A crisis in the standard cosmological model?

December 7th, 2020
Progress on Old and New Themes in cosmology
(PONT 2020)

Eleonora Di Valentino
Institute of Advanced Study,
Addison-Wheeler fellow
Durham University (UK)

The Standard cosmological model

The model that has now practically been selected as the "standard" cosmological model is the Lambda Cold Dark Matter (ΛCDM) model, that provides an amazing description of a wide range of astrophysical and astronomical data.
Over the last few years, the parameters governing the ΛCDM scenario have been constrained with unprecedented accuracy.

However, despite its incredible success, ΛCDM still cannot explain key concepts in our understanding of the structure and evolution of the Universe, now based on unknown quantities. At the moment, their physical evidence comes solely from cosmology without strong theoretical motivations. In addition, the ΛCDM model is based on the choice of three, very specific, solutions for these unknown quantities, mostly motivated by computational simplicity. In fact, the theoretical predictions under ΛCDM for several observables are, in general, easier to compute and include fewer free parameters than most other solutions.

The Standard cosmological model

Unknown quantities:

- an early stage of accelerated expansion (Inflation) which produces the initial, tiny, density perturbations, needed for structure formation.
- a clustering matter component to facilitate structure formation (Dark Matter),
- an energy component to explain the current stage of accelerated expansion (Dark Energy).

Specific solutions for ΛCDM:

- Inflation is given by a single, minimally coupled, slow-rolling scalar field;
- Dark Matter is a pressureless fluid made of cold, i.e., with low momentum, and collisionless particles;
- Dark Energy is a cosmological constant term.

Warning!

Therefore, the 6 parameter ΛCDM model can be rightly considered, at best, as an approximation to a more realistic scenario that still needs to be fully understood. With the increase in experimental sensitivity, observational evidence for deviations from ΛCDM is, therefore, expected.

And, actually, anomalies and tensions between model dependent observations at early cosmological time and direct observations at late cosmological time are present with different statistical significance.

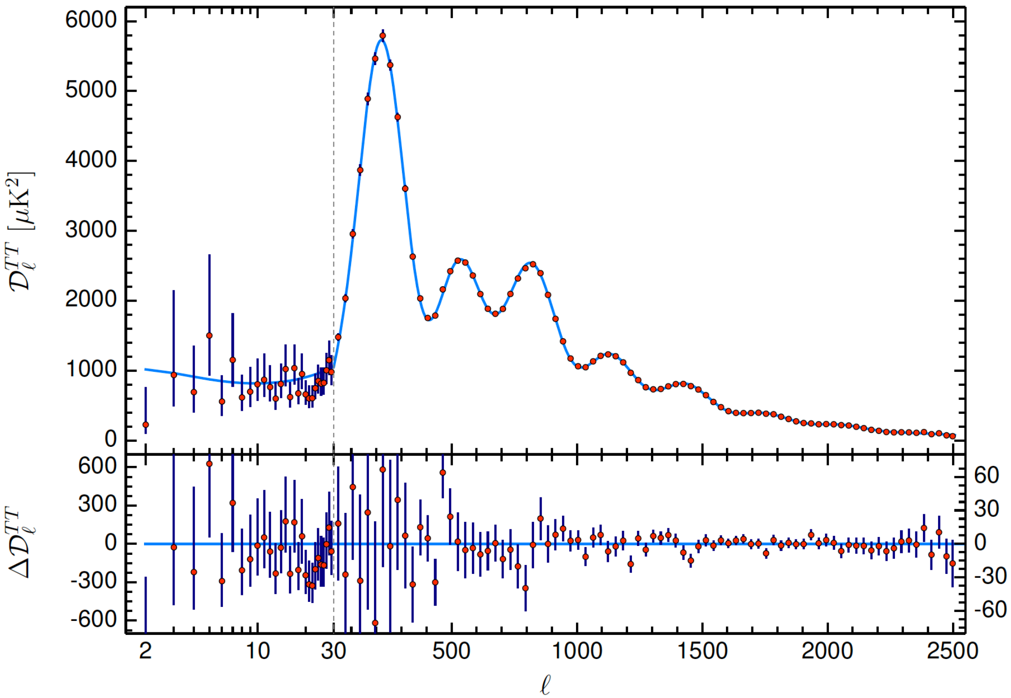
While some proportion of these discrepancies may have a systematic origin, their magnitude and persistence across probes strongly hint at cracks in the standard cosmological scenario and the need for new physics. In other words, if not due to systematics, the current anomalies could represent a crisis for the standard cosmological model and their experimental confirmation can bring a revolution in our current ideas of the structure and evolution of the Universe.

These tensions can indicate a failure in ΛCDM model.

CMB constraints

Most of the anomalies and tensions are involving the Planck data.

Parameter	TT+lowE	TE+lowE	EE+lowE	TT,TE,EE+lowE	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$					0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$					0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$					1.04092 ± 0.00031	1.04101 ± 0.00029
τ					0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$					3.044 ± 0.014	3.047 ± 0.014
n_s					0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [km s^{-1} Mpc^{-1}] .					67.36 ± 0.54	67.66 ± 0.42
Ω_Λ					0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m					0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$					0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$					0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8					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!

Silvia's talk for more details!

The most statistically significant and persisting anomalies and tensions of the CMB are:

- H0 with local measurements
- S8 with cosmic shear data
- A_L internal anomaly
- Ω_K different from zero

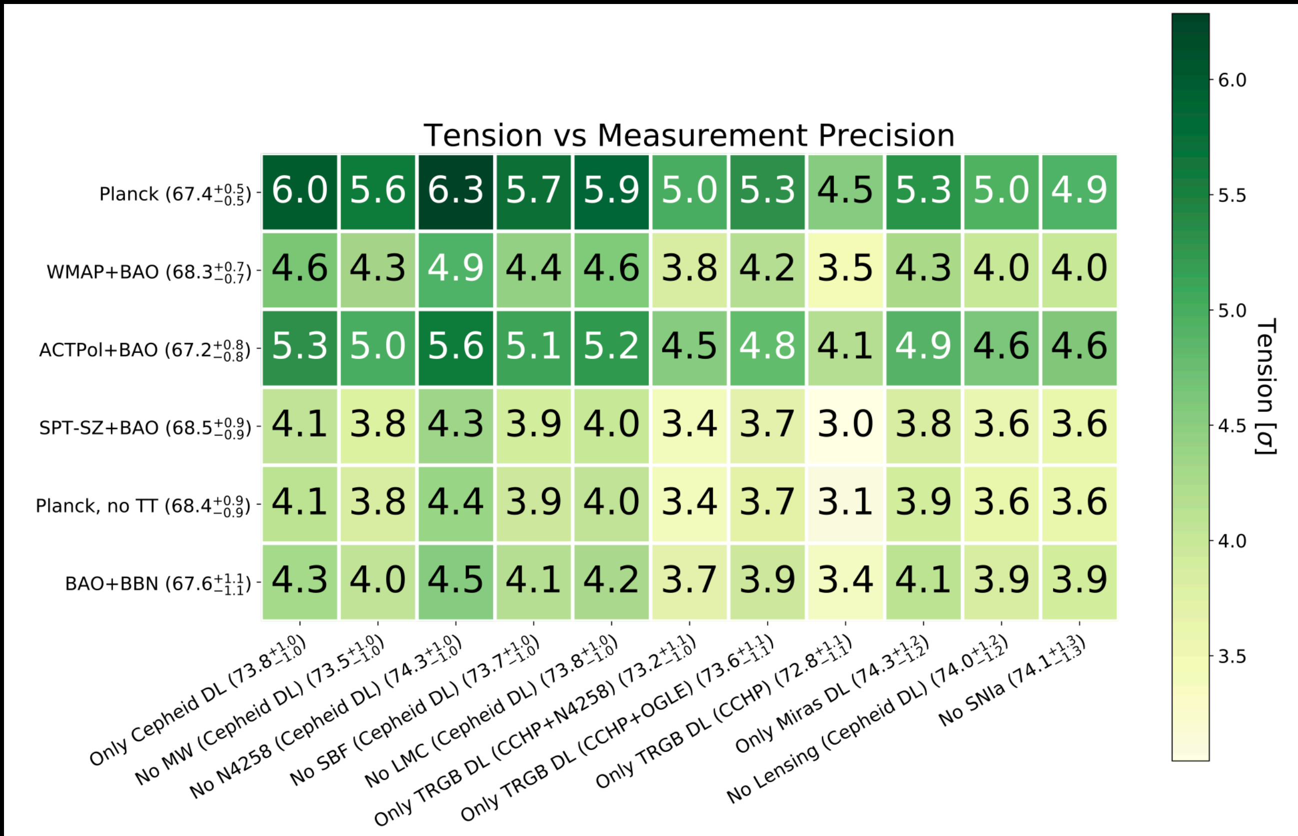
See Di Valentino et al. arXiv:2008.11283 [astro-ph.CO], arXiv:2008.11284 [astro-ph.CO], arXiv:2008.11285 [astro-ph.CO], arXiv:2008.11286 [astro-ph.CO] for an overview.

Afternoon talks for more details!

Adam's talk for more details!

H0 tension

Riess, Nature Reviews Physics (2019)



H0 = 67.27 ± 0.60 km/s/Mpc
in ΛCDM

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

H0 = 74.03 ± 1.42 km/s/Mpc

Riess et al. arXiv:1903.07603 [astro-ph.CO]

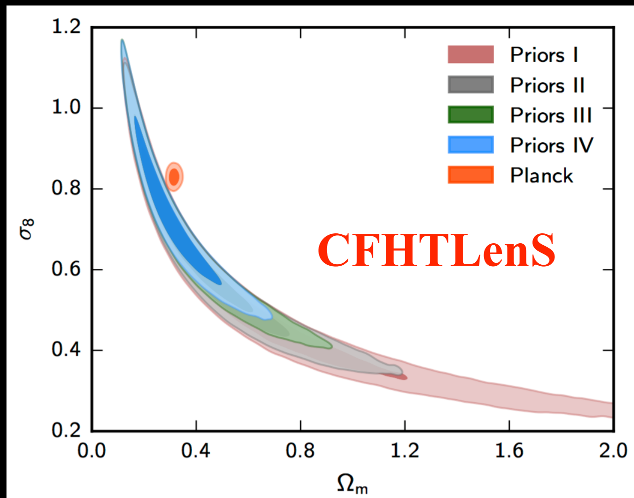
It is possible to compute different combinations of the late-time measurements, changing method, geometric calibration or team.
All of them are ranging from 4.5σ to 6.3σ tension with the Planck estimate.

Optimistic (> 6σ tension) → H0 = 73.27 ± 0.76 km/s/Mpc

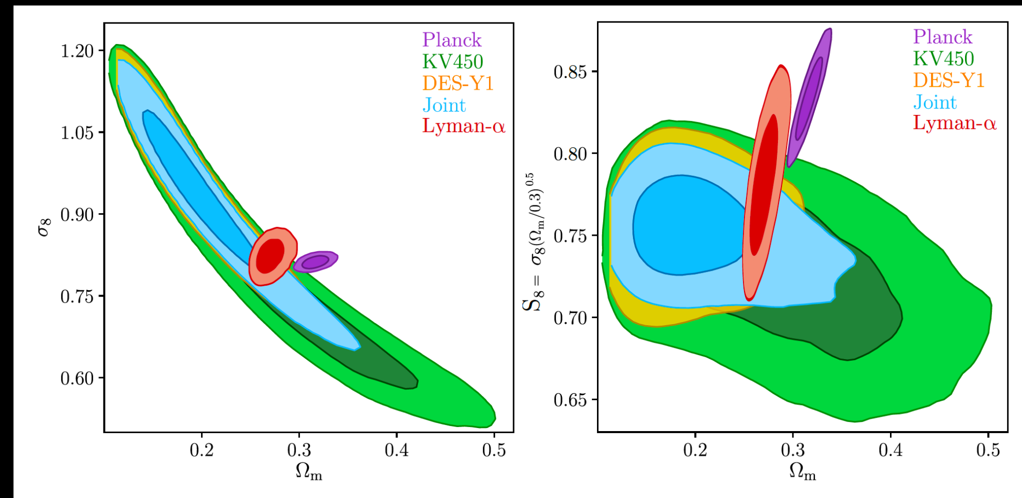
Ultra-conservative (4.5σ tension) → H0 = 73.3 ± 1.2 km/s/Mpc

Di Valentino, arXiv:2011.00246 [astro-ph.CO]

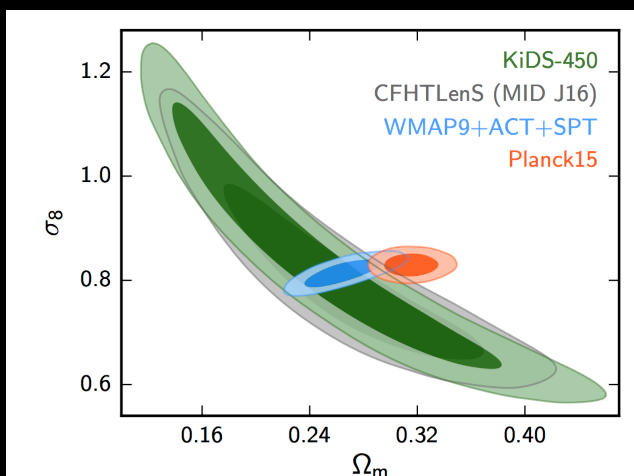
S8 tension



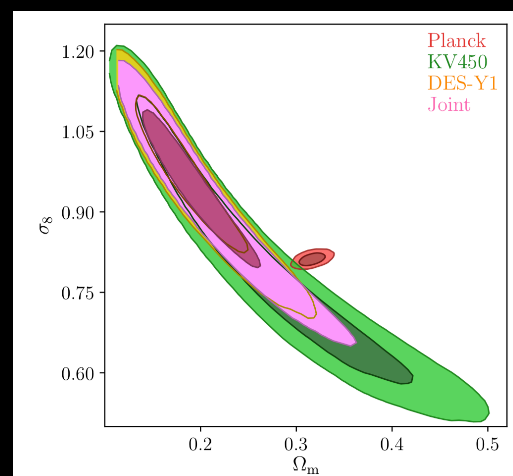
Joudaki et al, arXiv:1601.05786



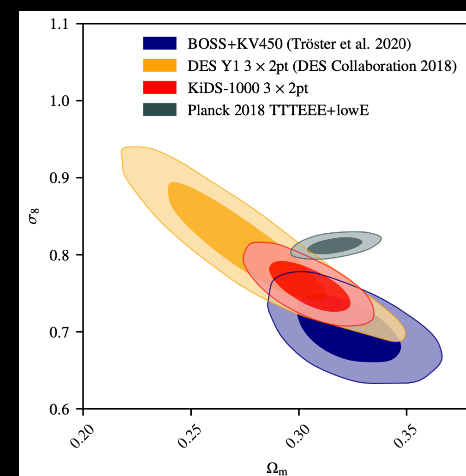
Palanque-Delabrouille et al., arXiv:1911.09073 [astro-ph.CO]



Hildebrandt et al., arXiv:1606.05338



Asgari et al., arXiv:1910.05336

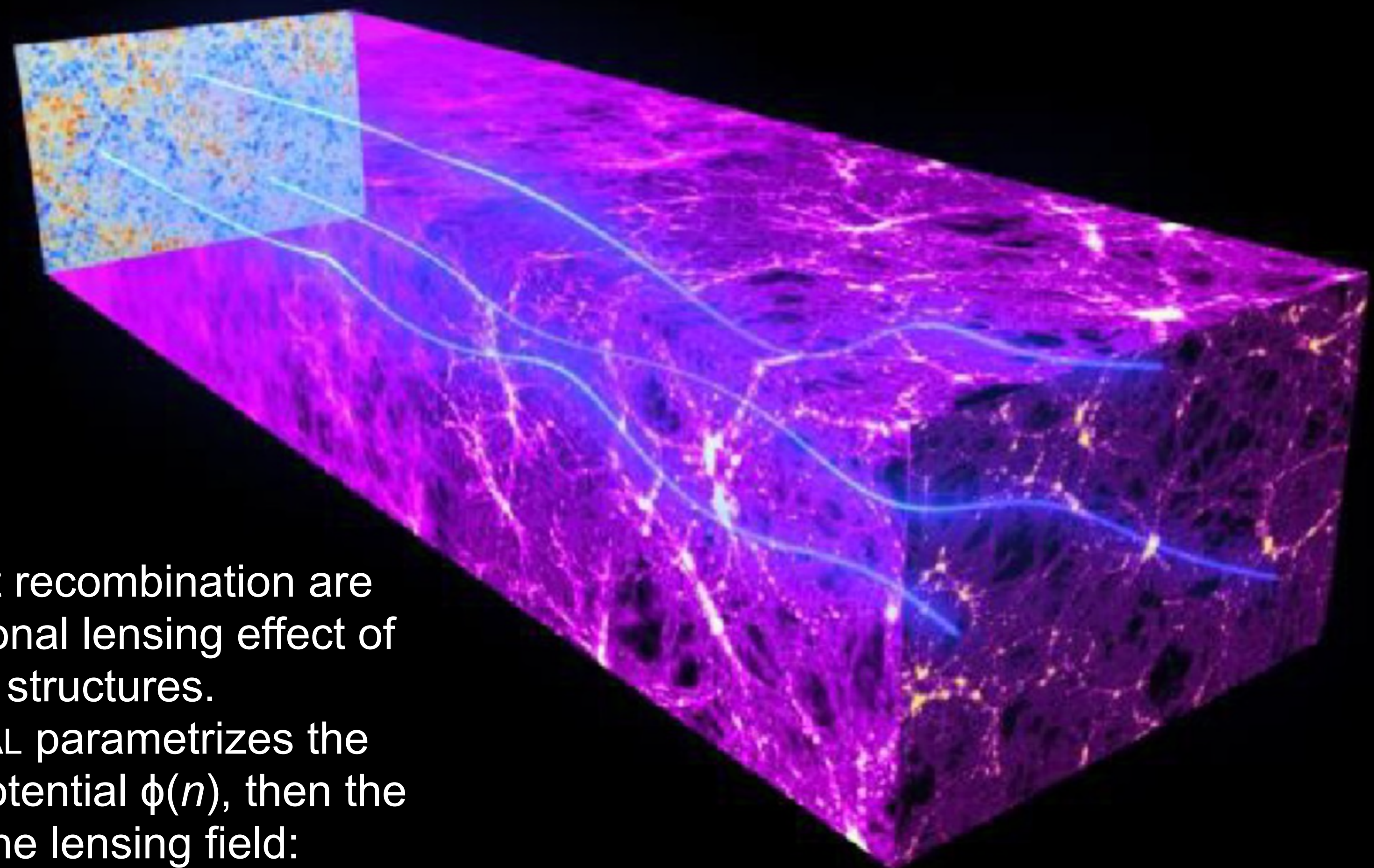


Heymans et al., arXiv:2007.15632

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

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

A_L : consistency check



CMB photons emitted at recombination are deflected by the gravitational lensing effect of massive cosmic structures.
The lensing amplitude A_L parametrizes the rescaling of the lensing potential $\phi(n)$, then the power spectrum of the lensing field:

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

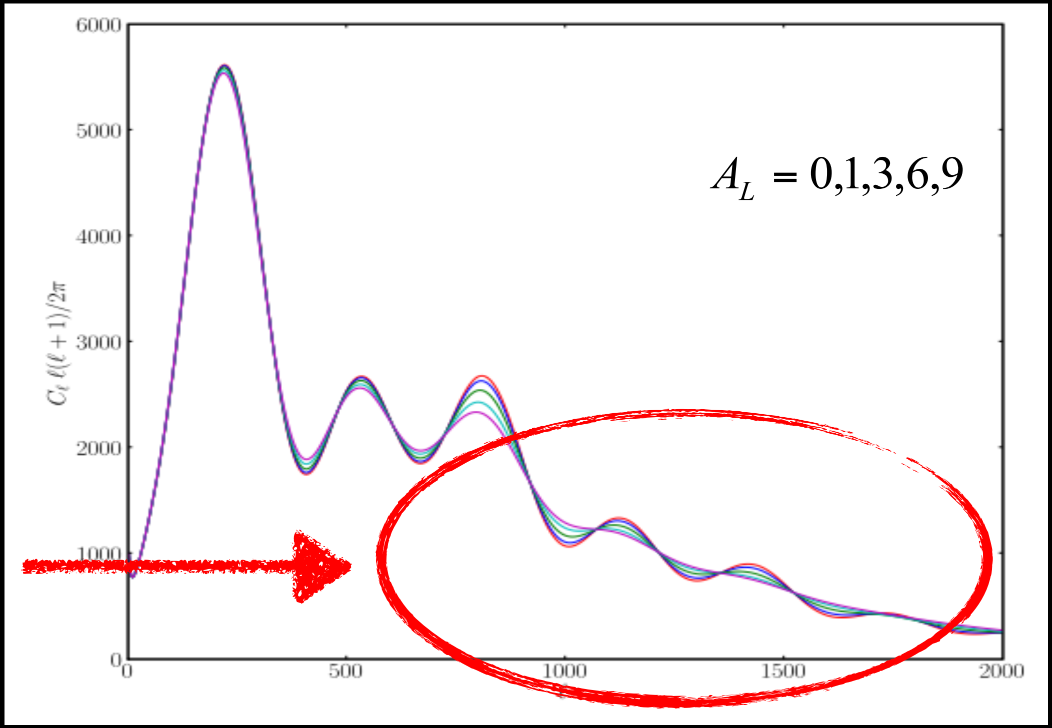
The gravitational lensing deflects the photon path by a quantity defined by the gradient of the lensing potential $\phi(n)$, integrated along the line of sight n, remapping the temperature field.

A_L : consistency check

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

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

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



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

A_L : a failed consistency check

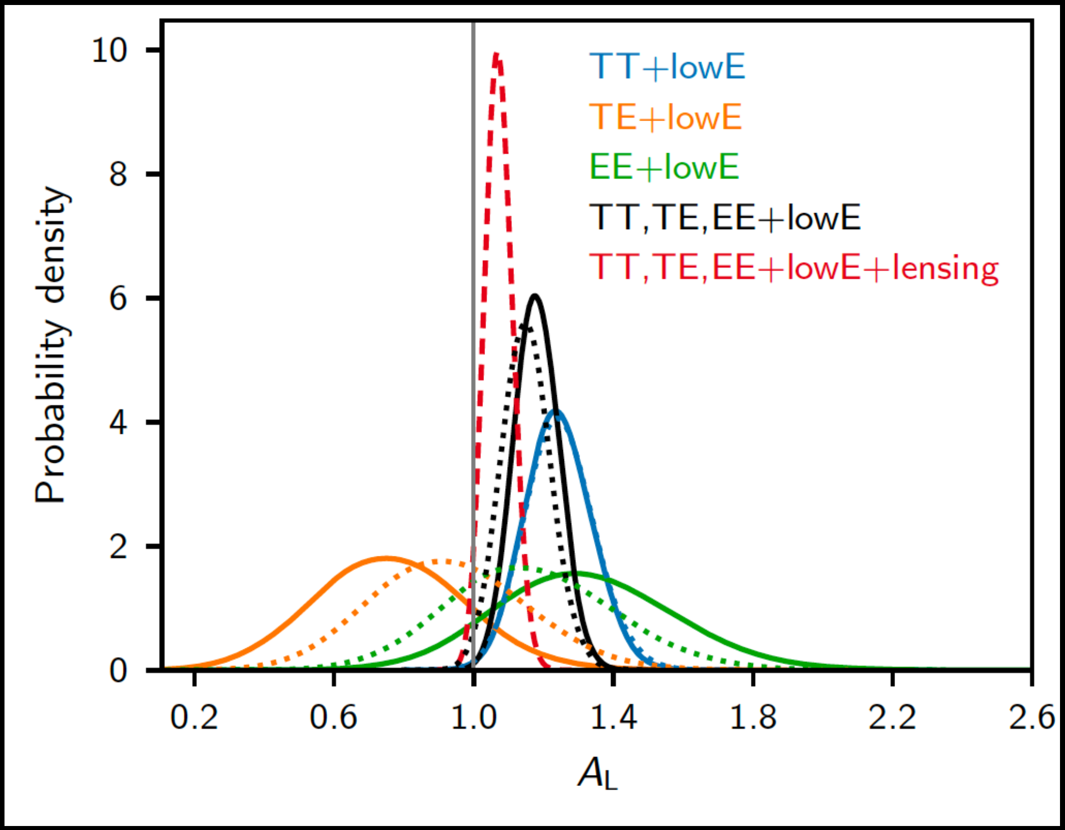
The Planck lensing-reconstruction power spectrum is consistent with the amplitude expected for LCDM models that fit the CMB spectra, so the Planck lensing measurement is compatible with AL = 1.

