** gives no evidence for a running of the spectral index (while mildly preferring negative small values)

- **ACT** gives a preference for a positive running of the spectral index at 2.5 standard deviations



Planck-2018 vs **ACT-DR4** Constraints on Parameters

② GLOBAL CONSISTENCY OF CMB EXPERIMENTS

WG - 2305.16919

THE UNKNOWNS OF THE COSMOLOGICAL MODEL

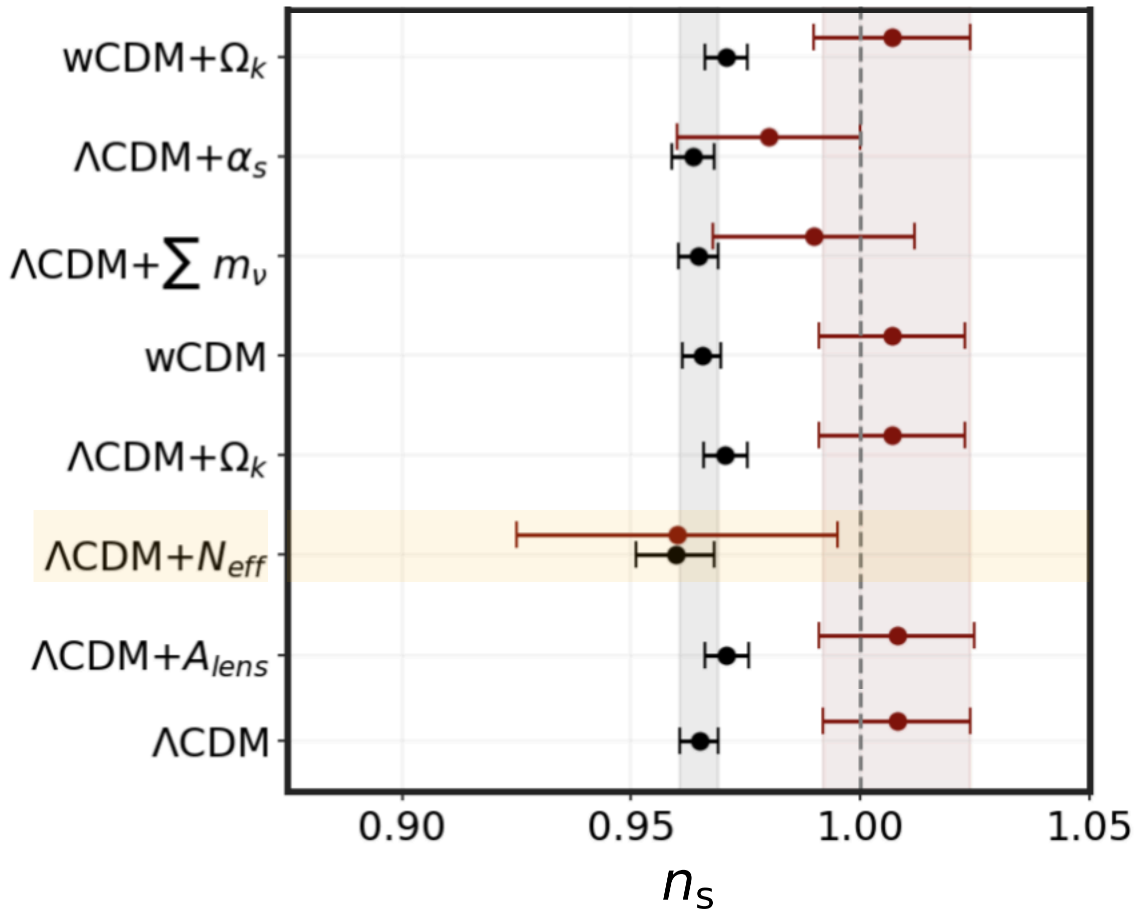
The ***global*** "tension" between the two experiments, isn't significantly reduced