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.

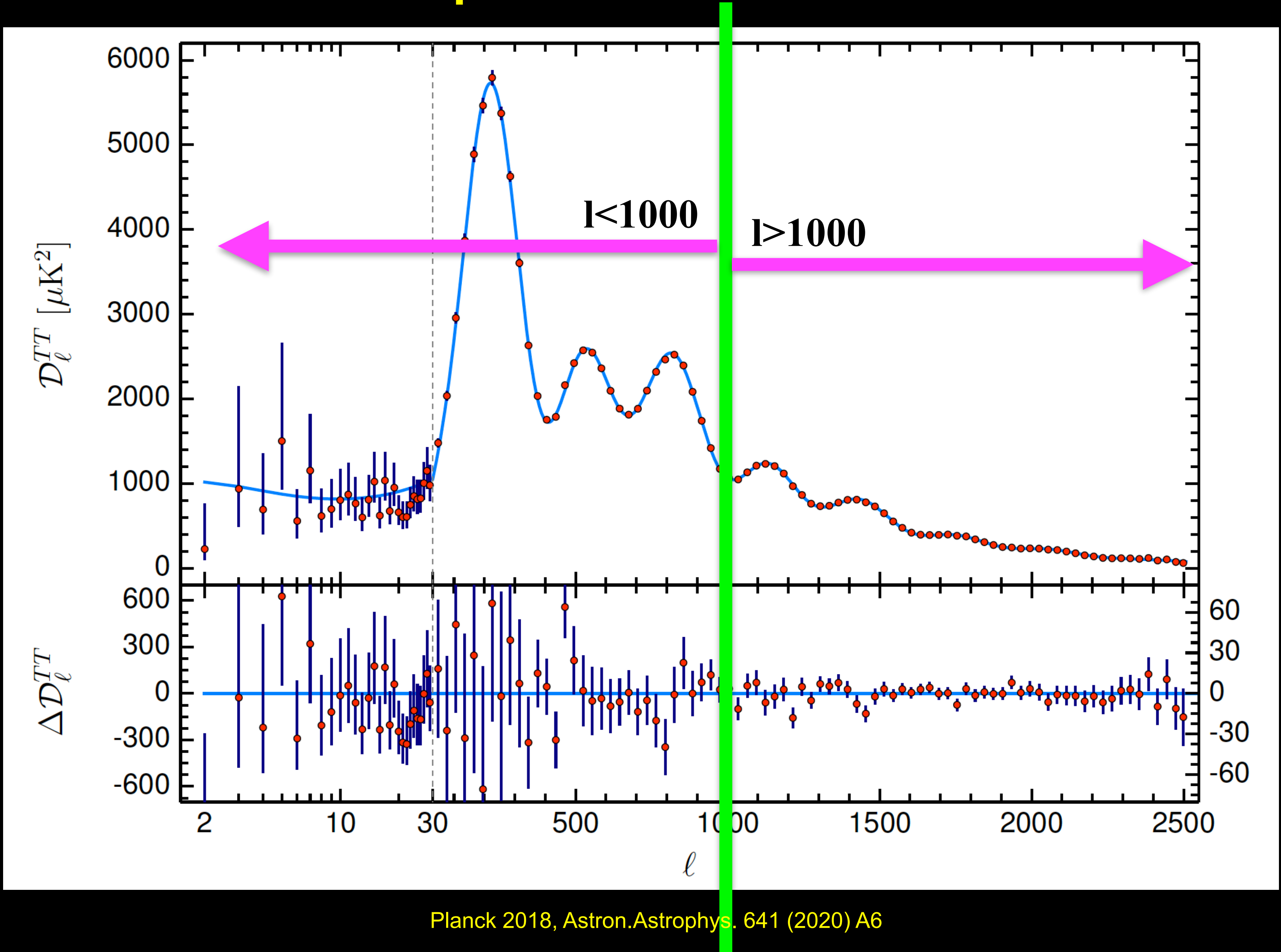
The preference for high AL is not just a volume effect in the full parameter space, with the best fit improved by $\Delta\chi^2 \sim 9$ when adding AL for TT+lowE and 10 for TTTEEE+lowE.

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



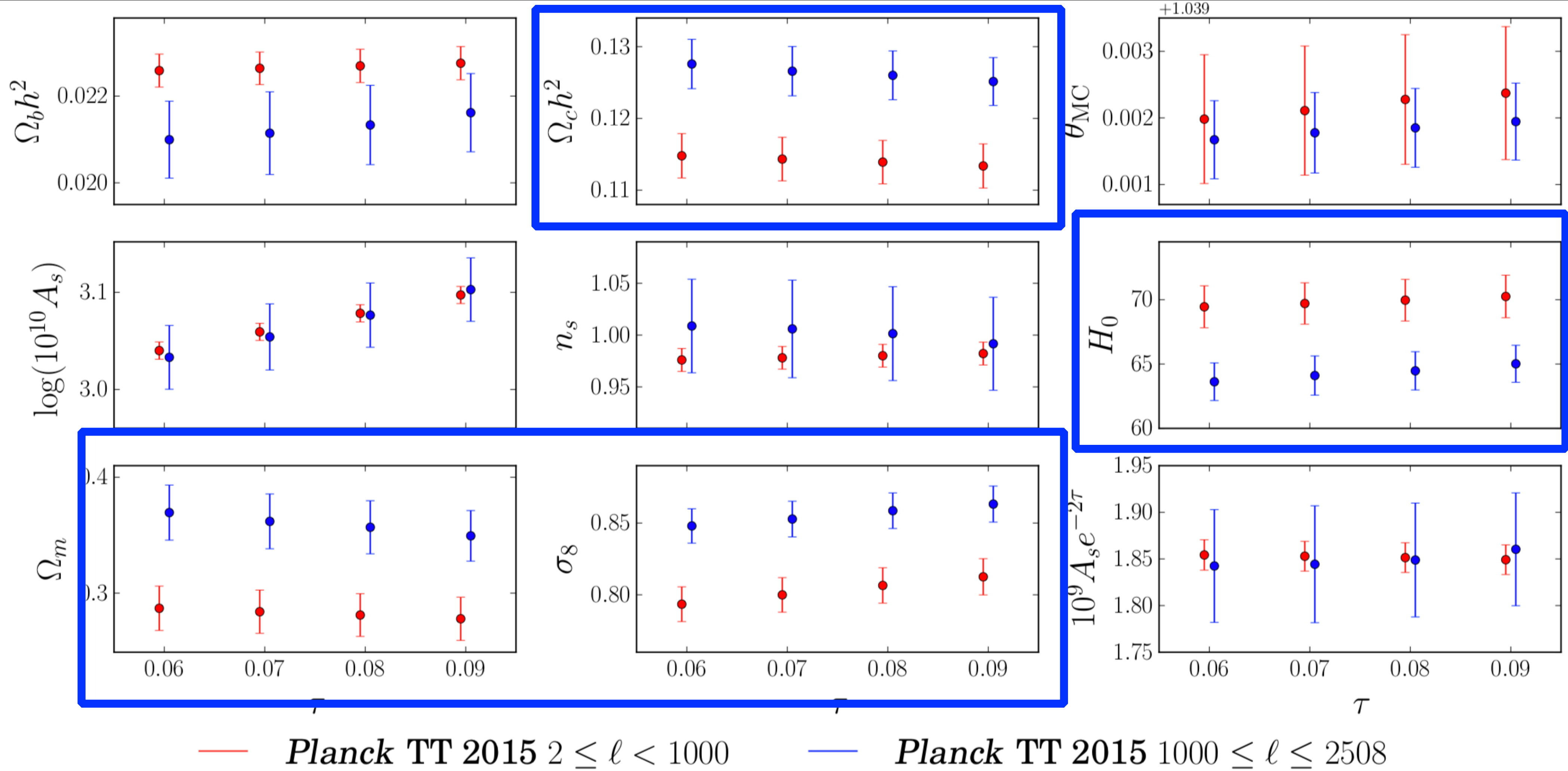
$$A_L = 1.243 \pm 0.096 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT{+}lowE}),$$
$$A_L = 1.180 \pm 0.065 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT,TE,EE{+}lowE}),$$

A_L can explain internal tension



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

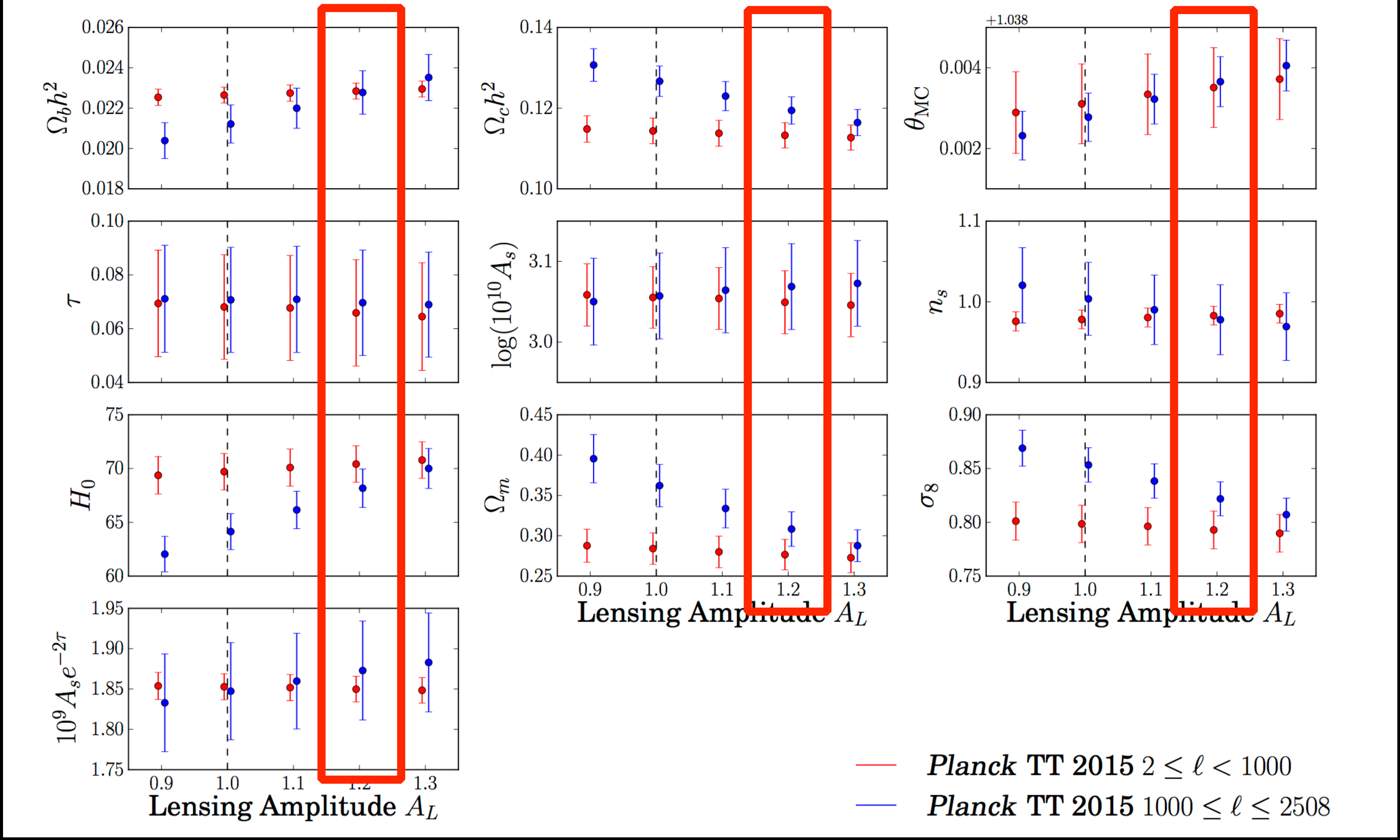
A_L can explain internal tension



Marginalized 68.3% confidence ΛCDM parameter constraints from fits to the l < 1000 and l ≥ 1000 Planck TT 2015 spectra. Tension at more than 2σ level appears in $\Omega_c h^2$ and derived parameters, including H0, Ωm, and σ8.

Addison et al., Astrophys.J. 818 (2016) no.2, 132

A_L can explain internal tension

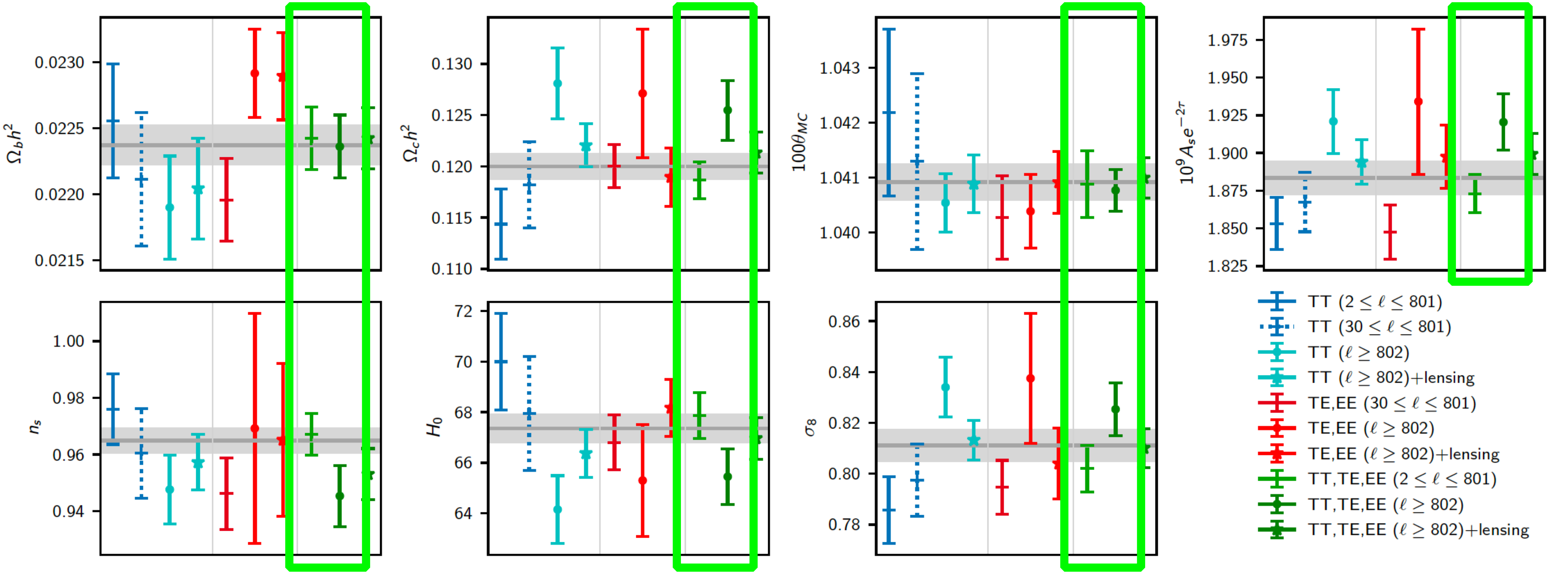


Increasing AL smooths out the high order acoustic peaks, improving the agreement between the two multipole ranges.

Addison et al., Astrophys.J. 818 (2016) no.2, 132

A_L can explain internal tension

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

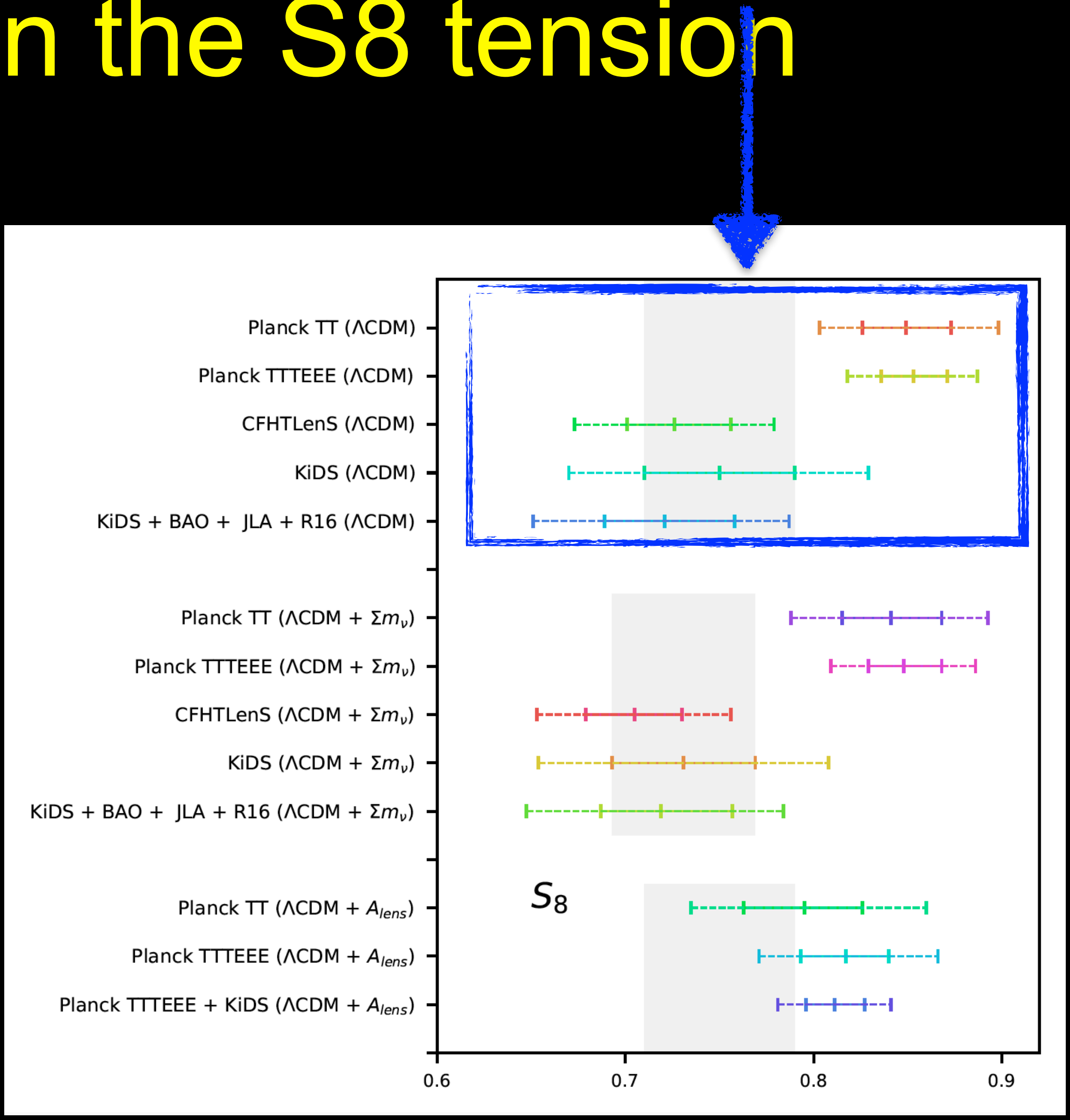


LCDM 68% marginalized parameter constraints for l=[2-801] (points marked with a cross), l>802 (points marked with a circle), and l>802 + lensing (points marked with a star). Correcting for the lensing, all the results from high multipoles are in better consistency with the results from lower multipoles.

Dotted error bars are the results from l=[30-801], without the large-scaleTT likelihood, showing that l< 30 pulls the low-multipole parameters further from the joint result.

A_L can explain the S8 tension

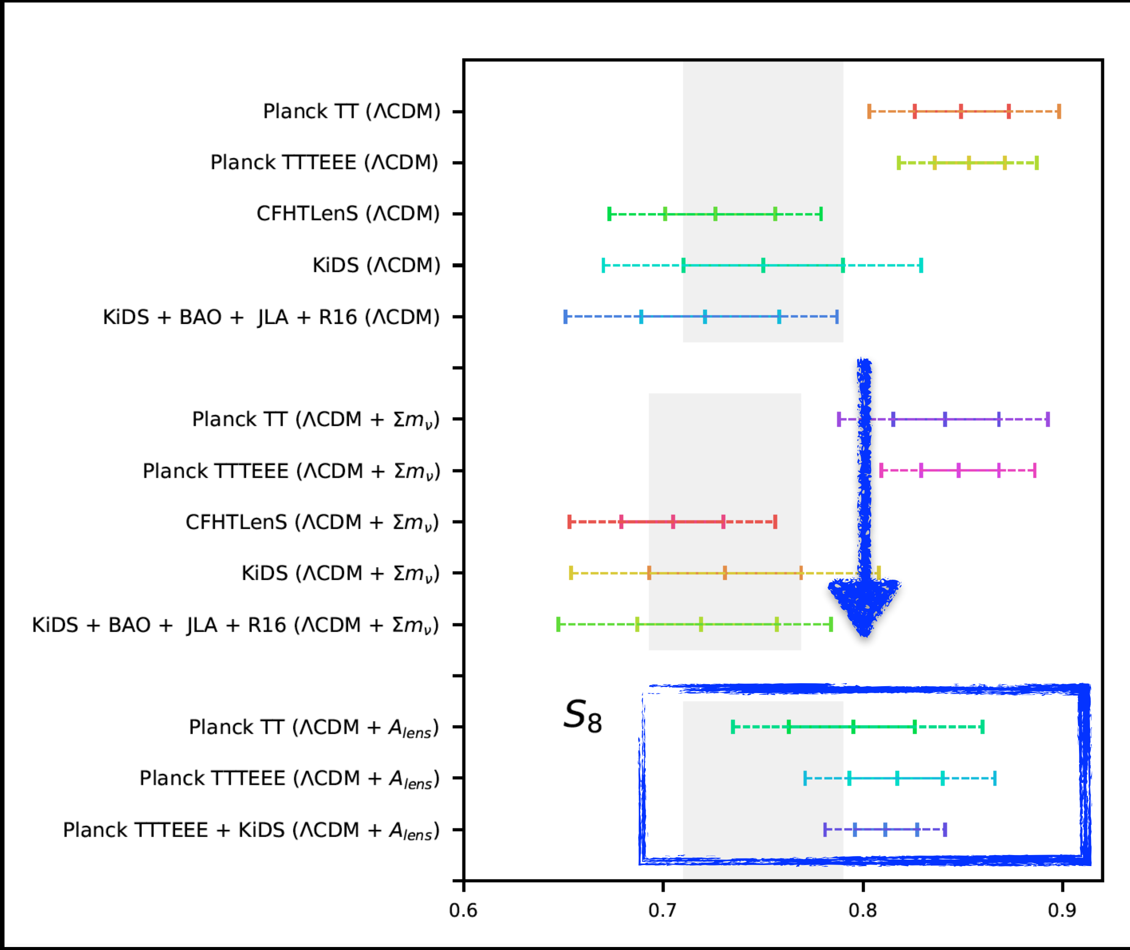
If we include the additional scaling parameter on the CMB lensing amplitude A_L, we find that this can put in agreement Planck 2015 with the cosmic shear data.



Di Valentino and Bridle, Symmetry 10 (2018) no.11, 585

A_L can explain the S8 tension

If we include the additional scaling parameter on the CMB lensing amplitude A_L, we find that this can put in agreement Planck 2015 with the cosmic shear data.



Di Valentino and Bridle, Symmetry 10 (2018) no.11, 585

What happens if we vary all the parameters together? Can we explain the AL anomaly?

In practice, we look for a possible combination of parameters that could solve or at least ameliorate, the current discordances.