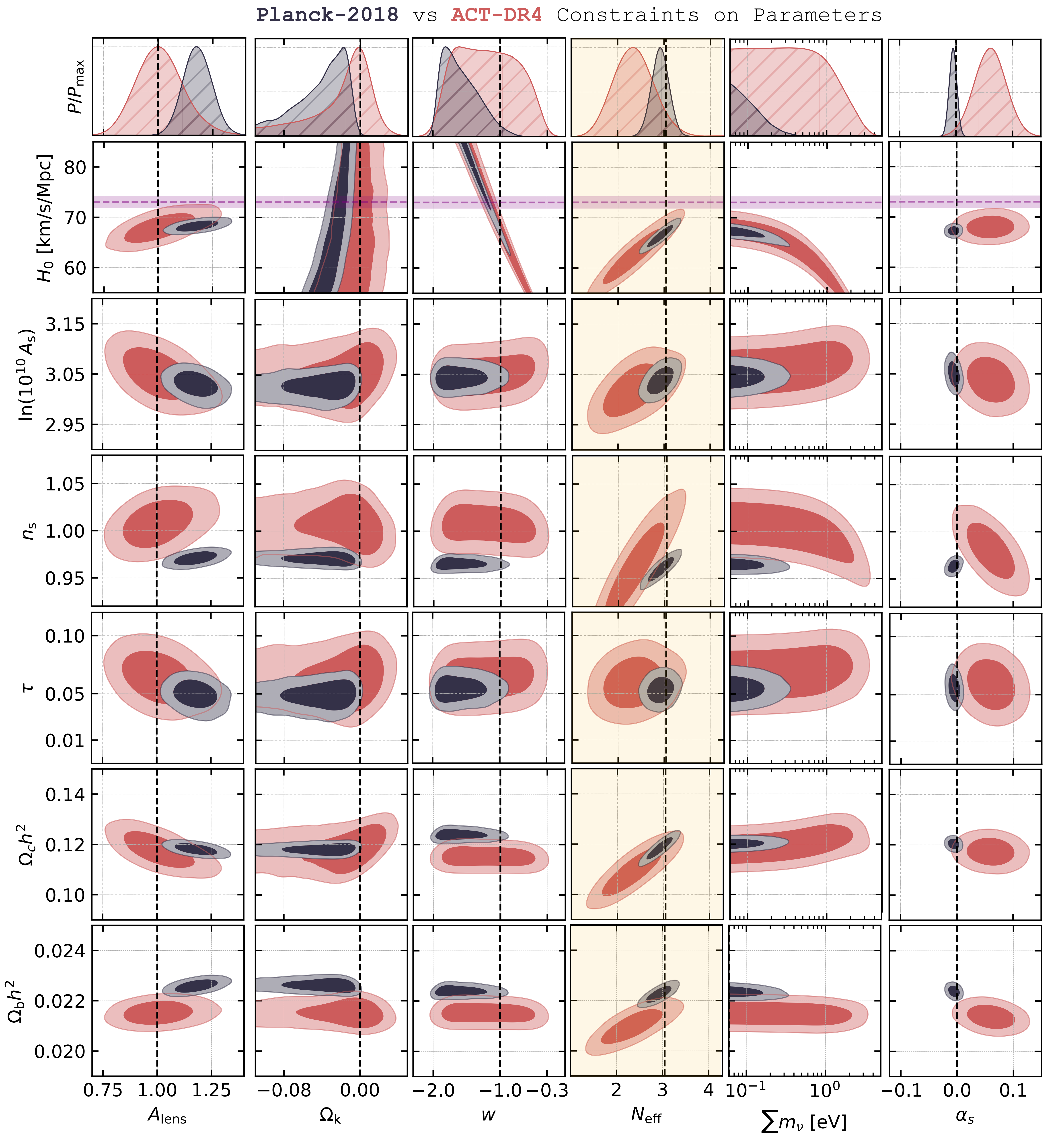
E. Di Valentino, WG, *et al* - 2209.14054

Cosmological model	d	χ^2	p	$\log S$	Tension
ΛCDM + $A_{\rm lens}$	7	18.5	0.00977	−5.77	2.58 σ
ΛCDM + Ω_k	7	16.5	0.0209	−4.75	2.31 σ
wCDM	7	16.8	0.0187	−4.9	2.35 σ
ΛCDM + $N_{\rm eff}$	7	13	0.0719	−3	1.80 σ
ΛCDM + $\sum m_\nu$	7	20.7	0.00421	−6.86	2.86 σ
ΛCDM + α_s	7	20.6	0.00448	−6.78	2.84 σ

A part when the effective number of relativistic particles is significantly less than the standard value…