While this ”minimal” 6 parameter approach is justified by the good fit to the data, some of the assumptions or simplifications made are indeed not anymore fully justified and risk an oversimplification of the physics that drives the evolution of the Universe.

In a larger parameter space, the constraints can be considered more conservative, while the anomalies more robust.

Beyond six parameters: extending ΛCDM

- The total neutrino mass is fixed arbitrary to 0.06eV. However, we know that neutrinos are massive and that current cosmological datasets are sensitive to variations in the absolute neutrino mass scale of order ~ 100 meV.
- The cosmological constant offers difficulties in any theoretical interpretation: fixing the dark energy equation of state to –1 is not favoured by any theoretical argument. Moreover, while both matter and radiation evolve rapidly, Λ is assumed not to change with time, so its recent appearance in the standard cosmological model implies an extreme fine-tuning of initial conditions. This fine-tuning is known as the coincidence problem. Therefore it seems reasonable to incorporate in the analysis a possible dynamical dark energy component, constant with redshift w, or redshift dependent w(z)=w0+(1-a)wa (CPL).
- Any inflationary model, because it is a dynamical process, predicts a running of the scalar spectral index, expected for slow rolling inflation at the level of $(1\text{-ns})^2 \sim 10^{-3}$.
- The effective number of relativistic degrees of freedom Neff could be easily different from the standard expected value of 3.046, for example for the presence of sterile neutrinos or thermal axions.
- We need to take into account the anomalous value for the lensing amplitude A_L. While this parameter is purely phenomenological, one should clearly consider it and check if the cosmology obtained is consistent with other datasets.

Constraints at 68% cl.

Beyond six parameters: extending ΛCDM

Parameters	Planck	Planck +R19	Planck +lensing	Planck +BAO	Planck + Pantheon
$\Omega_b h^2$	0.02246 ± 0.00028	$0.02248^{+0.00028}_{-0.00032}$	0.02228 ± 0.00026	0.02264 ± 0.00026	0.02250 ± 0.00028
$\Omega_c h^2$	0.1172 ± 0.0033	0.1174 ± 0.0035	0.1164 ± 0.0033	0.1175 ± 0.0033	$0.1174^{+0.0031}_{-0.0035}$
$100\theta_{\rm MC}$	1.04112 ± 0.00051	1.04111 ± 0.00052	1.04119 ± 0.00050	1.04120 ± 0.00049	1.04111 ± 0.00050
τ	0.0496 ± 0.0086	0.0508 ± 0.0091	$0.0494^{+0.0086}_{-0.0076}$	0.0502 ± 0.0087	$0.0499^{+0.0086}_{-0.0078}$
Σm_ν [eV]	< 0.863	< 0.821	< 0.714	< 0.352	< 0.822
w	-1.27 ± 0.53	$-1.33^{+0.17}_{-0.11}$	-1.33 ± 0.52	$-1.009^{+0.092}_{-0.070}$	$-1.071^{+0.073}_{-0.050}$
$N_{\rm eff}$	2.95 ± 0.24	2.97 ± 0.26	2.85 ± 0.23	3.04 ± 0.23	$2.98^{+0.23}_{-0.25}$
A_L	$1.25^{+0.09}_{-0.14}$	$1.21^{+0.09}_{-0.10}$	$1.116^{+0.061}_{-0.096}$	$1.213^{+0.076}_{-0.088}$	1.232 ± 0.090
$\ln(10^{10}A_s)$	3.027 ± 0.020	3.030 ± 0.022	3.024 ± 0.020	3.030 ± 0.020	$3.028^{+0.020}_{-0.018}$
n_s	0.964 ± 0.012	0.965 ± 0.013	0.958 ± 0.012	0.971 ± 0.012	0.965 ± 0.012
α_S	-0.0053 ± 0.0085	-0.0047 ± 0.0082	-0.0066 ± 0.0082	-0.0041 ± 0.0081	-0.0049 ± 0.0086
H_0[km/s/Mpc]	73^{+10}_{-20}	74.0 ± 1.4	74^{+10}_{-20}	67.9 ± 1.7	66.9 ± 2.0
σ_8	$0.79^{+0.15}_{-0.13}$	$0.811^{+0.051}_{-0.035}$	$0.80^{+0.15}_{-0.13}$	0.782 ± 0.025	$0.750^{+0.055}_{-0.034}$
S_8	$0.754^{+0.053}_{-0.041}$	$0.758^{+0.039}_{-0.027}$	$0.757^{+0.047}_{-0.038}$	$0.791^{+0.025}_{-0.019}$	$0.775^{+0.036}_{-0.026}$

In this Table we show the constraints obtained assuming our extended 11 parameters space, assuming a constant dark energy equation of state w.

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

Constraints at 68% cl.

Beyond six parameters: extending ΛCDM

Parameters	Planck	Planck +R19	Planck +lensing	Planck +BAO	Planck + Pantheon
$\Omega_b h^2$	0.02246 ± 0.00028	$0.02248^{+0.00028}_{-0.00032}$	0.02228 ± 0.00026	0.02264 ± 0.00026	0.02250 ± 0.00028
$\Omega_c h^2$	0.1172 ± 0.0033	0.1174 ± 0.0035	0.1164 ± 0.0033	0.1175 ± 0.0033	$0.1174^{+0.0031}_{-0.0035}$
$100\theta_{\mathrm{MC}}$	1.04112 ± 0.00051	1.04111 ± 0.00052	1.04119 ± 0.00050	1.04120 ± 0.00049	1.04111 ± 0.00050
τ	0.0496 ± 0.0086	0.0508 ± 0.0091	$0.0494^{+0.0086}_{-0.0076}$	0.0502 ± 0.0087	$0.0499^{+0.0086}_{-0.0078}$
Σm_ν [eV]	< 0.863	< 0.821	< 0.714	< 0.352	< 0.822
w	-1.27 ± 0.53	$-1.33^{+0.17}_{-0.11}$	-1.33 ± 0.52	$-1.009^{+0.092}_{-0.070}$	$-1.071^{+0.073}_{-0.050}$
N_{eff}	2.95 ± 0.24	2.97 ± 0.26	2.85 ± 0.23	3.04 ± 0.23	$2.98^{+0.23}_{-0.25}$
A_L	$1.25^{+0.09}_{-0.14}$	$1.21^{+0.09}_{-0.10}$	$1.116^{+0.061}_{-0.096}$	$1.213^{+0.076}_{-0.088}$	1.232 ± 0.090
$\ln(10^{10} A_s)$	3.027 ± 0.020	3.030 ± 0.022	3.024 ± 0.020	3.030 ± 0.020	$3.028^{+0.020}_{-0.018}$
n_s	0.964 ± 0.012	0.965 ± 0.013	0.958 ± 0.012	0.971 ± 0.012	0.965 ± 0.012
α_S	-0.0053 ± 0.0085	-0.0047 ± 0.0082	-0.0066 ± 0.0082	-0.0041 ± 0.0081	-0.0049 ± 0.0086
H_0[km/s/Mpc]	73^{+10}_{-20}	74.0 ± 1.4	74^{+10}_{-20}	67.9 ± 1.7	66.9 ± 2.0
σ_8	$0.79^{+0.15}_{-0.13}$	$0.811^{+0.051}_{-0.035}$	$0.80^{+0.15}_{-0.13}$	0.782 ± 0.025	$0.750^{+0.055}_{-0.034}$
S_8	$0.754^{+0.053}_{-0.041}$	$0.758^{+0.039}_{-0.027}$	$0.757^{+0.047}_{-0.038}$	$0.791^{+0.025}_{-0.019}$	$0.775^{+0.036}_{-0.026}$

The significant increase in the number of parameters produces, as expected, a relaxation in the constraints on the 6 ΛCDM parameters. It is impressive that despite the increase in the number of the parameters, some of the constraints on key parameters are relaxed but not significantly altered. The cold dark matter ansatz remains robust and the baryon density is compatible with BBN predictions.

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

Constraints at 68% cl.

Beyond six parameters: extending ΛCDM

Parameters	Planck	Planck +R19	Planck +lensing	Planck +BAO	Planck + Pantheon
$\Omega_b h^2$	0.02246 ± 0.00028	$0.02248^{+0.00028}_{-0.00032}$	0.02228 ± 0.00026	0.02264 ± 0.00026	0.02250 ± 0.00028
$\Omega_c h^2$	0.1172 ± 0.0033	0.1174 ± 0.0035	0.1164 ± 0.0033	0.1175 ± 0.0033	$0.1174^{+0.0031}_{-0.0035}$
$100\theta_{\rm MC}$	1.04112 ± 0.00051	1.04111 ± 0.00052	1.04119 ± 0.00050	1.04120 ± 0.00049	1.04111 ± 0.00050
τ	0.0496 ± 0.0086	0.0508 ± 0.0091	$0.0494^{+0.0086}_{-0.0076}$	0.0502 ± 0.0087	$0.0499^{+0.0086}_{-0.0078}$
Σm_ν [eV]	< 0.863	< 0.821	< 0.714	< 0.352	< 0.822
w	-1.27 ± 0.53	$-1.33^{+0.17}_{-0.11}$	-1.33 ± 0.52	$-1.009^{+0.092}_{-0.070}$	$-1.071^{+0.073}_{-0.050}$
$N_{\rm eff}$	2.95 ± 0.24	2.97 ± 0.26	2.85 ± 0.23	3.04 ± 0.23	$2.98^{+0.23}_{-0.25}$
A_L	$1.25^{+0.09}_{-0.14}$	$1.21^{+0.09}_{-0.10}$	$1.116^{+0.061}_{-0.096}$	$1.213^{+0.076}_{-0.088}$	1.232 ± 0.090
$\ln(10^{10} A_s)$	3.027 ± 0.020	3.030 ± 0.022	3.024 ± 0.020	3.030 ± 0.020	$3.028^{+0.020}_{-0.018}$
n_s	0.964 ± 0.012	0.965 ± 0.013	0.958 ± 0.012	0.971 ± 0.012	0.965 ± 0.012
α_S	-0.0053 ± 0.0085	-0.0047 ± 0.0082	-0.0066 ± 0.0082	-0.0041 ± 0.0081	-0.0049 ± 0.0086
H_0[km/s/Mpc]	73^{+10}_{-20}	74.0 ± 1.4	74^{+10}_{-20}	67.9 ± 1.7	66.9 ± 2.0
σ_8	$0.79^{+0.15}_{-0.13}$	$0.811^{+0.051}_{-0.035}$	$0.80^{+0.15}_{-0.13}$	0.782 ± 0.025	$0.750^{+0.055}_{-0.034}$
S_8	$0.754^{+0.053}_{-0.041}$	$0.758^{+0.039}_{-0.027}$	$0.757^{+0.047}_{-0.038}$	$0.791^{+0.025}_{-0.019}$	$0.775^{+0.036}_{-0.026}$

We see no evidence for ”new physics”: we just have (weaker) upper limits on the neutrino mass, the running of the spectral index is compatible with zero, the dark energy equation of state is compatible with w = −1, and the neutrino effective number is remarkably close to the standard value $N_{\rm eff}$ = 3.046.

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

Constraints at 68% cl.

Beyond six parameters: extending ΛCDM

Parameters	Planck	Planck +R19	Planck +lensing	Planck +BAO	Planck + Pantheon
$\Omega_b h^2$	0.02246 ± 0.00028	$0.02248^{+0.00028}_{-0.00032}$	0.02228 ± 0.00026	0.02264 ± 0.00026	0.02250 ± 0.00028
$\Omega_c h^2$	0.1172 ± 0.0033	0.1174 ± 0.0035	0.1164 ± 0.0033	0.1175 ± 0.0033	$0.1174^{+0.0031}_{-0.0035}$
$100\theta_{\rm MC}$	1.04112 ± 0.00051	1.04111 ± 0.00052	1.04119 ± 0.00050	1.04120 ± 0.00049	1.04111 ± 0.00050
τ	0.0496 ± 0.0086	0.0508 ± 0.0091	$0.0494^{+0.0086}_{-0.0076}$	0.0502 ± 0.0087	$0.0499^{+0.0086}_{-0.0078}$
Σm_ν [eV]	< 0.863	< 0.821	< 0.714	< 0.352	< 0.822
w	-1.27 ± 0.53	$-1.33^{+0.17}_{-0.11}$	-1.33 ± 0.52	$-1.009^{+0.092}_{-0.070}$	$-1.071^{+0.073}_{-0.050}$
$N_{\rm eff}$	2.95 ± 0.24	2.97 ± 0.26	2.85 ± 0.23	3.04 ± 0.23	$2.98^{+0.23}_{-0.25}$
A_L	$1.25^{+0.09}_{-0.14}$	$1.21^{+0.09}_{-0.10}$	$1.116^{+0.061}_{-0.096}$	$1.213^{+0.076}_{-0.088}$	1.232 ± 0.090
$\ln(10^{10} A_s)$	3.027 ± 0.020	3.030 ± 0.022	3.024 ± 0.020	3.030 ± 0.020	$3.028^{+0.020}_{-0.018}$
n_s	0.964 ± 0.012	0.965 ± 0.013	0.958 ± 0.012	0.971 ± 0.012	0.965 ± 0.012
α_S	-0.0053 ± 0.0085	-0.0047 ± 0.0082	-0.0066 ± 0.0082	-0.0041 ± 0.0081	-0.0049 ± 0.0086
H_0[km/s/Mpc]	73^{+10}_{-20}	74.0 ± 1.4	74^{+10}_{-20}	67.9 ± 1.7	66.9 ± 2.0
σ_8	$0.79^{+0.15}_{-0.13}$	$0.811^{+0.051}_{-0.035}$	$0.80^{+0.15}_{-0.13}$	0.782 ± 0.025	$0.750^{+0.033}_{-0.034}$
S_8	$0.754^{+0.053}_{-0.041}$	$0.758^{+0.039}_{-0.027}$	$0.757^{+0.047}_{-0.038}$	$0.791^{+0.025}_{-0.019}$	$0.775^{+0.036}_{-0.026}$

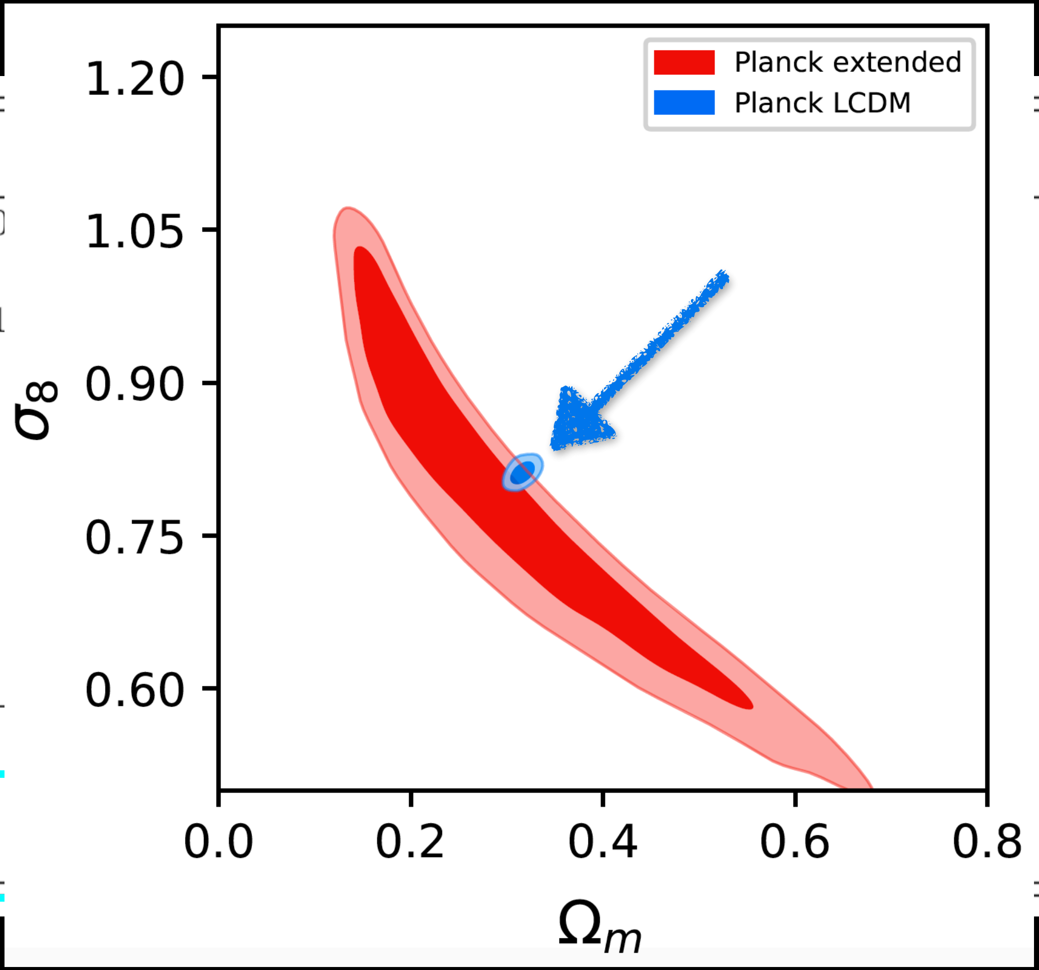
We find a relaxed value for the Hubble constant, with respect to the one derived under the assumption of ΛCDM. The main reason for this relaxation is the inclusion in the analysis of the dark energy equation of state w, that introduces a geometrical degeneracy with the matter density and the Hubble constant. In this way, we can solve the existing tensions with the direct measurements.

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

Constraints at 68% cl.

Beyond six parameters: extending ΛCDM

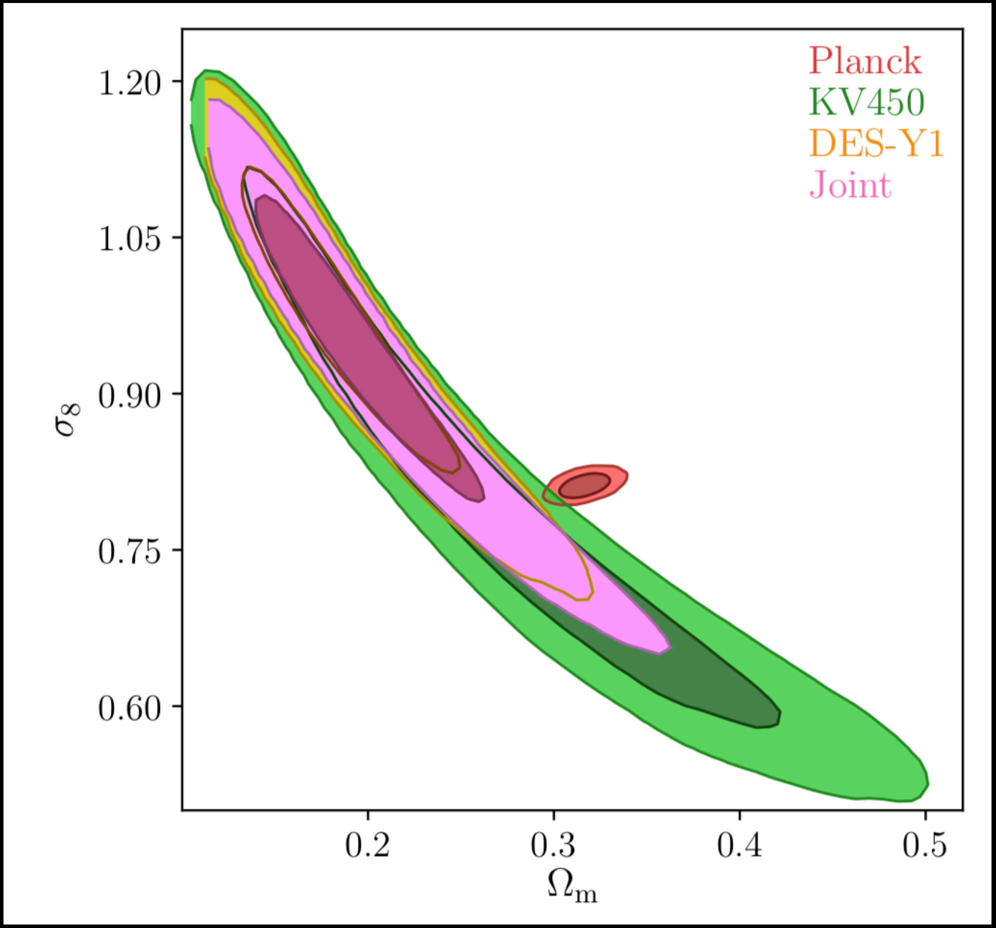
Parameters	Planck	Planck +R19
$\Omega_b h^2$	0.02246 ± 0.00028	$0.02248^{+0.00028}_{-0.00032}$
$\Omega_c h^2$	0.1172 ± 0.0033	0.1174 ± 0.0035
$100\theta_{MC}$	1.04112 ± 0.00051	1.04111 ± 0.00052
τ	0.0496 ± 0.0086	0.0508 ± 0.0091
Σm_ν [eV]	< 0.863	< 0.821
w	-1.27 ± 0.53	$-1.33^{+0.17}_{-0.11}$
$N_{\rm eff}$	2.95 ± 0.24	2.97 ± 0.26
A_L	$1.25^{+0.09}_{-0.14}$	$1.21^{+0.09}_{-0.10}$
$\ln(10^{10}A_s)$	3.027 ± 0.020	3.030 ± 0.022
n_s	0.964 ± 0.012	0.965 ± 0.013
α_S	-0.0053 ± 0.0085	-0.0047 ± 0.0082
H_0[km/s/Mpc]	73^{+10}_{-20}	74.0 ± 1.4
σ_8	$0.79^{+0.15}_{-0.13}$	$0.811^{+0.051}_{-0.035}$
S_8	$0.754^{+0.053}_{-0.041}$	$0.758^{+0.039}_{-0.027}$



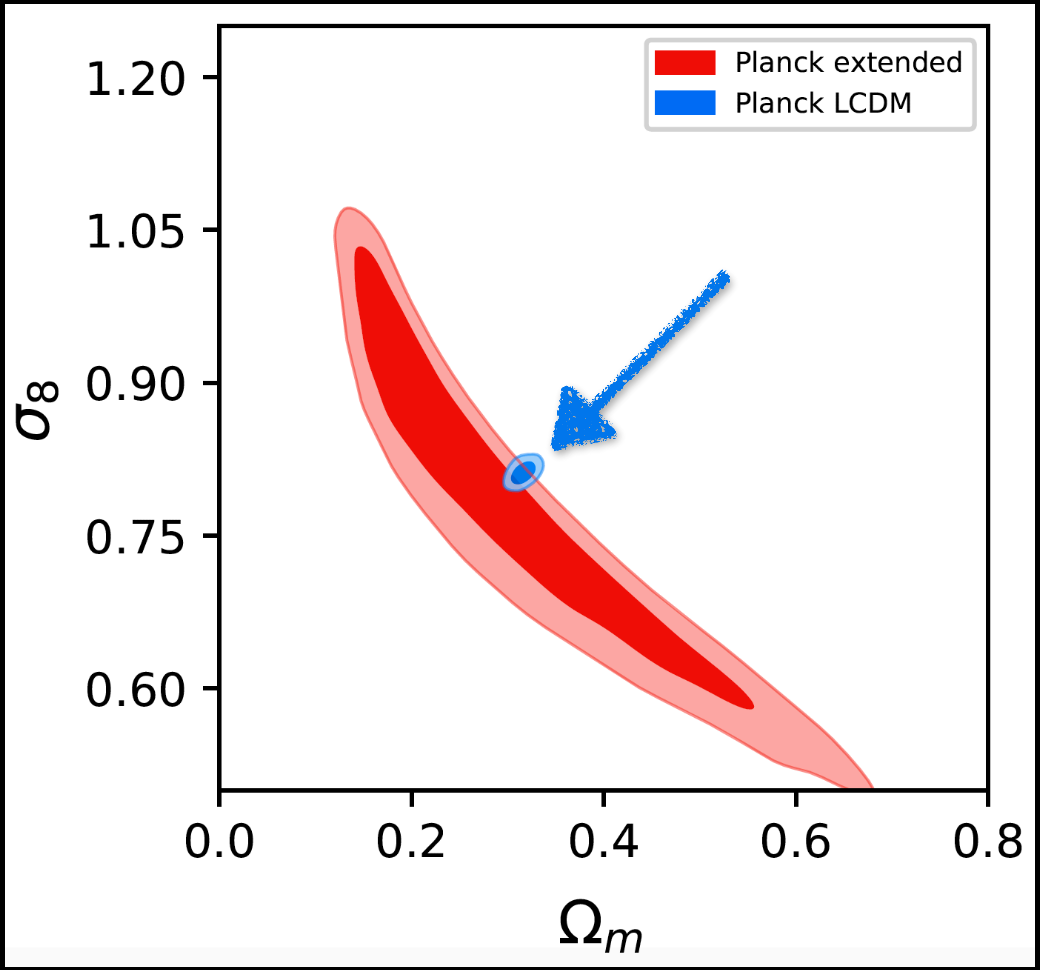
We find relaxed and lower values for the clustering parameter σ8 and S8, with respect to those derived under the assumption of ΛCDM.