WG *et al,* - 2210.09018





② Global Consistency of CMB experiments

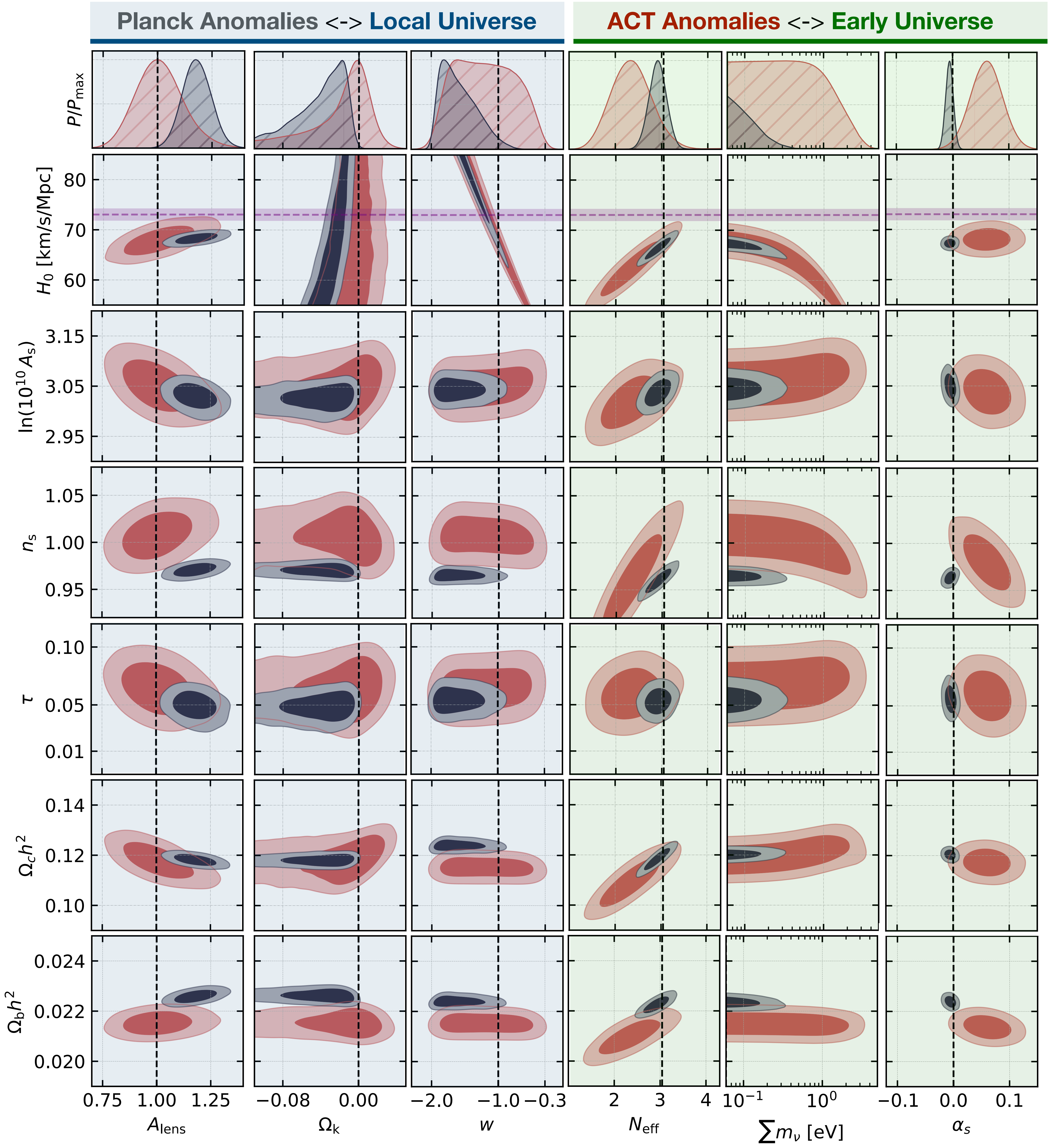
WG - 2305.16919

How Many Early-Late time Mismatches Are There?

- **Planck** anomalies ***always*** involve parameters associated with the **local Universe** such as the lensing amplitude, the spacetime geometry, and the dark energy equation of state. **[Cleaned away by Astrophysical data!]**

- **ACT** anomalies ***always*** involve parameters associated with the ***early Universe*** such as the baryon energy density, the spectral index, its running, and $N_{\rm eff}$. **[NOT cleaned away by Astrophysical data!]**

Considering also the large experimental uncertainties obtained when extending the late-time sector of the theory, **the difference** between the two probes **remains mostly caused by a mismatch in the early Universe.**



3 Implications for the Hubble Tension

How do we Measure H_0 for the CMB?

- The angular size of the sound horizon (θ_s)
- The baryon density ($\Omega_b h^2$)
- The cold dark matter density ($\Omega_c h^2$)

Model of Early Universe

$$r_s = \int_{z_{CMB}}^{\infty} dz \, \frac{c_s(z)}{H(z)}$$

- The sound horizon (r_s)
- The Distance from the CMB ($D_A = r_s / \theta_s$)