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

Beyond six parameters: extending ΛCDM



Asgari et al., arXiv:1910.05336 [astro-ph.CO]



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

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

In this way, we can solve the existing S8 tensions with the CFHTlenS and KiDS-450 cosmic shear surveys.

Constraints at 68% cl.

Beyond six parameters: extending ΛCDM

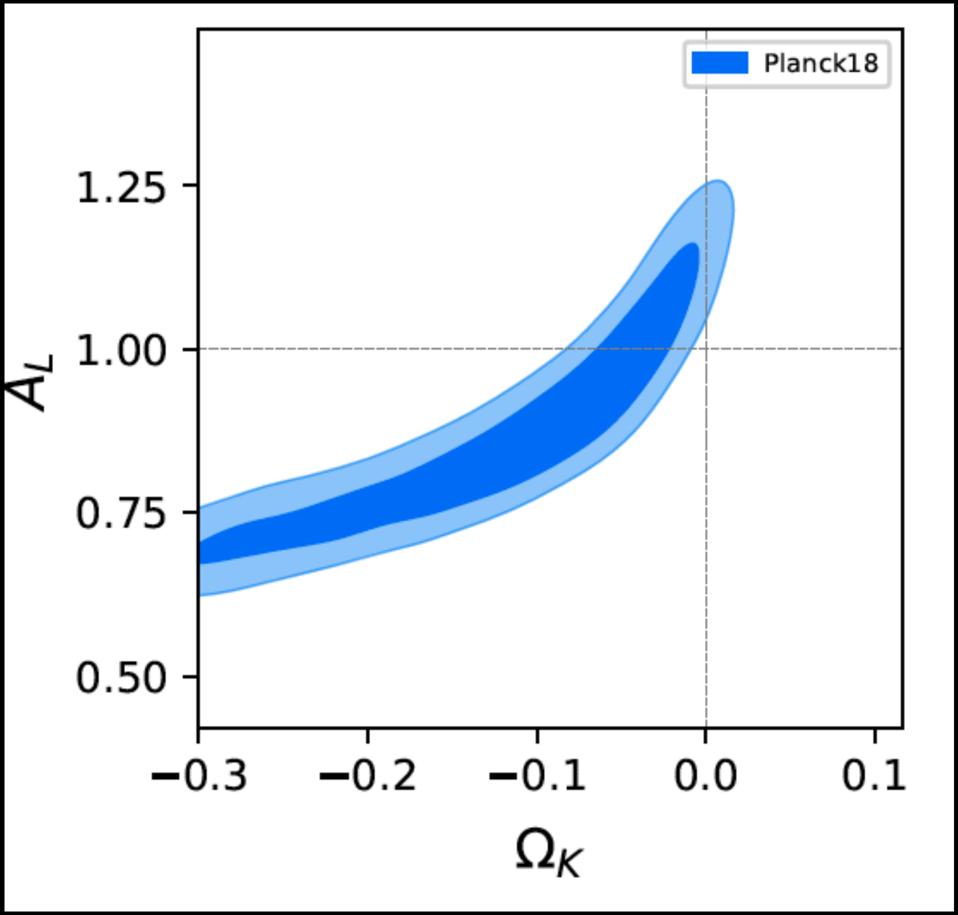
Parameters	Planck	Planck +R19	Planck +lensing	Planck +BAO	Planck + Pantheon
$\Omega_b h^2$	0.02246 ± 0.00028	$0.02248^{+0.00028}_{-0.00032}$	0.02228 ± 0.00026	0.02264 ± 0.00026	0.02250 ± 0.00028
$\Omega_c h^2$	0.1172 ± 0.0033	0.1174 ± 0.0035	0.1164 ± 0.0033	0.1175 ± 0.0033	$0.1174^{+0.0031}_{-0.0035}$
$100\theta_{\rm MC}$	1.04112 ± 0.00051	1.04111 ± 0.00052	1.04119 ± 0.00050	1.04120 ± 0.00049	1.04111 ± 0.00050
τ	0.0496 ± 0.0086	0.0508 ± 0.0091	$0.0494^{+0.0086}_{-0.0076}$	0.0502 ± 0.0087	$0.0499^{+0.0086}_{-0.0078}$
Σm_ν [eV]	< 0.863	< 0.821	< 0.714	< 0.352	< 0.822
w	-1.27 ± 0.53	$-1.33^{+0.17}_{-0.11}$	-1.33 ± 0.52	$-1.009^{+0.092}_{-0.070}$	$-1.071^{+0.073}_{-0.050}$
$N_{\rm eff}$	2.95 ± 0.24	2.97 ± 0.26	2.85 ± 0.23	3.04 ± 0.23	$2.98^{+0.23}_{-0.25}$
A_L	$1.25^{+0.09}_{-0.14}$	$1.21^{+0.09}_{-0.10}$	$1.116^{+0.061}_{-0.096}$	$1.213^{+0.076}_{-0.088}$	1.232 ± 0.090
$\ln(10^{10} A_s)$	3.027 ± 0.020	3.030 ± 0.022	3.024 ± 0.020	3.030 ± 0.020	$3.028^{+0.020}_{-0.018}$
n_s	0.964 ± 0.012	0.965 ± 0.013	0.958 ± 0.012	0.971 ± 0.012	0.965 ± 0.012
α_S	-0.0053 ± 0.0085	-0.0047 ± 0.0082	-0.0066 ± 0.0082	-0.0041 ± 0.0081	-0.0049 ± 0.0086
H_0[km/s/Mpc]	73^{+10}_{-20}	74.0 ± 1.4	74^{+10}_{-20}	67.9 ± 1.7	66.9 ± 2.0
σ_8	$0.79^{+0.15}_{-0.13}$	$0.811^{+0.051}_{-0.035}$	$0.80^{+0.15}_{-0.13}$	0.782 ± 0.025	$0.750^{+0.055}_{-0.034}$
S_8	$0.754^{+0.053}_{-0.041}$	$0.758^{+0.039}_{-0.027}$	$0.757^{+0.047}_{-0.038}$	$0.791^{+0.025}_{-0.019}$	$0.775^{+0.036}_{-0.026}$

The only notable exception is the angular power spectrum lensing amplitude: A_L that is larger than the expected value at 3 standard deviations, making this anomaly really robust because doesn't correlate with these extra parameters.

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

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

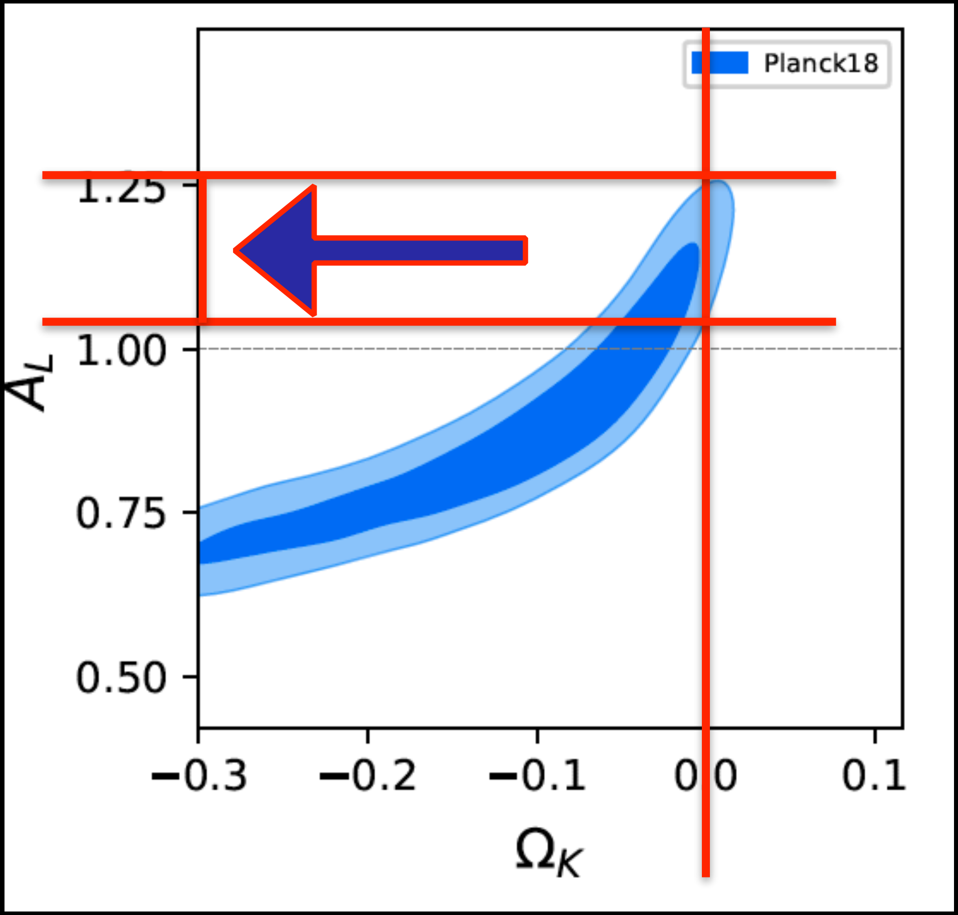
A closed universe (Friedmann 1922) can explain A_L!



Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

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.

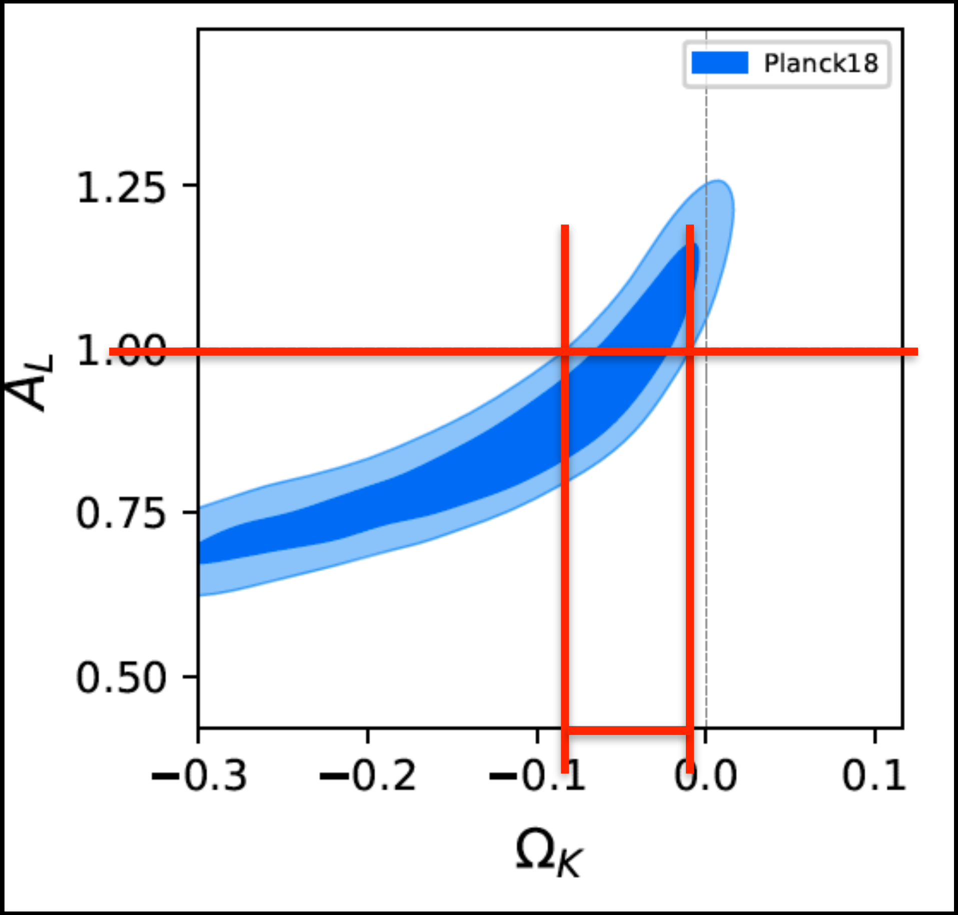
A closed universe (Friedmann 1922) can explain A_L!



Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

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.

A closed universe (Friedmann 1922) can explain A_L!



Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

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.

Curvature of the universe

The ΛCDM model assumes that the universe is specially flat.
The combination of the Planck temperature and polarization power spectra gives:

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

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

a detection of curvature at about 3.4σ,
with a 99% probability region of $-0.095 \leq \Omega_K \leq -0.007$.

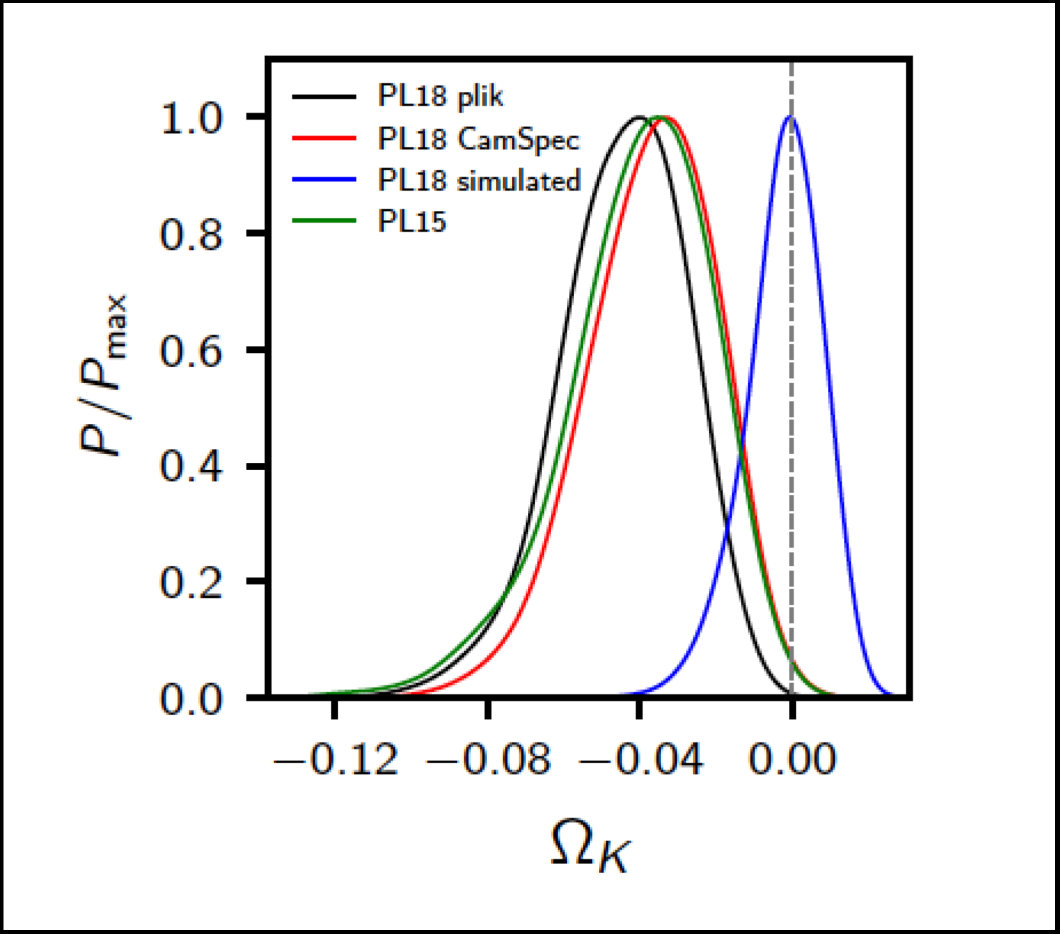
Curvature of the universe

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

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

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

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

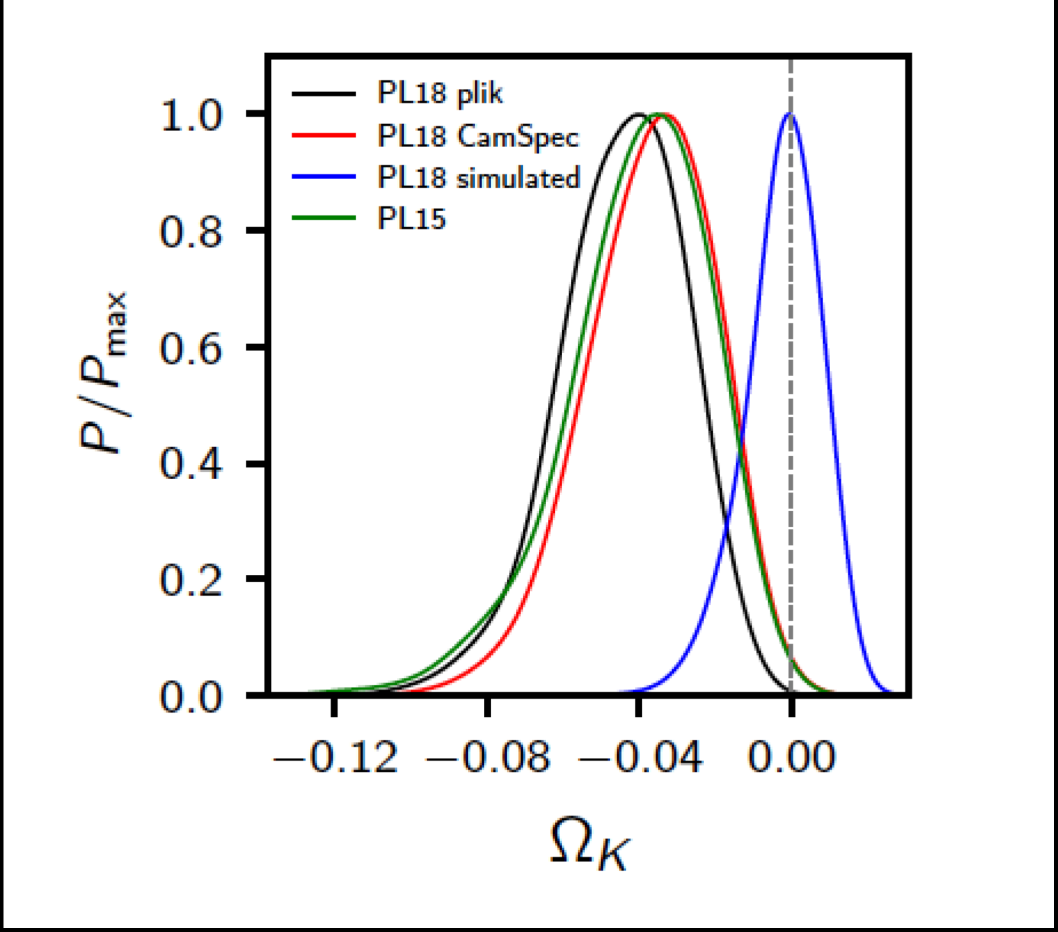


Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

Curvature of the universe

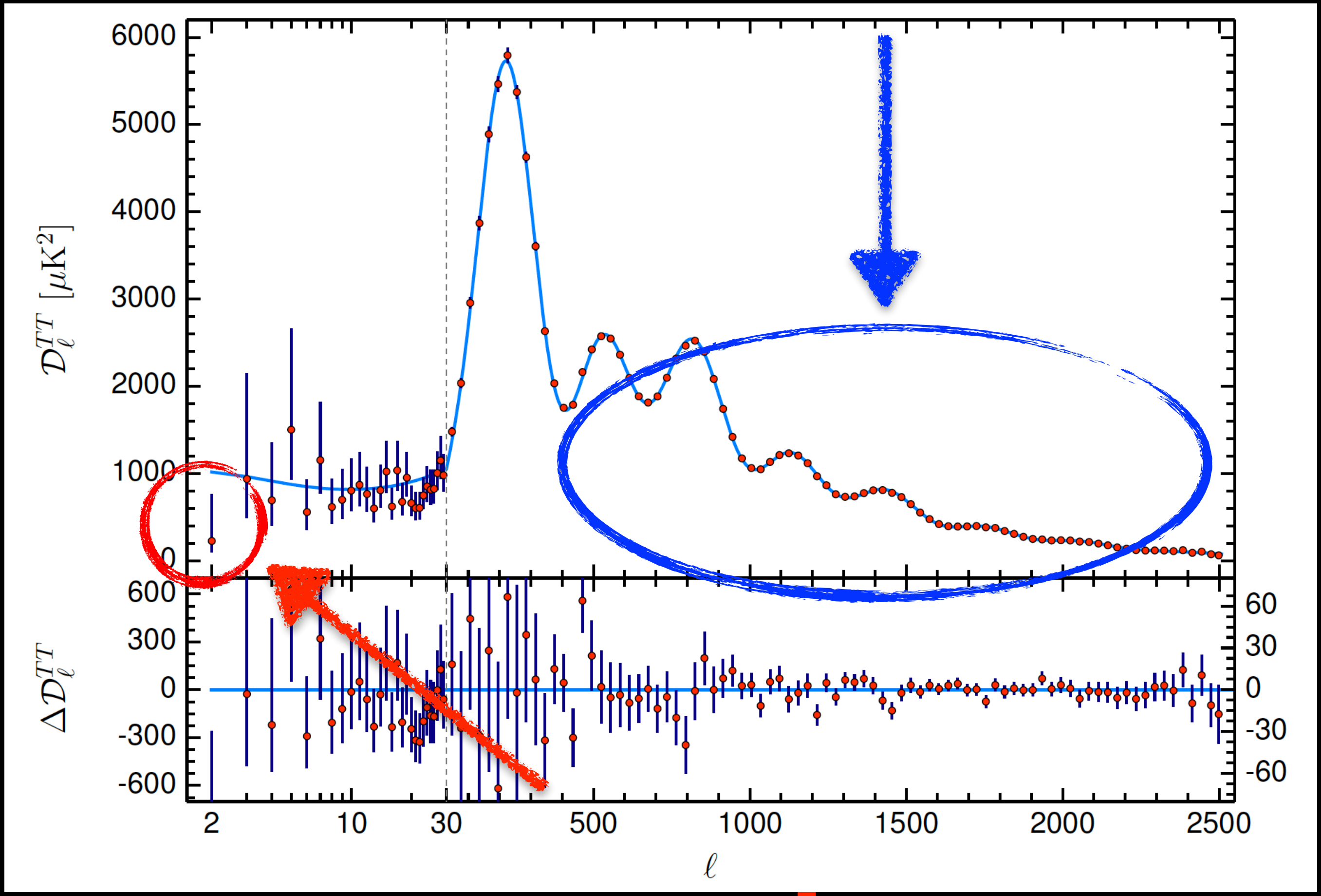
Planck favours a closed Universe ($\Omega k<0$) with 99.985% probability.
A closed Universe with $\Omega K = -0.0438$ provides a better fit to PL18 with respect to a flat model.

This is not entirely a volume effect, since the best-fit $\Delta\chi^2$ changes by -11 compared to base ΛCDM when adding the one additional curvature parameter.
The improvement is due also to the fact that closed models could also lead to a large-scale cut-off in the primordial density fluctuations in agreement with the observed low CMB anisotropy quadrupole.



Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

A closed universe fits Planck better than A_L



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

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

arXiv.org > astro-ph > arXiv:astro-ph/0303127

Search...

Help | Advanced

Astrophysics

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

Is the Low CMB Quadrupole a Signature of Spatial Curvature?

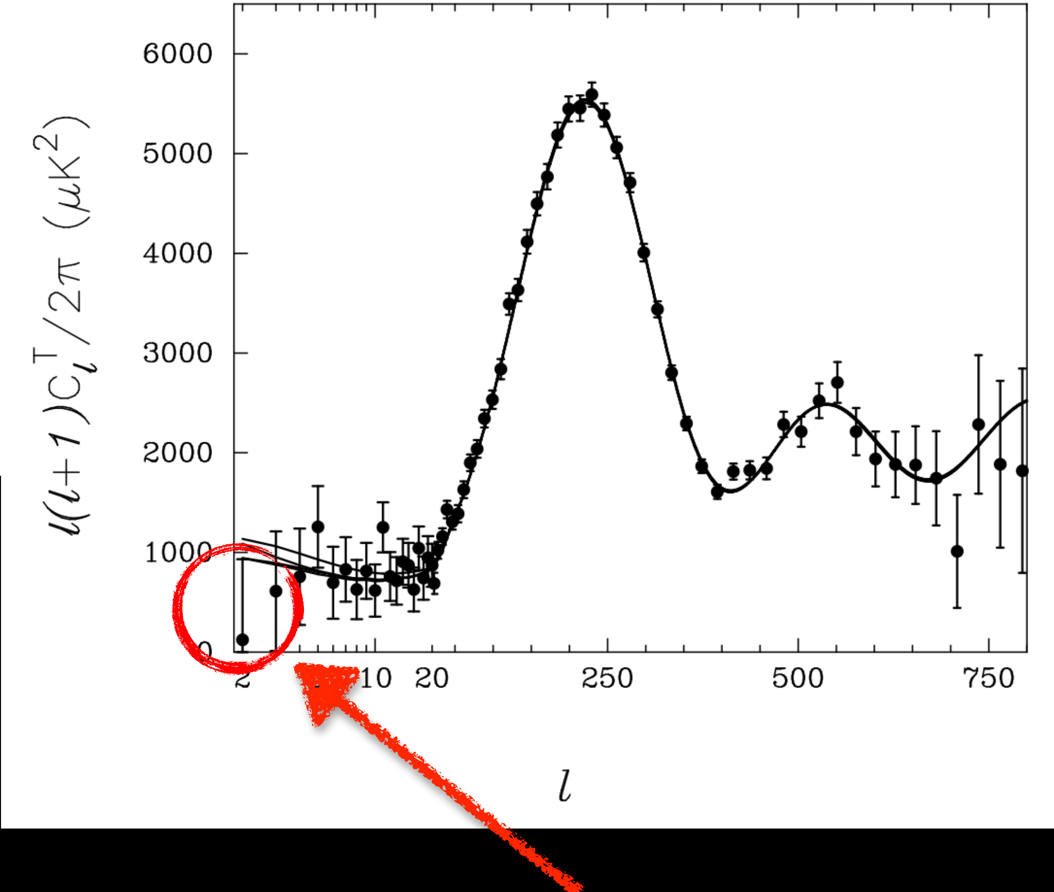
G. Efstathiou (University of Cambridge)

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

Comments: 4 pages, Latex, 2 figs, revised version accepted by MNRAS
Subjects: **Astrophysics (astro-ph)**
Journal reference: Mon.Not.Roy.Astron.Soc. 343 (2003) L95
DOI: 10.1046/j.1365-8711.2003.06940.x
Cite as: arXiv:astro-ph/0303127
(or arXiv:astro-ph/0303127v2 for this version)

Submission history

From: George Efstathiou [view email]
[v1] Wed, 5 Mar 2003 23:30:33 UTC (21 KB)
[v2] Wed, 30 Jul 2003 10:16:45 UTC (22 KB)



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

Astrophysics

[Submitted on 9 Oct 2003]

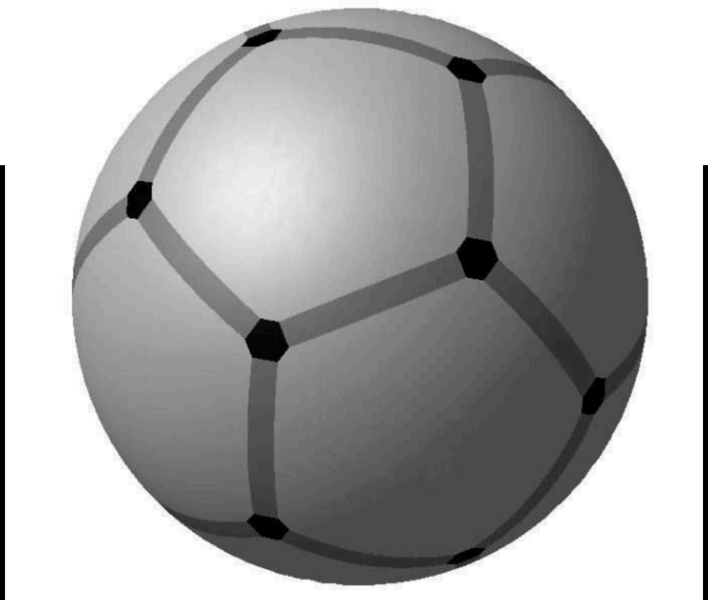
Dodecahedral space topology as an explanation for weak wide-angle temperature correlations in the cosmic microwave background

J.-P. Luminet, J. Weeks, A. Riazuelo, R. Lehoucq, J.-P. Uzan

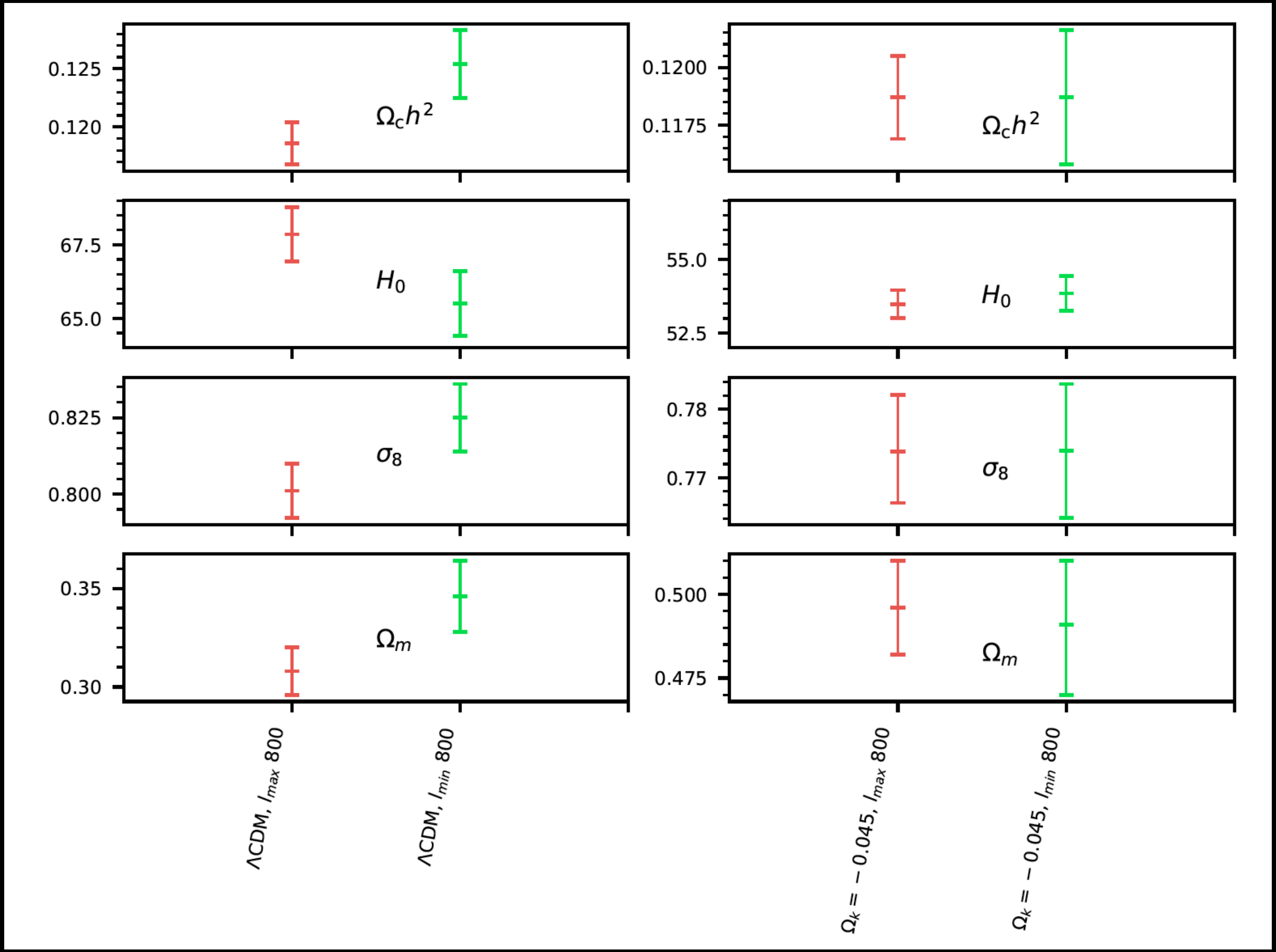
Cosmology's standard model posits an infinite flat universe forever expanding under the pressure of dark energy. First-year data from the Wilkinson Microwave Anisotropy Probe (WMAP) confirm this model to spectacular precision on all but the largest scales (Bennett {\it et al.}, 2003 ; Spergel {\it et al.}, 2003). Temperature correlations across the microwave sky match expectations on scales narrower than 60° , yet vanish on scales wider than 60° . Researchers are now seeking an explanation of the missing wide-angle correlations (Contaldi {\it et al.}, 2003 ; Cline {\it et al.}, 2003). One natural approach questions the underlying geometry of space, namely its curvature (Efstathiou, 2003) and its topology (Tegmark {\it et al.}, 2003). In an infinite flat space, waves from the big bang would fill the universe on all length scales. The observed lack of temperature correlations on scales beyond 60° means the broadest waves are missing, perhaps because space itself is not big enough to support them.
Here we present a simple geometrical model of a finite, positively curved space -- the Poincaré dodecahedral space -- which accounts for WMAP's observations with no fine-tuning required. Circle searching (Cornish, Spergel and Starkman, 1998) may confirm the model's topological predictions, while upcoming Planck Surveyor data may confirm its predicted density of $\Omega_0 \simeq 1.013 > 1$. If confirmed, the model will answer the ancient question of whether space is finite or infinite, while retaining the standard Friedmann-Lema\^ıtre foundation for local physics.

Comments: 10 pages, 4 figures. This is a slightly longer version of the paper published in Nature 425, p. 593, 2003
Subjects: **Astrophysics (astro-ph)**; General Relativity and Quantum Cosmology (gr-qc)
Journal reference: Nature 425 (2003) 593
DOI: 10.1038/nature01944
Cite as: arXiv:astro-ph/0310253
(or arXiv:astro-ph/0310253v1 for this version)

Luminet et al. propose a simple geometrical model of a finite, positively curved space – the Poincaré dodecahedral space – which accounts for WMAP's observations with no fine-tuning required.



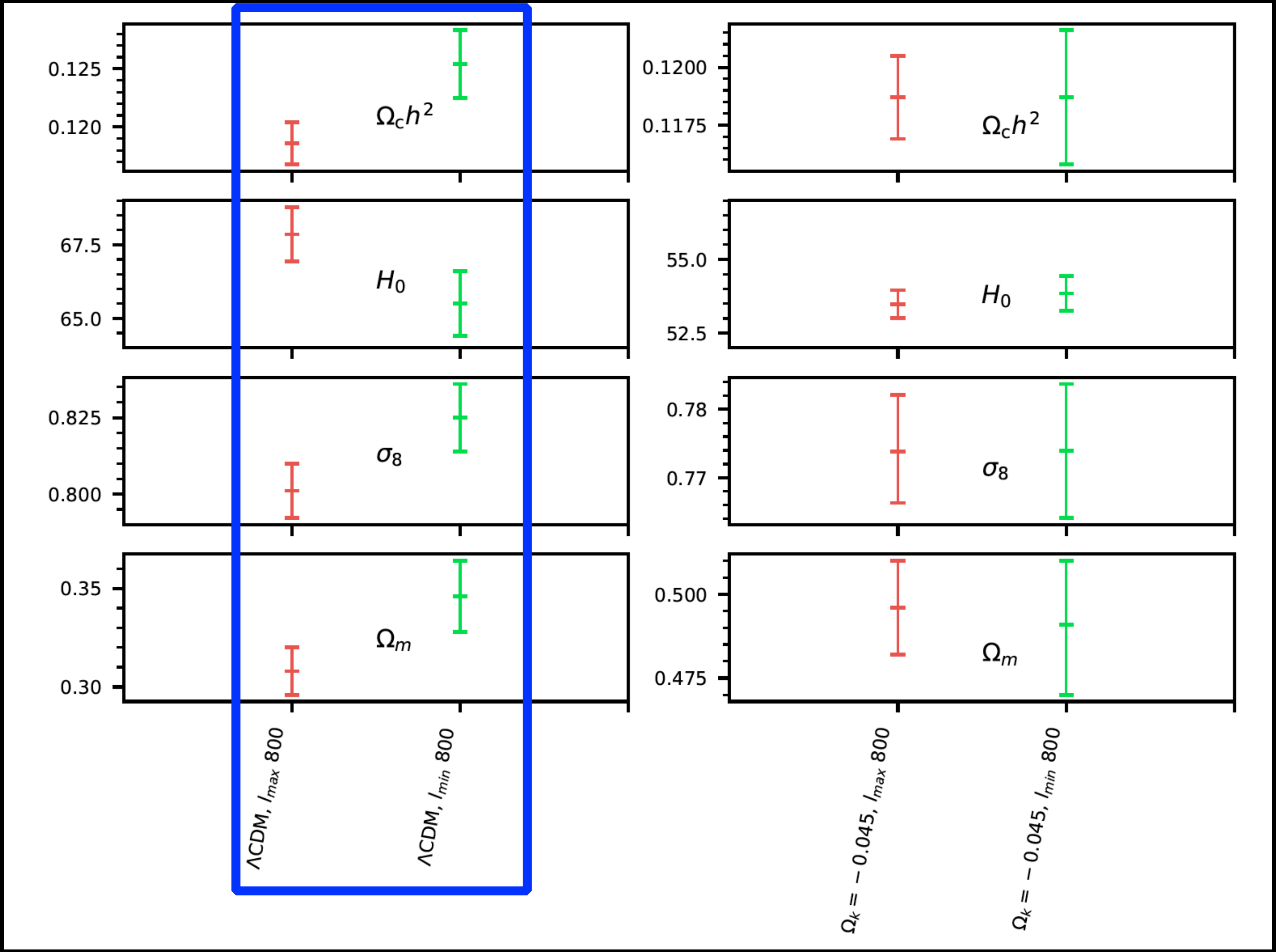
Curvature can explain internal tension



Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

In a closed Universe with ΩK = –0.045, the cosmological parameters derived in the two different multipole ranges are now fully compatible.

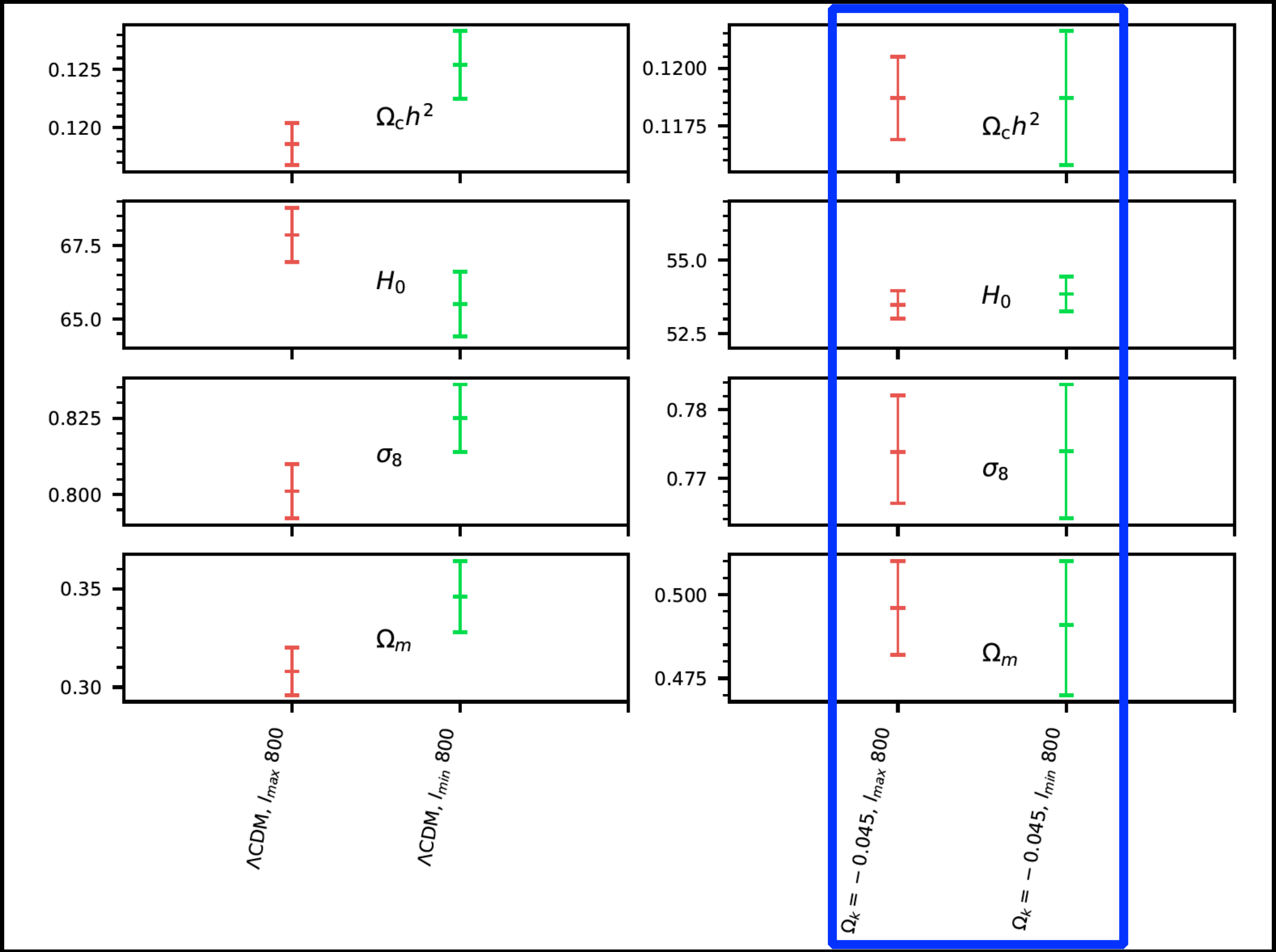
Curvature can explain internal tension



Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

In a closed Universe with ΩK = –0.045, the cosmological parameters derived in the two different multipole ranges are now fully compatible.

Curvature can explain internal tension



Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

In a closed Universe with ΩK = –0.045, the cosmological parameters derived in the two different multipole ranges are now fully compatible.

Curvature of the universe

To better quantify the preference for a closed model, we adopt the deviance information criterion (DIC), which takes into account the Bayesian complexity, that is, the effective number of parameters, of the extended model and is defined as

$$\mathrm{DIC} = 2\overline{\chi^2_{\mathrm{eff}}} - \chi^2_{\mathrm{eff}}$$

where the bar denotes a mean over the posterior distribution. We find that the Planck data yield $\Delta\mathrm{DIC} = -7.4$; that is, a closed Universe with $\Omega k = -0.0438$ is preferred, with a probability ratio of about 1/41, with respect to a flat model.

Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

Curvature of the universe

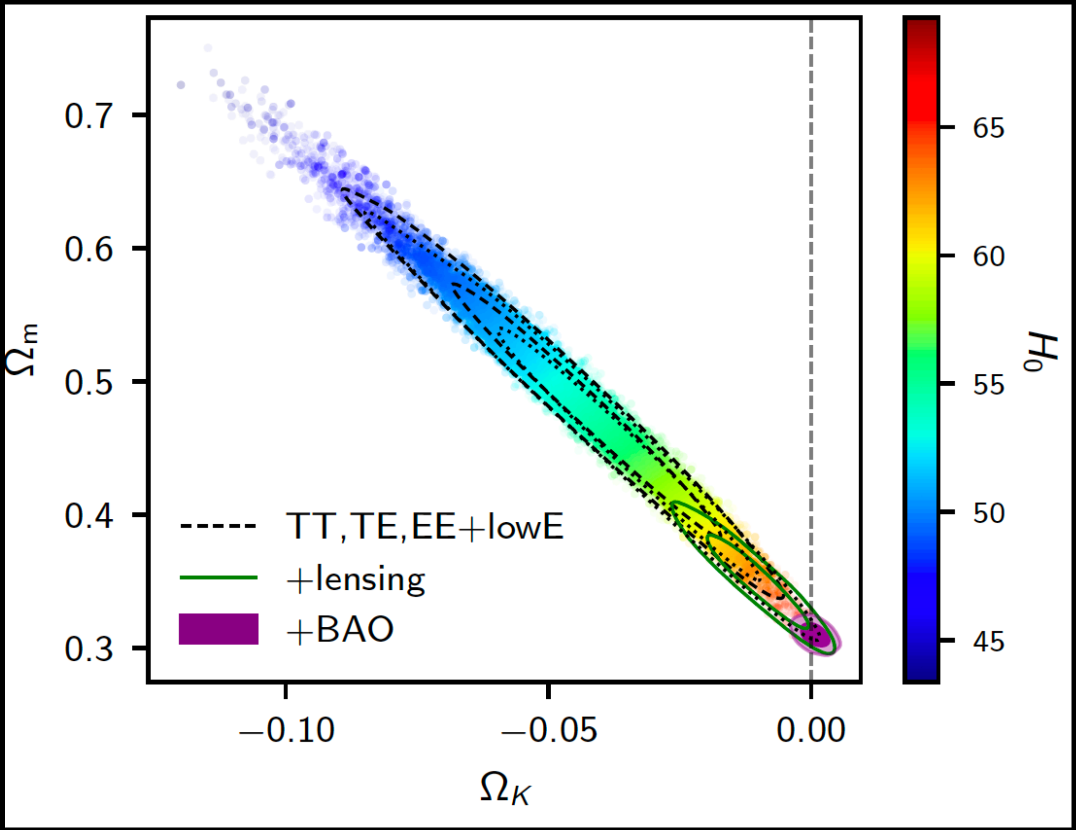
We also compute the Bayesian evidence ratio by making use of the Savage–Dickey density ratio. In this case the Bayes factor can be written as

$$B_{01} = \left. \frac{p(\Omega_K|d, M_1)}{\pi(\Omega_K|M_1)} \right|_{\Omega_K=0}$$

where M1 denotes the model with curvature, p(ΩK|d, M1) is the posterior for ΩK in this theoretical framework, computed from a specific dataset d, and π(ΩK|M1) is the prior on ΩK that we assume to be flat in the range –0.2 ≤ ΩK ≤ 0.
For Planck we obtain a Bayes ratio of | ln B01 | = 3.3, i.e. a strong evidence for a closed universe with respect to a flat one.

Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

Curvature of the universe



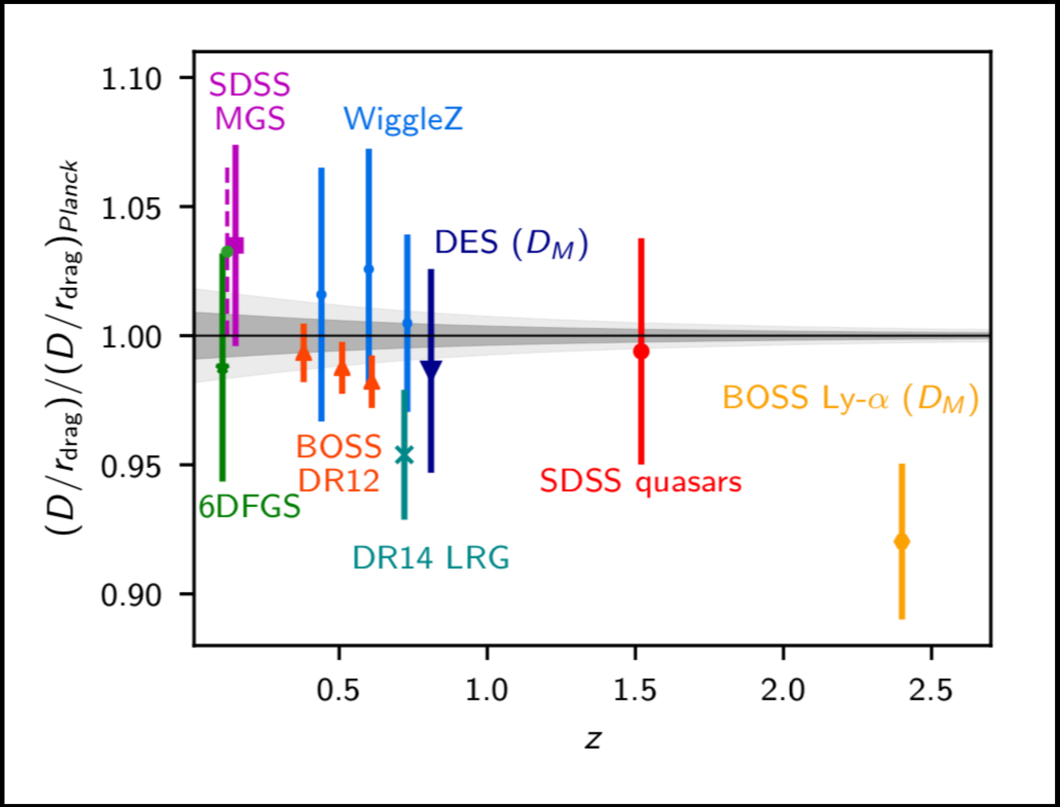
Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

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

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

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

BAO tension

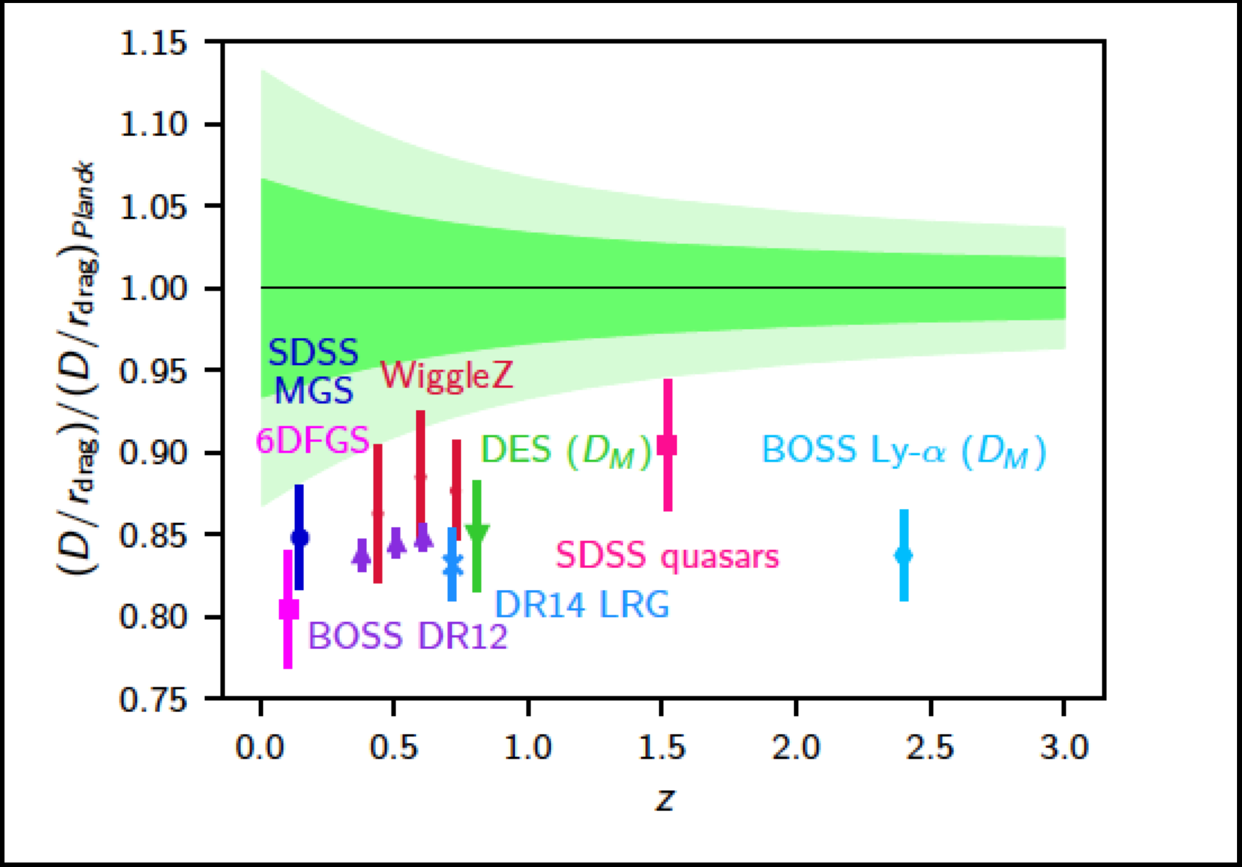


Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

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

In a ΛCDM model the BAO data agree really well with the Planck measurements…

BAO tension



Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

… but when we let curvature to vary

there is a striking disagreement between Planck spectra and BAO measurements!

BAO tension

Observable	Redshift	BAO (68% CL)	Planck (68% CL)	Tension
$D_M(r_{d,fid}/r_d)$ (Mpc)	0.38	$1{,}518 \pm 22.8$	$1{,}843 \pm 100$	2.9σ
$D_M(r_{d,fid}/r_d)$ (Mpc)	0.51	$1{,}977 \pm 26.9$	$2{,}361 \pm 115$	3.0σ
$D_M(r_{d,fid}/r_d)$ (Mpc)	0.61	$2{,}283 \pm 32.3$	$2{,}726 \pm 130$	3.3σ
$H(r_{d,fid}/r_d)$ ($\mathrm{km\,s^{-1}\,Mpc^{-1}}$)	0.38	81.5 ± 1.9	71.6 ± 3.3	2.6σ
$H(r_{d,fid}/r_d)$ ($\mathrm{km\,s^{-1}\,Mpc^{-1}}$)	0.51	90.5 ± 1.97	78.9 ± 3.1	3.1σ
$H(r_{d,fid}/r_d)$ ($\mathrm{km\,s^{-1}\,Mpc^{-1}}$)	0.61	97.3 ± 2.1	85.0 ± 3.0	3.3σ

Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

In the Table we have the constraints on DM and H(z) from the recent analysis of BOSS DR12 data and the corresponding constraints obtained indirectly from Planck, assuming a ΛCDM model with curvature.

Planck is inconsistent with each of the BAO measurements at more than 3σ!

The assumption of a flat universe could therefore mask a cosmological crisis where disparate observed properties of the Universe appear to be mutually inconsistent.

BAO tension

Additional dataset	$\Delta\chi^2_{\mathrm{eff}}$	ΔN_{data}	$\log_{10}\mathcal{I}$
flat ΛCDM			
+BAO	+6.15	8	0.2
+CMB lensing	+8.9	9	0.6
$\Lambda\mathrm{CDM}+\Omega_K$			
+BAO	+16.9	8	−1.8
+CMB lensing	+16.9	9	−0.84

Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

As we can see from the Table, the Planck χ2 best fit is worse by Δχ2 ≈ 16.9 when the BAO data are included under the assumption of curvature. This is a significantly larger Δχ2 than obtained for the case of ΛCDM (Δχ2 ≈ 6.15).
The BAO dataset that we adopted consists of two independent measurements (6dFGS36 and SDSS-MGS37) with relatively large error bars, and six correlated measurements from BOSS DR12.

BAO tension

Additional dataset	$\Delta\chi^2_{\rm eff}$	$\Delta N_{\rm data}$	$\log_{10}\mathcal{I}$
flat ΛCDM			
+ BAO	+6.15	8	0.2
+ CMB lensing	+8.9	9	0.6
ΛCDM + Ω_K			
+ BAO	+16.9	8	−1.8
+ CMB lensing	+16.9	9	−0.84

Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

To quantify the discrepancy between two cosmological datasets, D1 and D2, we use the following quantity based on the DIC approach:

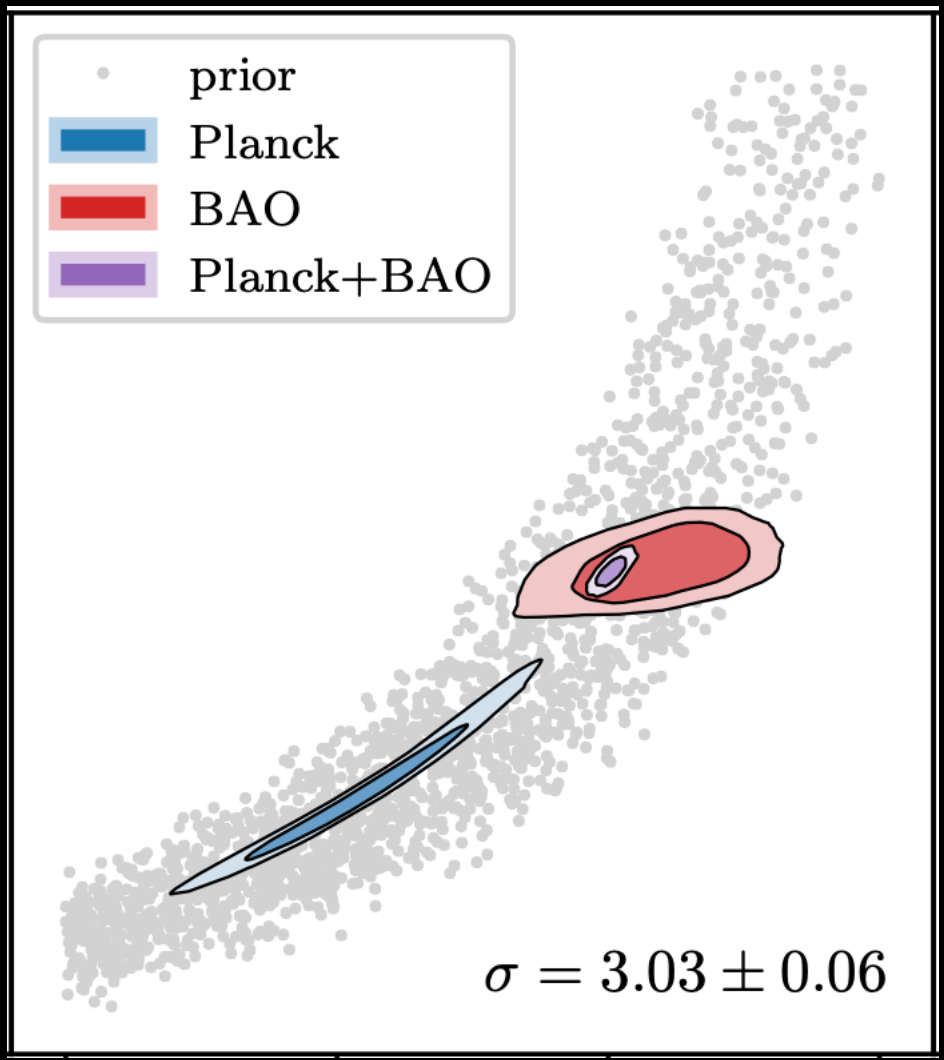
$$\mathcal{I}(D_1, D_2) \equiv \exp\{-\mathcal{F}(D_1, D_2)/2\}$$

where

$$\mathcal{F}(D_1, D_2) = \mathrm{DIC}(D_1 \cup D_2) - \mathrm{DIC}(D_1) - \mathrm{DIC}(D_2)$$

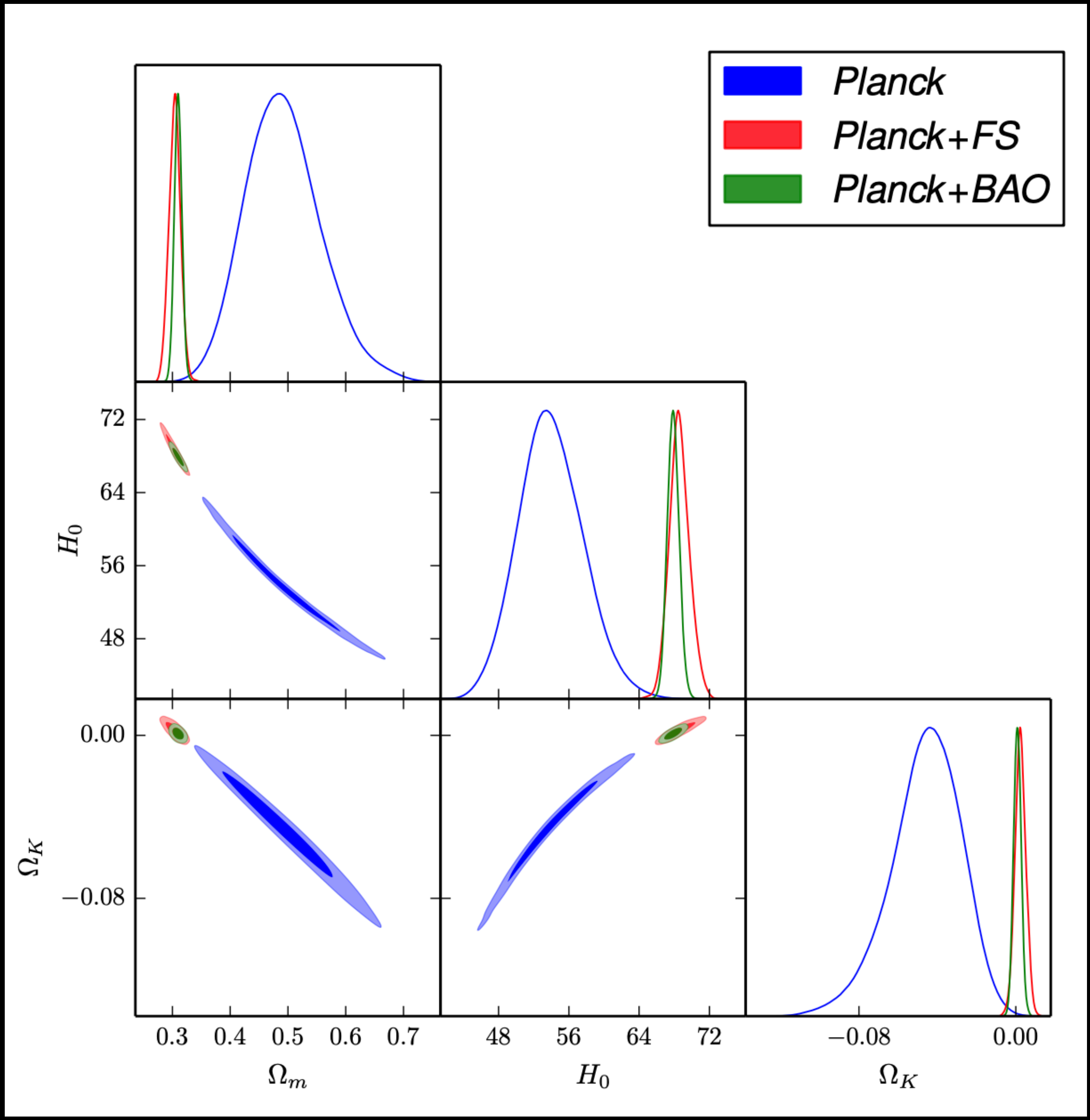
Following the Jeffreys scale the agreement/disagreement is considered ‘substantial’ if | log10 I |>0.5, ‘strong’ if | log10 I |>1.0 and ‘decisive’ if | log10 I |>2.0. When is positive, then two datasets are in agreement, whereas they are in tension if this parameter is negative. We find a strong disagreement between Planck and BAO.

BAO tension



In agreement with Handley, 1908.09139

FS tension



Vagnozzi, Di Valentino, et al., arXiv:2010.02230 [astro-ph.CO]

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

For Planck and FS we find $\log_{10} I \sim -2.5$, i.e. a decisive disagreement on the Jeffreys-like scale.

CMB lensing tension

Additional dataset	$\Delta\chi^2_{\rm eff}$	$\Delta N_{\rm data}$	$\log_{10}\mathcal{I}$
flat ΛCDM			
+BAO	+6.15	8	0.2
+CMB lensing	+8.9	9	0.6
$\Lambda\mathrm{CDM}+\Omega_K$			
+BAO	+16.9	8	−1.8
+CMB lensing	+16.9	9	−0.84

Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

Another tension is present between Planck power spectra and the constraints on the lensing potential derived from the four-point correlation function of Planck CMB maps.

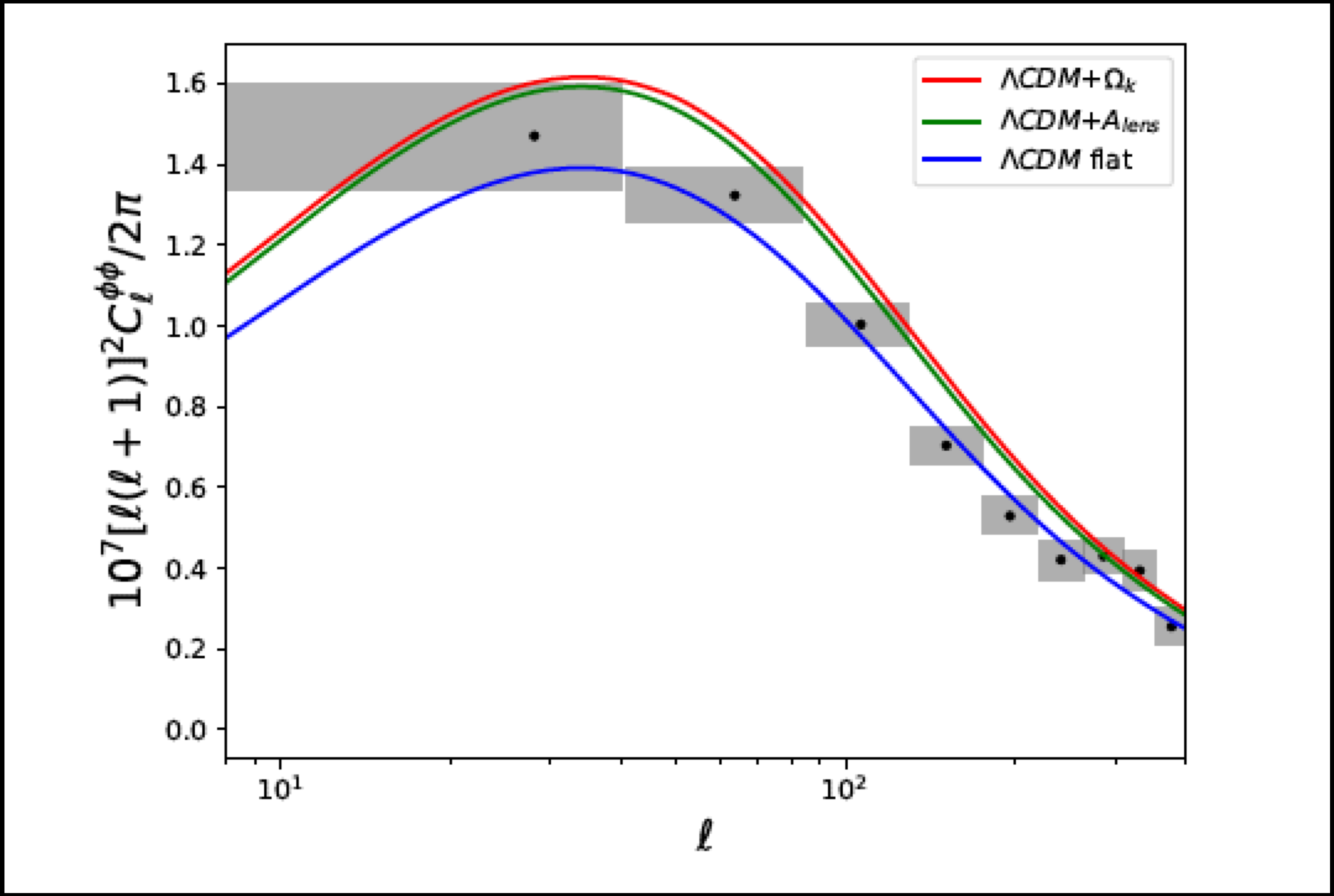
The inclusion of CMB lensing in Planck increases the best-fit Δχ2 = 16.9 in the case of ΛCDM + ΩK (while in the case of the ΛCDM model, we have Δχ2 = 8.9). The CMB lensing dataset consists of nine correlated data points.

We identify substantial discordance between Planck and CMB lensing.

The combination of Planck with external datasets should be, therefore, considered with caution when working within a non-flat Universe.

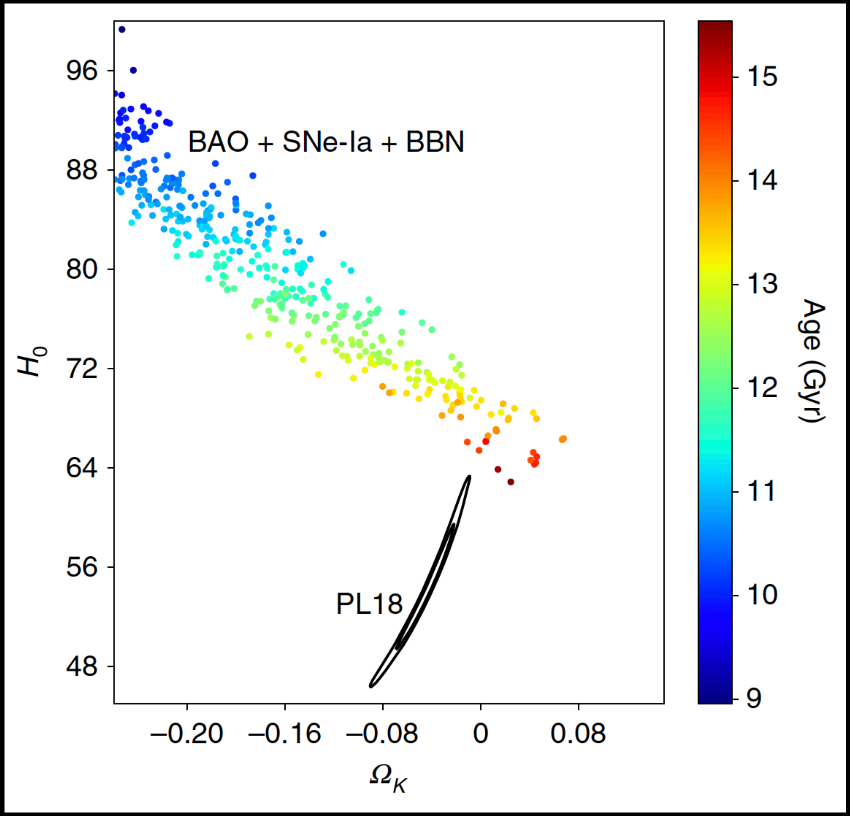
CMB lensing tension

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



Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

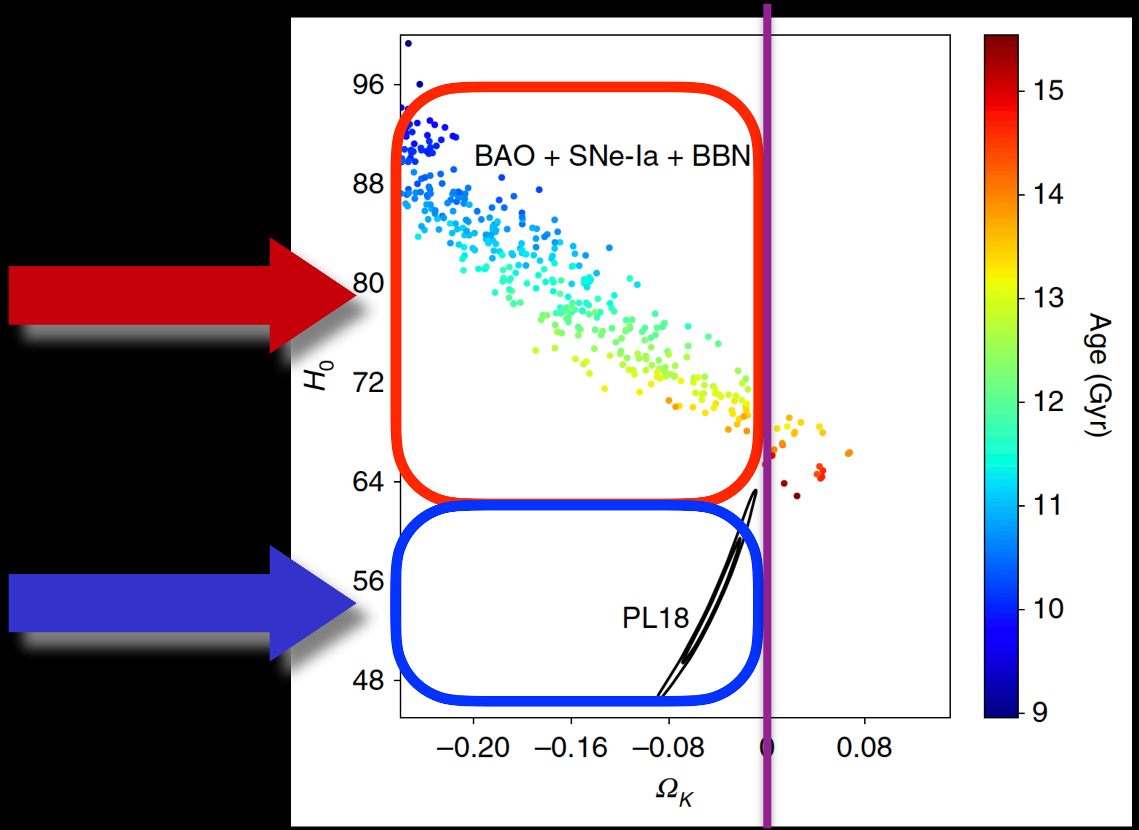
What about non-CMB data?



Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

It is now interesting to address the compatibility of Planck with combined datasets, like BAO + type-Ia supernovae + big bang nucleosynthesis data.
In principle, each dataset prefers a closed universe,
but BAO+SN-Ia+BBN gives H0 = 79.6 ± 6.8 km/s/Mpc at 68%cl, perfectly consistent with R19, but at 3.4σ tension with Planck.

What about non-CMB data?

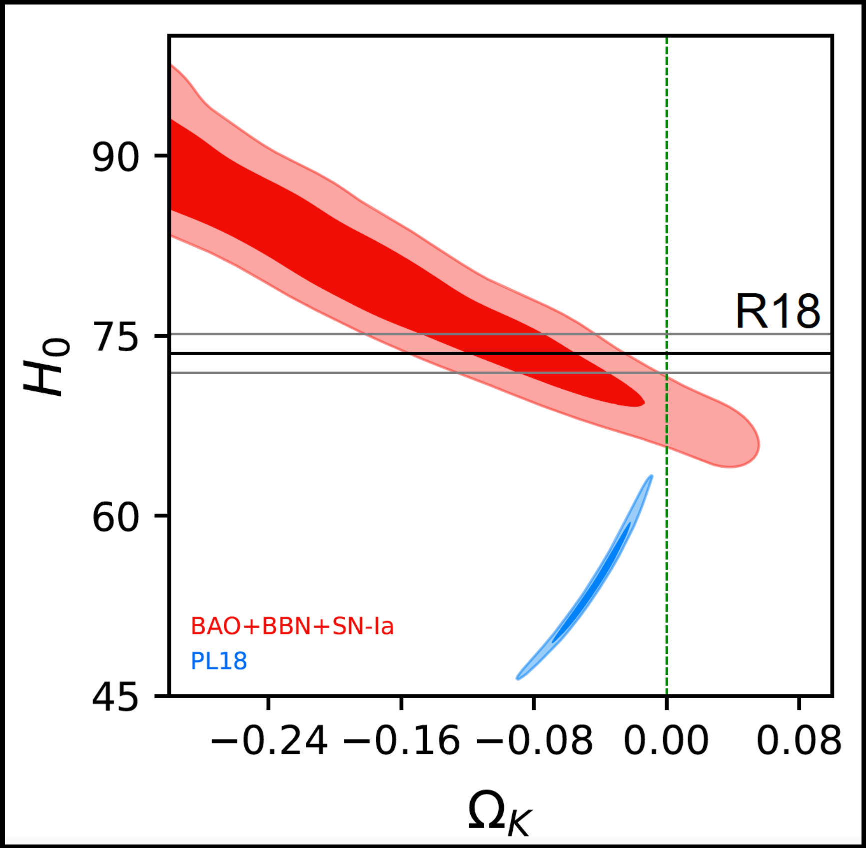


Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

It is now interesting to address the compatibility of Planck with combined datasets, like BAO + type-Ia supernovae + big bang nucleosynthesis data.
In principle, each dataset prefers a closed universe,
but BAO+SN-Ia+BBN gives H0 = 79.6 ± 6.8 km/s/Mpc at 68%cl, perfectly consistent with R19, but at 3.4σ tension with Planck.

BAO+SNIa+BBN+R18 gives Ωk = -0.091 ± 0.037 at 68%cl.

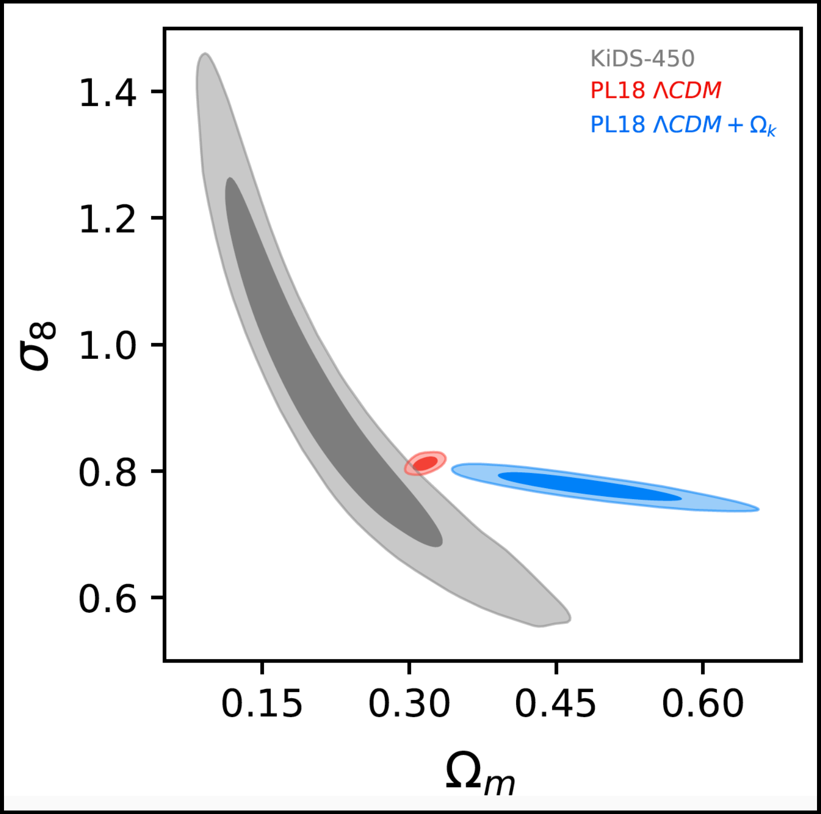
Curvature can’t explain external tensions



Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

Varying Ω_κ, both the well know tensions on H0 and S8 are exacerbates.
In a ΛCDM + ΩK model, Planck gives $H0 = 54.4^{+3.3}_{-4.0}$ km/s/Mpc at 68% cl., increasing the tension with R19 at 5.4σ.

Curvature can't explain external tensions



Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

Varying Ωκ, both the well know tensions on H0 and S8 are exacerbates.
In a ΛCDM + ΩK model, Planck gives S8 in disagreement at about 3.8σ with KiDS-450, and more than 3.5σ with DES.

Very well welcomed!

New Scientist:
“If this is true, it would have profound implications on our understanding of the universe,” says David Spergel at Princeton University. “It’s a really important claim, but I’m not sure it’s one that’s backed by the data. In fact, I’d say the evidence is actually against it.”

Quanta Magazine:
Antony Lewis, a cosmologist at the University of Sussex and a member of the Planck team who worked on that analysis, said:“is that it is just a statistical fluke.” Lewis and other experts say they’ve already closely scrutinized the issue, along with related puzzles in the data.

Salon:
“The result is intriguing, but only of borderline statistical significance to be believed. There are several independent lines of evidence that suggest the Universe is flat, and that this claim is a statistical fluke or a misinterpretation of the data,” Avi Loeb, chair of Harvard's astronomy department, told Salon via email.

Scientific American:
Efstathiou asked not to be directly quoted, but pointed out in an email to Live Science that if the universe were curved, it would raise a number of problems contradicting those other data sets from the early universe and making discrepancies in the universe’s observed rate of expansion much worse. Gratton said he agreed.

Astrophysics > Cosmology and Nongalactic Astrophysics

The evidence for a spatially flat Universe

George Efstathiou, Steven Gratton

(Submitted on 17 Feb 2020)

We revisit the observational constraints on spatial curvature following recent claims that the Planck data favour a closed Universe. We use a new and statistically powerful Planck likelihood to show that the Planck temperature and polarization spectra are consistent with a spatially flat Universe, though because of a geometrical degeneracy cosmic microwave background spectra on their own do not lead to tight constraints on the curvature density parameter Omega_K. When combined with other astrophysical data, particularly geometrical measurements of baryon acoustic oscillations, the Universe is constrained to be spatially flat to extremely high precision, with Omega_ K = 0.0004 +/-0.0018 in agreement with the 2018 results of the Planck team. In the context of inflationary cosmology, the observations offer strong support for models of inflation with a large number of e-foldings and disfavour models of incomplete inflation.

Comments: submitted to MNRAS

4 CONCLUSIONS

The geometry of the Universe is a question of fundamental importance to cosmology. We have argued that the claims in Di Valentino et al. (2019) that *Planck* data strongly favour closed Universes at high significance are a consequence of using the `Plik` TTTEEE likelihood which differs from the `CamSpec` likelihood and ignoring the importance of priors.

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], R. B. Barreiro[61], N. Bartolo[29,62], S. Basak[85], R. Battye[64], K. Benabed[55,90], J.-P. Bernard[95,8], M. Bersanelli[32,45], P. Bielewicz[75,78], J. J. Bock[63,10], J. R. Bond[7], J. Borrill[12,93], F. R. Bouchet[55,90], F. Boulanger[89,54,55], M. Bucher[2,6], C. Burigana[44,30,47], R. C. Butler[41], E. Calabrese[82], J.-F. Cardoso[55,90], J. Carron[23], A. Challinor[58,65,11], H. C. Chiang[25,6], J. Chluba[64], L. P. L. Colombo[32], C. Combet[68], D. Contreras[20], B. P. Crill[63,10],
F. Cuttaia[41], P. de Bernardis[31], G. de Zotti[42], J. Delabrouille[2],
A. Ducout[66], X. Dupac[35], S. Dusini[62], G. Efstathiou[65,58*],
J. Fergusson[11], R. Fernandez-Cobos[61], F. Finelli[41,47], F. Forastie
S. Galli[55,90†], K. Ganga[2], R. T. Génova-Santos[60,16], M. Gerb
A. Gruppuso[41,47], J. E. Gudmundsson[94,25], J. Hamann[86], W. H
Z. Huang[83], A. H. Jaffe[53], W. C. Jones[25], A. Karakci[59], E. K
N. Krachmalnicoff[78], M. Kunz[14,54,3], H. Kurki-Suonio[24,40], G.
M. Le Jeune[2], P. Lemos[58,65], J. Lesgourgues[56], F. Levrier[89]
M. López-Caniego[35], P. M. Lubin[28], Y.-Z. Ma[77,80,74], J. F. M
A. Marcos-Caballero[61], M. Maris[43], P. G. Martin[7], M. Martinel
P. R. Meinhold[28], A. Melchiorri[31,50], A. Mennella[32,45], M.
D. Molinari[30,41,48], L. Montier[95,8], G. Morgante[41], A. Moss[8
B. Partridge[39], G. Patanchon[2], H. V. Peiris[22], F. Perrotta[7
J. P. Rachen[18], M. Reinecke[72], M. Remazeilles[64], A. Re
B. Ruiz-Granados[60,16], L. Salvati[54], M. Sandri[41], M. Savelainen
R. Sunyaev[72,91], A.-S. Suur-Uski[24,40], J. A. Tauber[36], D. T
L. Valenziano[41], J. Valiviita[24,40], B. Van Tent[69], L. Vibert[54,55], P
S. D. M. White

(*Affiliations c*

Page 40

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

an apparent detection of curvature at well over $2\,\sigma$. 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

We present cosmological parameter results from the final full- isotropies, combining information from the temperature and p improved measurements of large-scale polarization allow the re cant gains in the precision of other correlated parameters. Impr many parameters, with residual modelling uncertainties estimate spatially-flat 6-parameter ΛCDM cosmology having a power-law from polarization, temperature, and lensing, separately and in co baryon density $\Omega_b h^2 = 0.0224 \pm 0.0001$, scalar spectral index n_s 68 % confidence regions on measured parameters and 95 % on $100\theta_* = 1.0411 \pm 0.0003$. These results are only weakly depende in many commonly considered extensions. Assuming the base-ΛCDM cosmology, the inferred (model-dependent) late-Universe parameters are: Hubble constant $H_0 = (67.4\pm0.5)\,\mathrm{km\,s^{-1}Mpc^{-1}}$; matter density parameter $\Omega_m = 0.315\pm0.007$; and matter fluctuation amplitude $\sigma_8 = 0.811\pm0.006$. 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 effective extra relativistic degrees of freedom to be $N_{\rm eff} = 2.99\pm0.17$, in agreement with the Standard Model prediction $N_{\rm eff} = 3.046$, and find that the neu to prefer higher lensing amplitudes than predicted in base ΛCDM from the ΛCDM model; however, this is not supported by the l BAO data. The joint constraint with BAO measurements on spatia with Type Ia supernovae (SNe), the dark-energy equation of stat constant. We find no evidence for deviations from a purely pow Keck Array data, we place a limit on the tensor-to-scalar ratio deuterium abundances for the base-ΛCDM cosmology are in exc agreement with BAO, SNe, and some galaxy lensing observatio including galaxy clustering (which prefers lower fluctuation amp measurements of the Hubble constant (which prefer a higher value). Simple model extensions that partially resolve these tensions are not favoured by the *Planck* data.

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

*Corresponding author: G. Efstathiou, gpe@ast.cam.ac.uk
†Corresponding author: S. Galli, gallis@iap.fr
‡Corresponding author: A. Lewis, antony@cosmologist.info

*Corresponding author: G. Efstathiou, gpe@ast.cam.ac.uk
†Corresponding author: S. Galli, gallis@iap.fr
‡Corresponding author: A. Lewis, antony@cosmologist.info

arXiv.org > astro-ph > arXiv:2002.06892

Search...

Help | Advanced

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 17 Feb 2020]

The evidence for a spatially flat Universe

George Efstathiou, Steven Gratton

Objections raised in the paper are:

- Use of the Plik likelihood instead of CamSpec.

arXiv.org > astro-ph > arXiv:2002.06892

Search...

Help | Advanced

Astrophysics > Cosmology and Nongalactic Astrophysics

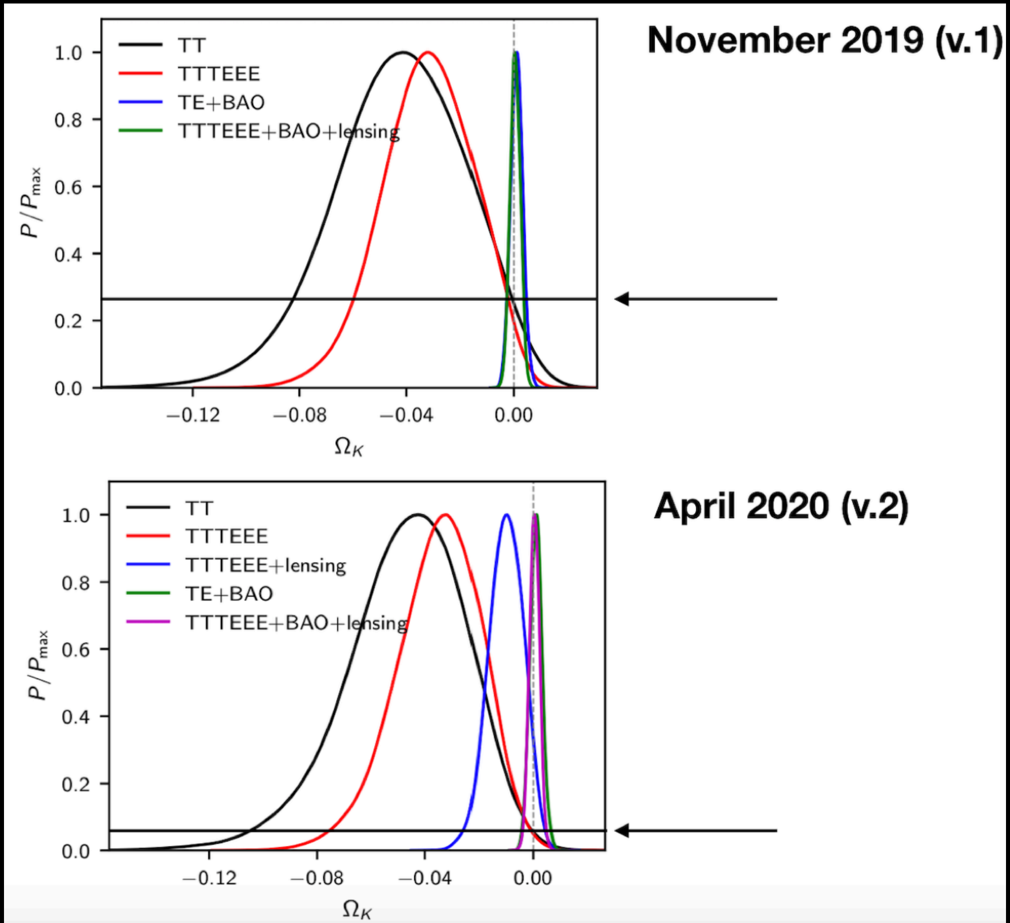
[Submitted on 17 Feb 2020]

The evidence for a spatially flat Universe

George Efstathiou, Steven Gratton

Objections raised in the paper are:

- Use of the Plik likelihood instead of CamSpec.



Plik is the baseline likelihood of Planck, while CamSpec was not publicly available.

Efstathiou and Gratton, arXiv:1910.00483

In the meantime, comparing the different versions of the CamSpec paper, we can see an increase of the evidence for a curvature different from zero, now preferring $-0.083<\Omega_K<-0.001$ at 99% CL.

arXiv.org > astro-ph > arXiv:2002.06892

Search...

Help | Advanced

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 17 Feb 2020]

The evidence for a spatially flat Universe

George Efstathiou, Steven Gratton

Objections raised in the paper are:

- Uniform prior on omegak instead of a prior peaked in zero, as predicted by inflation.

arXiv.org > astro-ph > arXiv:2002.06892

Search...

Help | Advanced

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 17 Feb 2020]

The evidence for a spatially flat Universe

George Efstathiou, Steven Gratton

Objections raised in the paper are:

- Uniform prior on omegak instead of a prior peaked in zero, as predicted by inflation.

Our prior is flat and uniform on Omegak as done by Planck and as adopted for all the other parameters.

We are deriving observational constraints on Ω_K, therefore an inflationary prior that strongly prefers a flat Universe could bias our results.

We are looking for a constraint independent from any underlying theoretical model.

arXiv.org > astro-ph > arXiv:2002.06892

Search...

Help | Advanced

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 17 Feb 2020]

The evidence for a spatially flat Universe

George Efstathiou, Steven Gratton

Objections raised in the paper are:

- Use of the low multipoles (ell<30) data showing an amplitude suppression as predicted by a closed universe.

[Submitted on 17 Feb 2020]

The evidence for a spatially flat Universe

George Efstathiou, Steven Gratton

Objections raised in the paper are:

- Use of the low multipoles (ell<30) data showing an amplitude suppression as predicted by a closed universe.

For a curved universe the primordial power spectrum used by the Boltzmann code to analyse the data is parametrised as:

$$\Delta(k) = \frac{(q^2 - 4K)^2}{q(q^2 - K)} k^{n_s - 1}$$

$$q = \sqrt{k^2 + K}$$

where K is the curvature parameter (+1 = closed, 0 = flat, -1 = open).

This form ensures that potential fluctuations are constant per logarithmic interval in wavenumber k. This is a strong assumption about how primordial fluctuations behave to scales larger than the curvature scale, and wants to generalize the concept of scale-invariant fluctuations to scales close to it.

This has not a theoretical motivation, so the $\chi 2$ shouldn't be over-interpreted.

arXiv.org > astro-ph > arXiv:2002.06892

Search...

Help | Advanced

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 17 Feb 2020]

The evidence for a spatially flat Universe

George Efstathiou, Steven Gratton

Objections raised in the paper are:

- Use of the low multipoles (ell<30) data showing an amplitude suppression as predicted by a closed universe.

For a curved universe the primordial power spectrum used by the Boltzmann code to analyse the data is parametrised as:

$$\Delta(k) = \frac{(q^2 - 4K)^2}{q(q^2 - K)} k^{n_s - 1}$$

$$q = \sqrt{k^2 + K}$$

where K is the curvature parameter (+1 = closed, 0 = flat, -1 = open).

A more accurate predictions for the primordial power spectrum in a curved Universe can be found in Handley, Phys. Rev. D100 (2019) 123517, and this increases the evidence for a closed universe from Planck.

arXiv.org > astro-ph > arXiv:2002.06892

Search...

Help | Advanced

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 17 Feb 2020]

The evidence for a spatially flat Universe

George Efstathiou, Steven Gratton

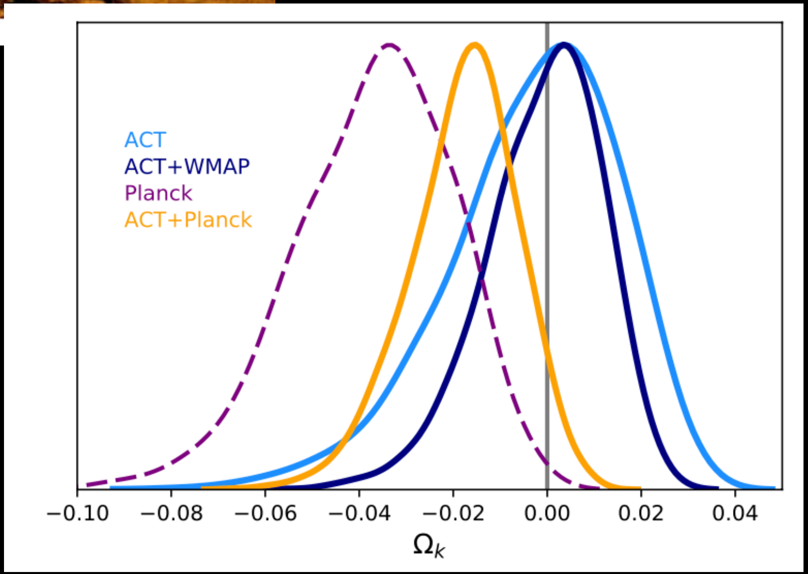
Objections raised in the paper are:

- Possible statistical fluctuation or possible systematics in Planck.

Agree! We need more data!