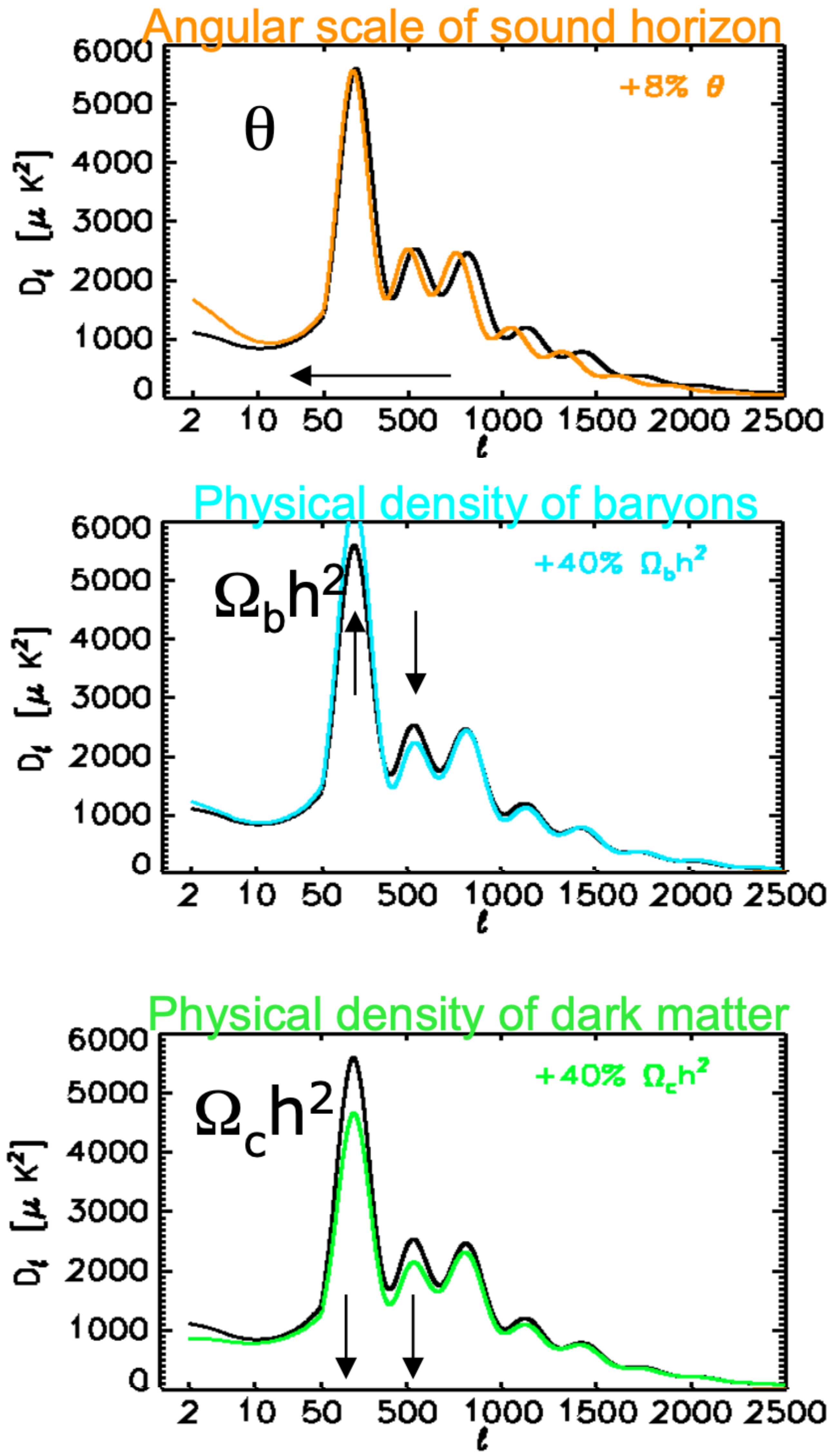
Model of Late Universe

$$D_A(z_{CMB}) = \int_0^{z_{CMB}} dz \, H(z)^{-1}$$

$$H^2(z) = H_0^2 \left[\Omega_m (1+z)^3 + \Omega_{\mathrm{DE}} (1+z)^{3(1+w)} + \ldots\right]$$

- <u>The Hubble Parameter (H_0)</u>

S. Galli
'The H_0 debate form a CMB prospective'



3 Implications for the Hubble Tension

Late Time Solutions

Given the sound horizon and the distance from the CMB we can try to change the late-time (i.e., post recombination) expansion to get a different H₀:

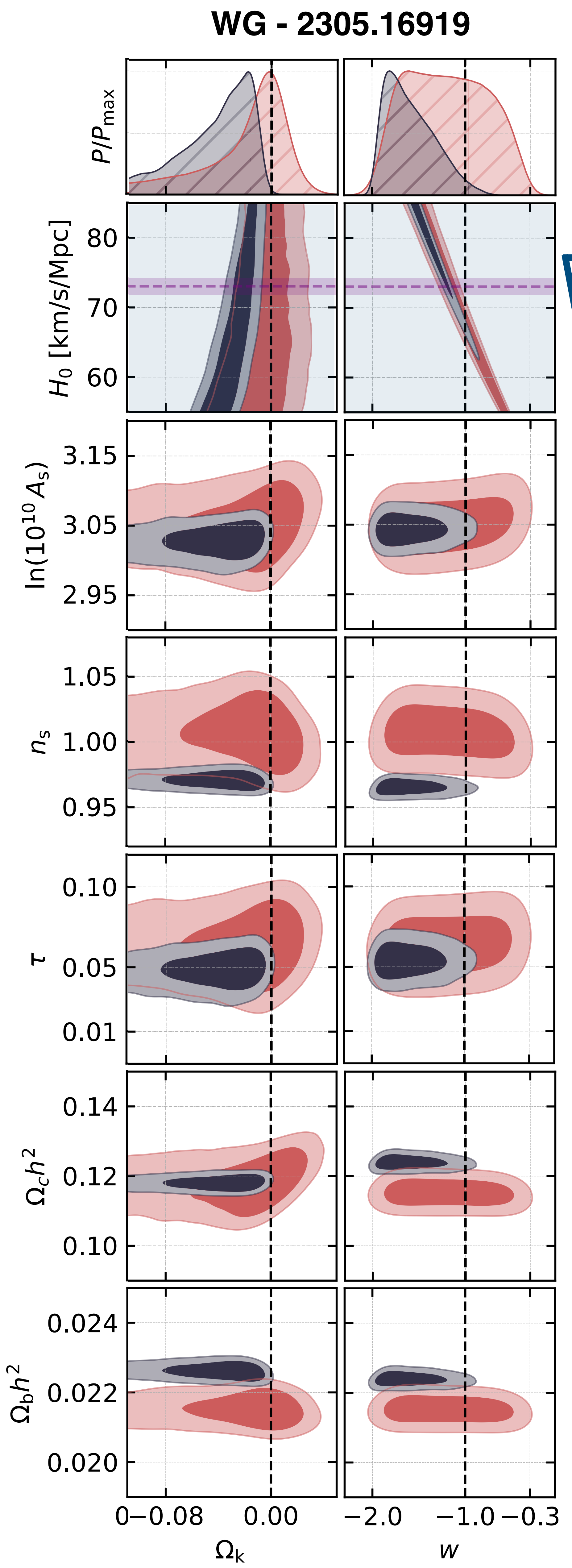
$$D_A(z_{CMB}) = \int_0^{z_{CMB}} dz\, H(z)^{-1}$$

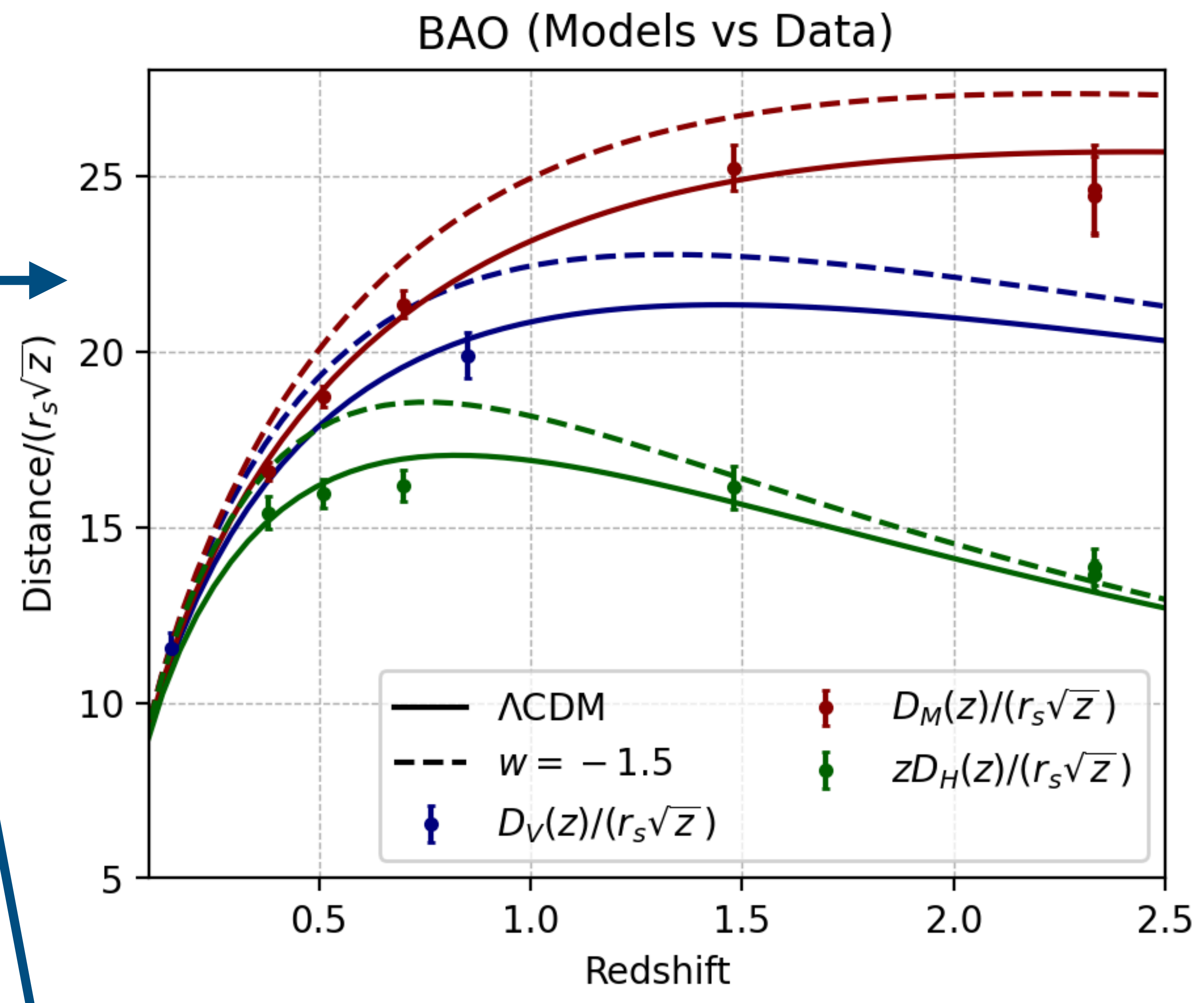
$$H^2(z) = H_0^2\left[\Omega_m(1+z)^3 + \Omega_{\rm DE}(1+z)^{3(1+w)} + \ldots\right]$$

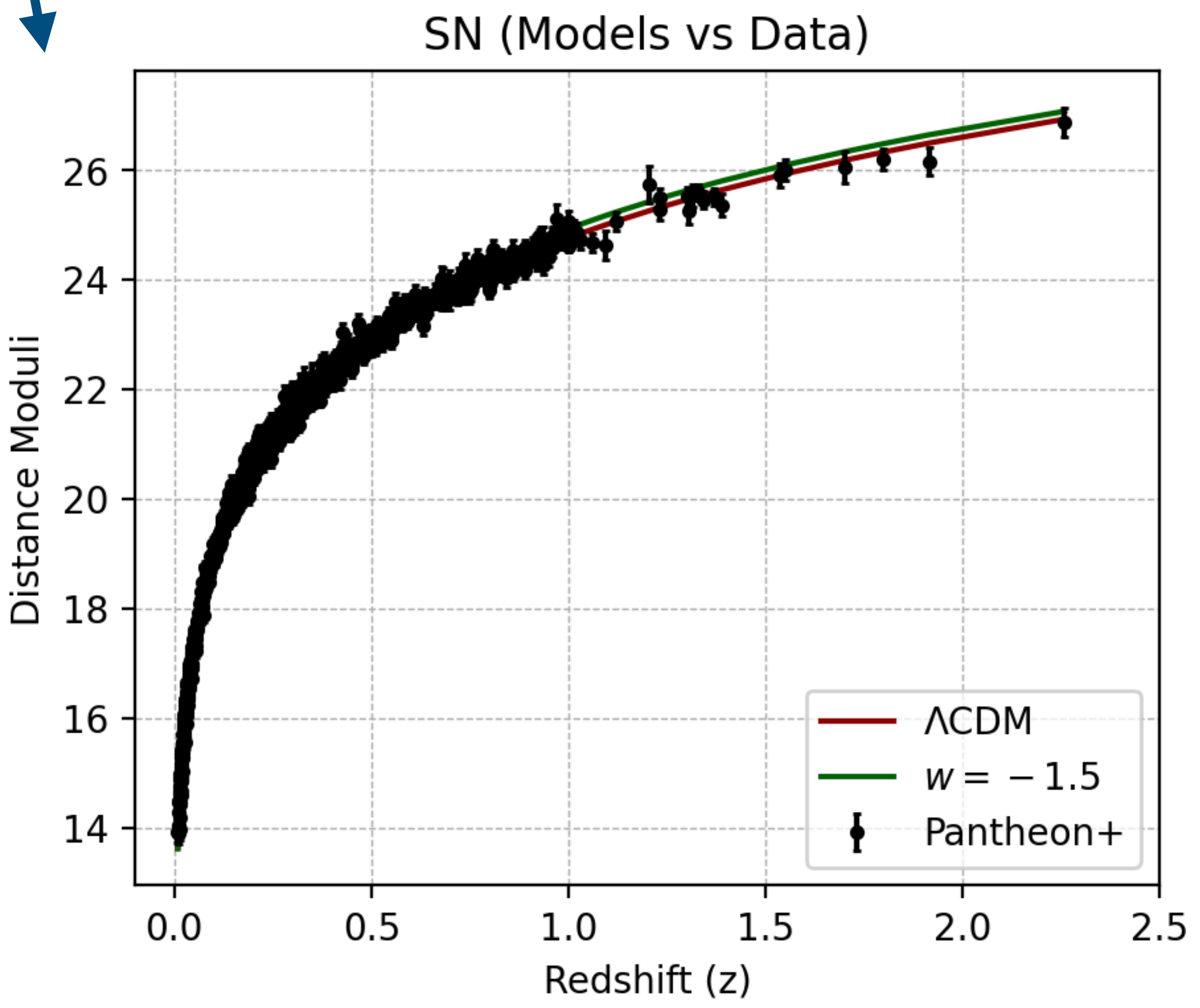
One might expect these solutions to be preferred by data, given the significant room left by the CMB observations for new physics at late-times.

Instead when including local probes there is **very little room to accommodate new physics at late-times.**

In any case, it is **unlikely that the tension between ACT and Planck will have a significant impact** on these solutions since these experiments primarily disagree at early times.







③ Implications for the Hubble Tension

Early Time Solutions

Considering **new physics in early Universe** to change the physical size of the sound horizon

$$r_s = \int_{z_{CMB}}^{\infty} dz \, \frac{c_s(z)}{H(z)}$$

Many indications of this kind of new early-time physics arise when combining multiple CMB measurements (such as Planck and ACT), without finding clear cross-validation when these experiments are considered separately

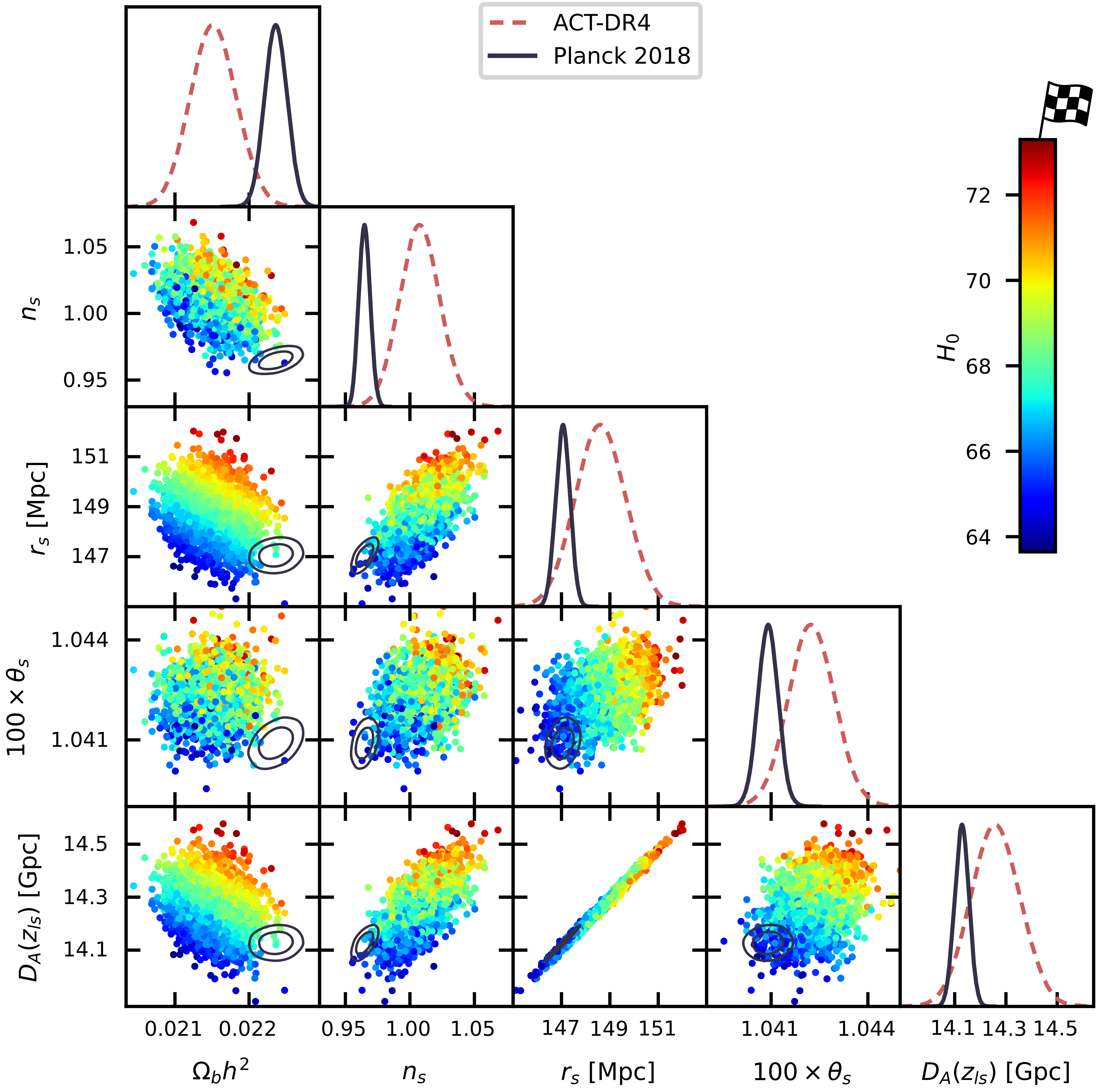
ACT allows for greater flexibility in accommodating higher values of the sound horizon.

Planck peaks where ACT prefers very low values of H_0.

Increasing H_0 requires moving towards the region of the parameter space where the disagreement becomes more significant.

The spectral index and the Hubble constant (and the sound horizon) are all positively correlated: increasing H_0 naturally pushes n_s towards higher values

WG - 2305.16919



Conclusions

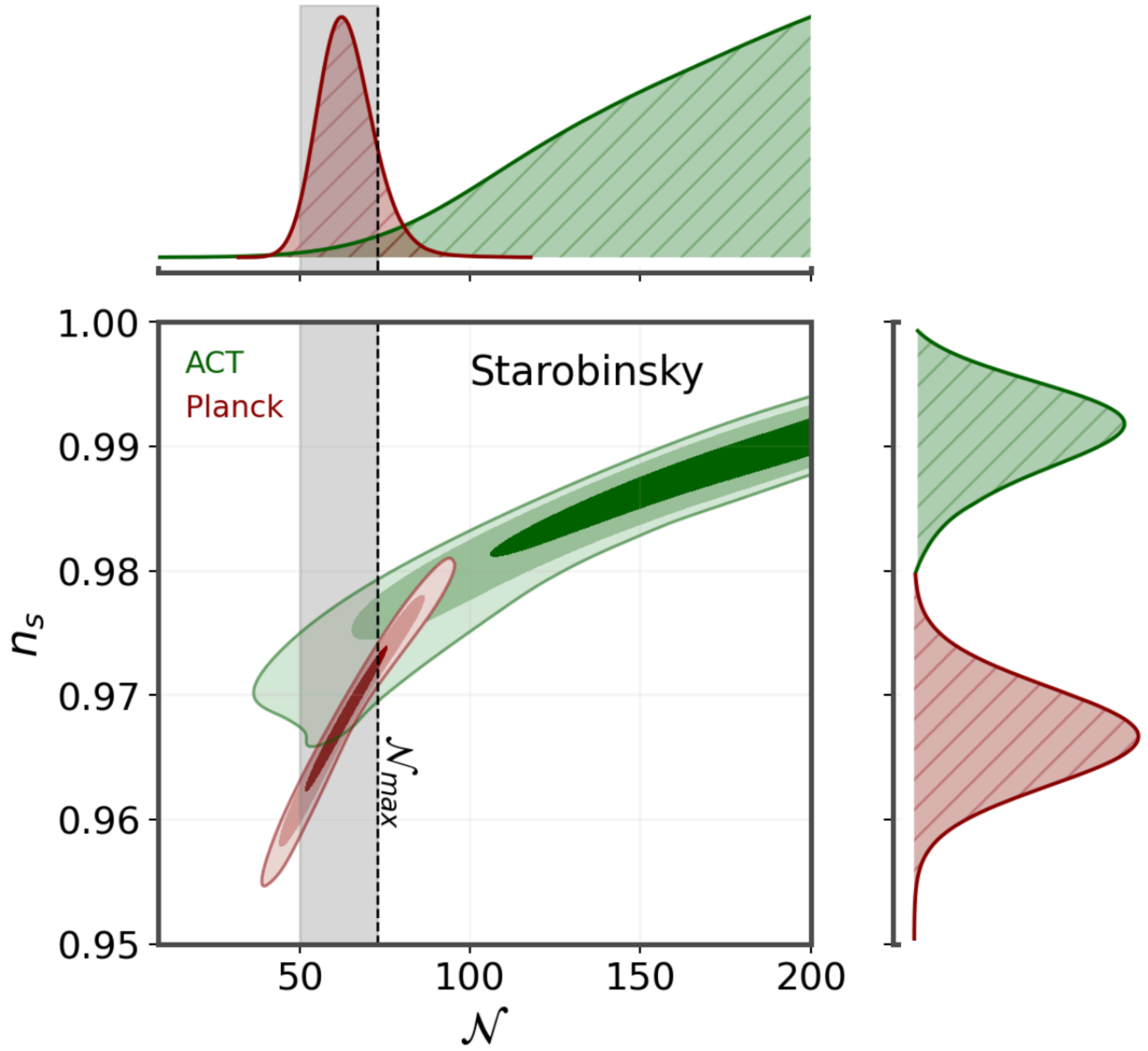
① CMB Anomalies: a brief multi-experiment overview

- There is a ***global*** “tension” between ACT and Planck that can be quantified at the level of ~2.6 σ

② Global Consistency of CMB experiments

- It can reflect limitations in the current data or new physics in the cosmological model.
- It warrants further investigations if we aim to use these data to study fundamental physics

Example →



WG, *et. al.* - 2305.15378

③ Implications for the Hubble Tension

- The tension between ACT and Planck is mainly driven by a **mismatch in the early Universe** parameters

Possible solutions to H₀	**ACT**	**PLANCK**
Early Universe **New physics at early times?**	**Deviations** from ΛCDM, in **tension** with Planck ↓ **Hints** for new physics	**Agreement** with ΛCDM ↓ **No clear evidence** for new physics
Late Universe **New physics at late times?**	**Agreement** with ΛCDM ↓ **Little room** when local probes are considered	**Deviations** from ΛCDM (**erased** by local probes) ↓ **Little room** when local probes are considered

Thank you!