The latest ACT results

To thicken the mystery we have the new ACT results:



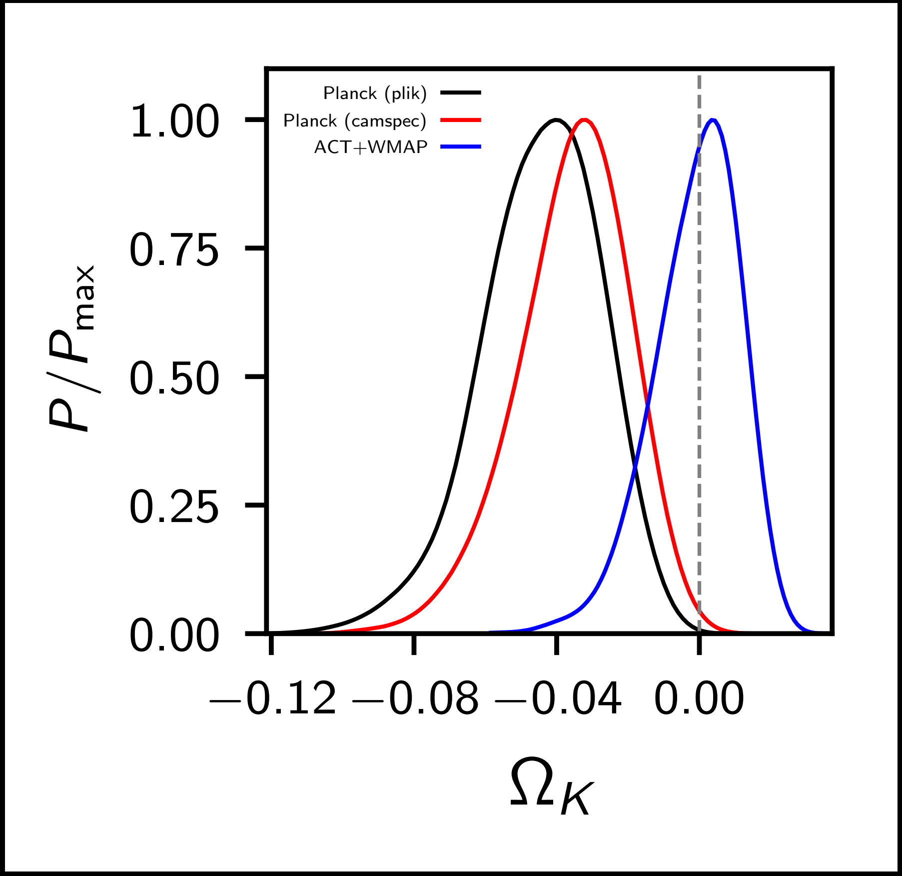
ACT-DR4 + WMAP give at 68% CL

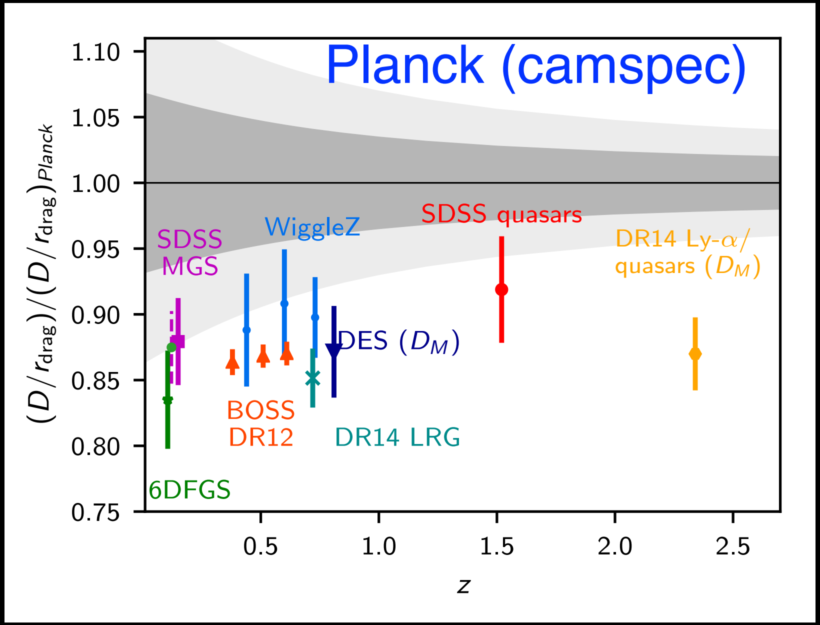
$$\Omega_k = -0.001 \pm 0.012$$

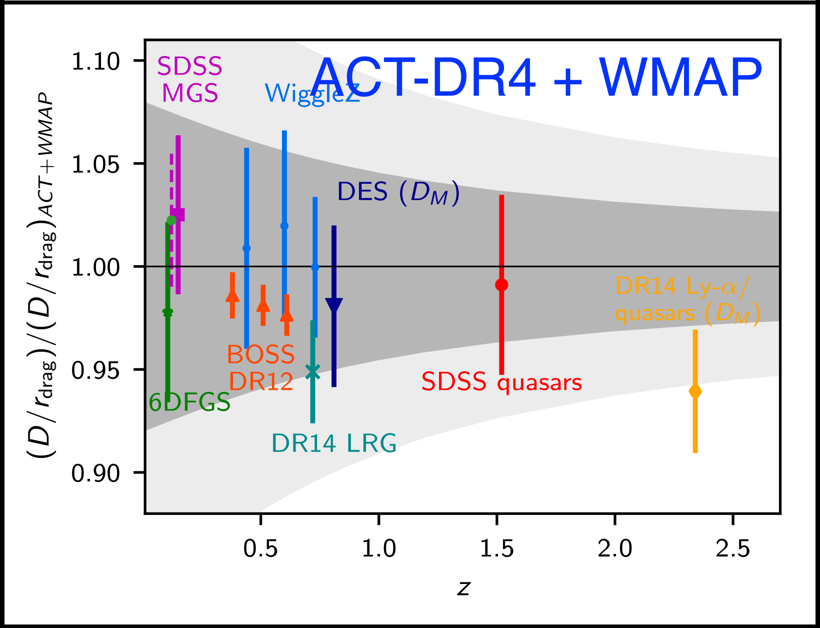
ACT-DR4 2020, Aiola et al., arXiv:2007.07288 [astro-ph.CO]

The curvature of the universe

Di Valentino et al. in preparation





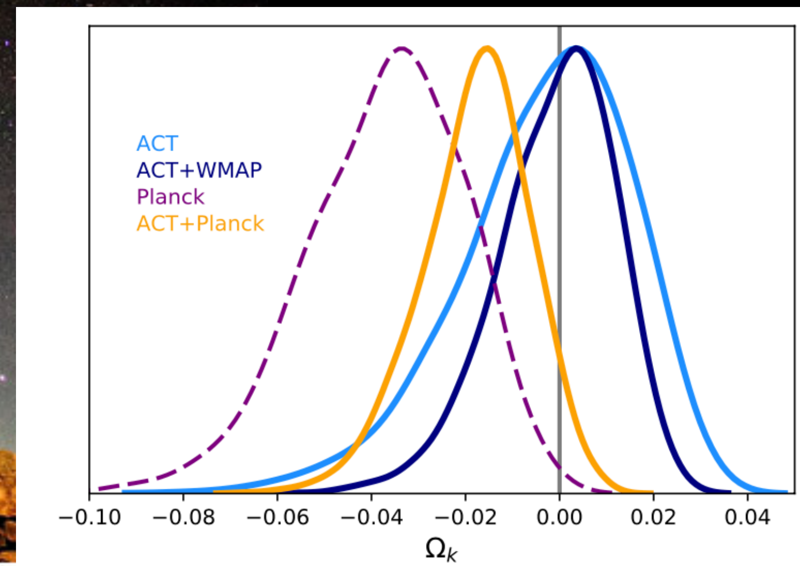


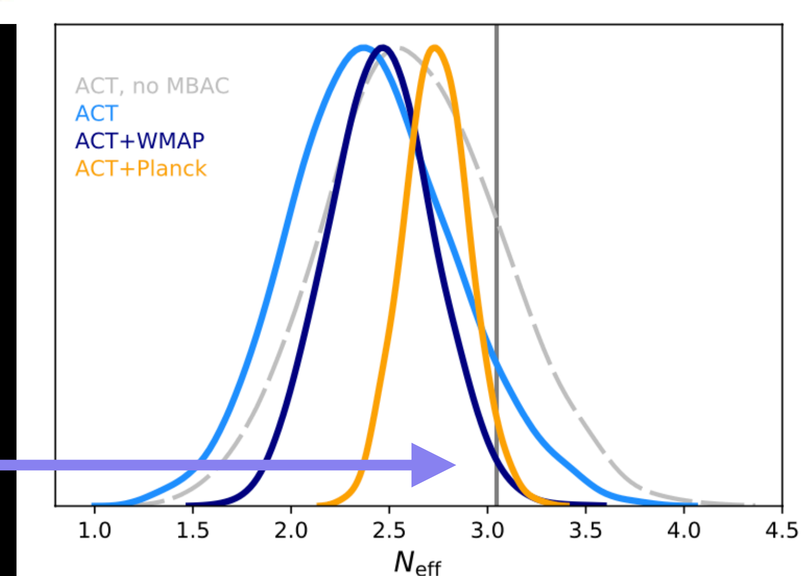
From this analysis we can learn two things:

- the Ωk prior and the low-l multipoles are not important
- new camspec prefers Ωk <0 at more than 99% CL and it is in disagreement with the BAO data.

The latest ACT results

To thicken the mystery we have the new ACT results:





ACT-DR4 + WMAP give at 68% CL also

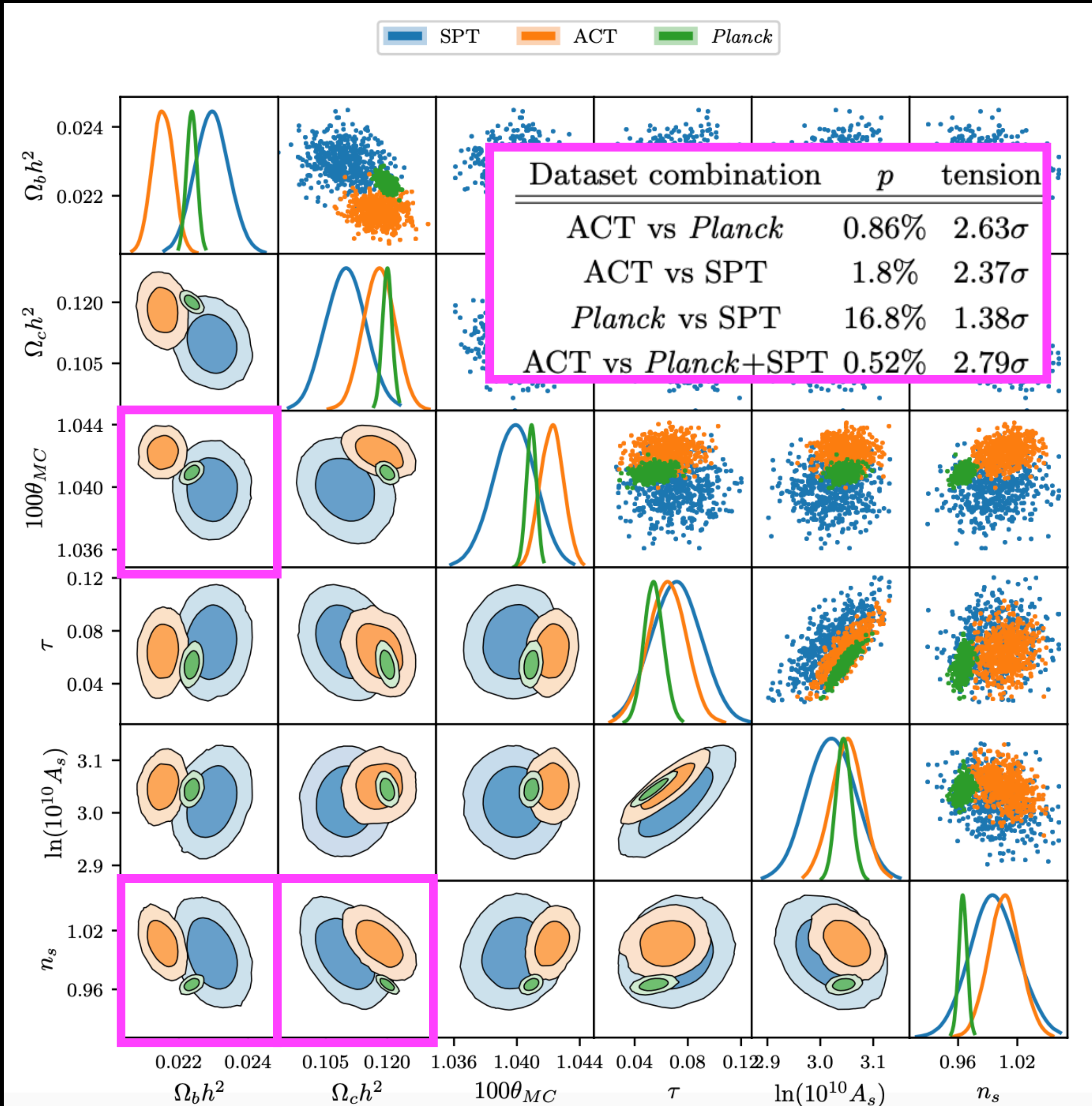
$N_{\text{eff}} = 2.46 \pm 0.26$

ruling out a third neutrino at about 2.8σ.

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

The latest ACT results

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

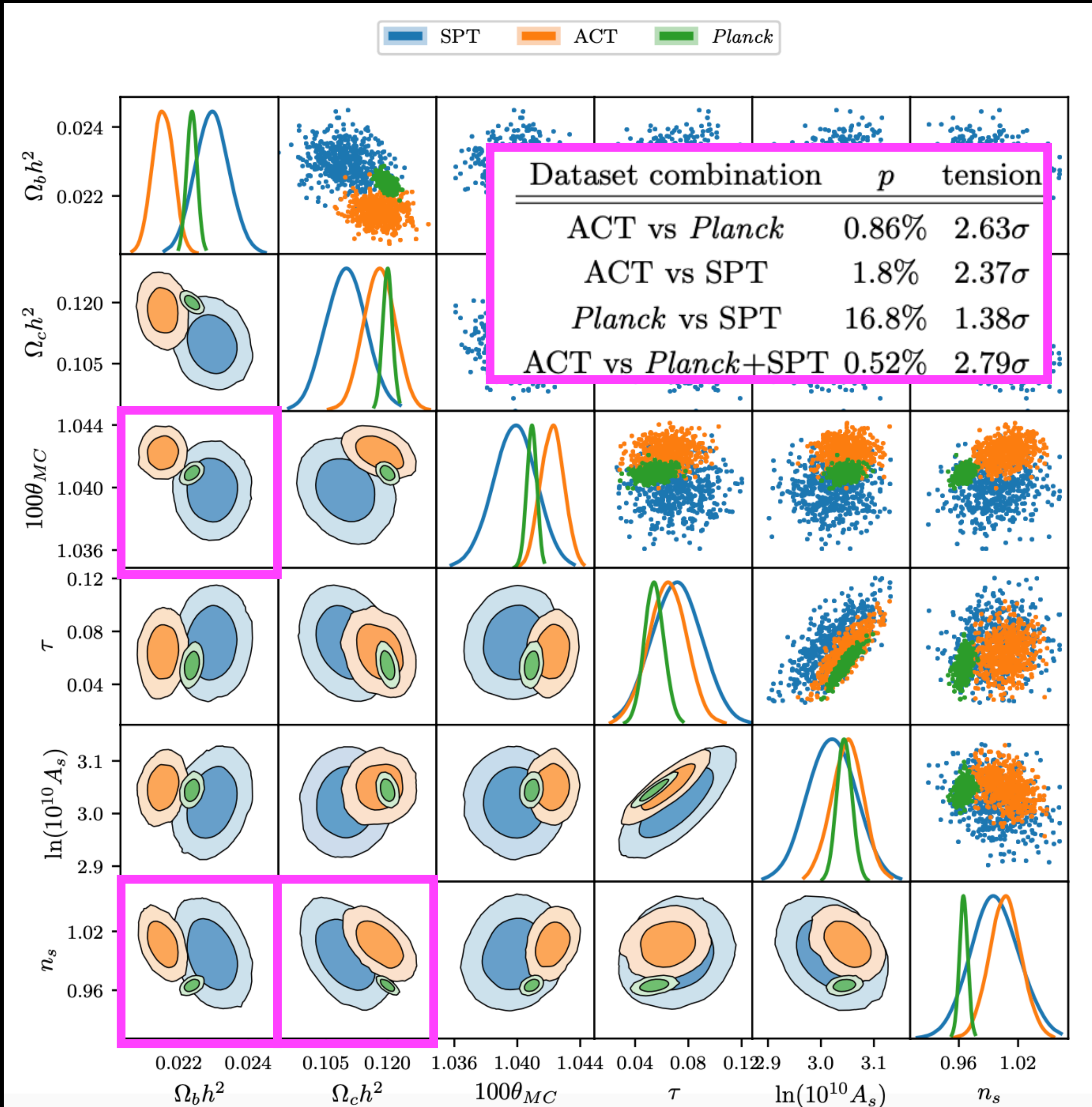
Global tensions between CMB datasets.

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.

The latest ACT results

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

At this point, given the quality of all the analyses, it is more likely that these discrepancies are indicating a problem with the underlying cosmology and our understanding of the Universe, rather than the presence of systematic effects.

And this suspect is corroborated by the many other tensions we saw emerging between the other cosmological probes.

arXiv.org > astro-ph > arXiv:2002.06892

Search...

Help | Advanced

Astrophysics > Cosmology and Nongalactic Astrophysics

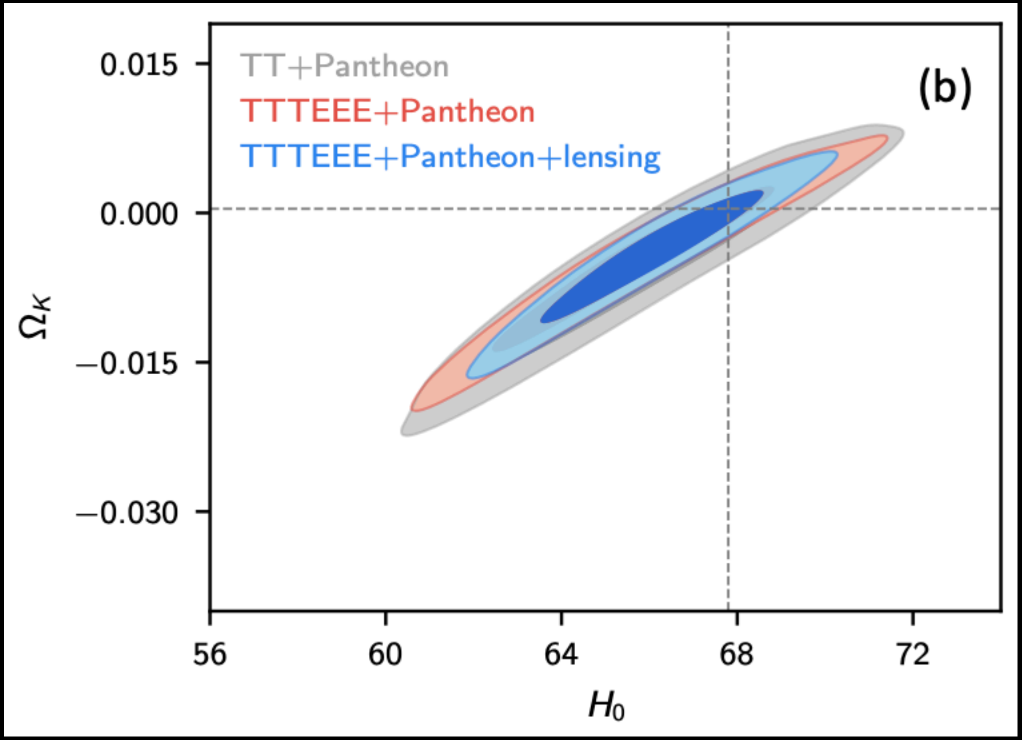
[Submitted on 17 Feb 2020]

The evidence for a spatially flat Universe

George Efstathiou, Steven Gratton

Objections raised in the paper are:

- Indication for a flat universe by combining Planck with other datasets (CMB lensing, BAO and Pantheon) — in particular Planck + Pantheon not discussed in our paper.



The Dark energy equation of state

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

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

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

w introduces a geometrical degeneracy with the Hubble constant that is almost unconstrained using the CMB data only, resulting in agreement with R19.

What happens if we vary all the parameters together?
Planck + Pantheon is still in agreement with a flat Universe?
Can we improve the agreement with H0?

Constraints at 68% cl.

10 parameters: replacing Alens with curvature

Parameters	Planck	Planck +R19	Planck +F20	Planck +BAO	Planck + Pantheon
$\Omega_b h^2$	0.02253 ± 0.00019	$0.02253^{+0.00020}_{-0.00016}$	$0.02255^{+0.00019}_{-0.00017}$	0.02243 ± 0.00016	0.02255 ± 0.00018
$\Omega_c h^2$	0.1183 ± 0.0016	$0.1187^{+0.0015}_{-0.0018}$	0.1184 ± 0.0015	0.1198 ± 0.0014	0.1186 ± 0.0015
$100\theta_{\rm MC}$	1.04099 ± 0.00035	$1.04103^{+0.00034}_{-0.00031}$	1.04105 ± 0.00034	1.04095 ± 0.00032	1.04107 ± 0.00034
τ	0.0473 ± 0.0083	$0.052^{+0.009}_{-0.011}$	0.0491 ± 0.0079	0.0563 ± 0.0081	0.0506 ± 0.0082
Σm_ν [eV]	$0.43^{+0.16}_{-0.37}$	< 0.513	$0.28^{+0.11}_{-0.23}$	< 0.194	< 0.420
w	$-1.6^{+1.0}_{-0.8}$	$-2.11^{+0.35}_{-0.77}$	-2.14 ± 0.46	$-1.038^{+0.098}_{-0.088}$	$-1.27^{+0.14}_{-0.09}$
Ω_k	$-0.074^{+0.058}_{-0.025}$	$-0.0192^{+0.0036}_{-0.0099}$	$-0.0263^{+0.0060}_{-0.0077}$	$0.0003^{+0.0027}_{-0.0037}$	$-0.029^{+0.011}_{-0.010}$
$\ln(10^{10} A_s)$	3.025 ± 0.018	$3.037^{+0.016}_{-0.026}$	3.030 ± 0.017	3.049 ± 0.017	3.034 ± 0.017
n_s	0.9689 ± 0.0054	$0.9686^{+0.0056}_{-0.0050}$	0.9693 ± 0.0051	0.9648 ± 0.0048	0.9685 ± 0.0051
α_S	-0.0005 ± 0.0067	-0.0012 ± 0.0066	-0.0010 ± 0.0068	-0.0054 ± 0.0068	-0.0023 ± 0.0065
H_0[km/s/Mpc]	53^{+6}_{-16}	73.8 ± 1.4	69.3 ± 2.0	$68.6^{+1.5}_{-1.8}$	60.5 ± 2.5
σ_8	$0.74^{+0.08}_{-0.16}$	0.932 ± 0.040	0.900 ± 0.039	0.821 ± 0.027	$0.812^{+0.031}_{-0.018}$
S_8	$0.989^{+0.095}_{-0.063}$	0.874 ± 0.032	$0.900^{+0.034}_{-0.031}$	0.826 ± 0.016	0.927 ± 0.037
Age[Gyr]	$16.10^{+0.92}_{-0.80}$	$14.90^{+0.72}_{-0.32}$	$15.22^{+0.054}_{-0.038}$	13.77 ± 0.10	14.98 ± 0.39
Ω_m	$0.61^{+0.21}_{-0.34}$	$0.264^{+0.010}_{-0.013}$	$0.300^{+0.017}_{-0.020}$	0.305 ± 0.016	$0.393^{+0.030}_{-0.036}$
$\Delta\chi^2_{bestfit}$	0.0	0.62	0.88	14.77	1037.82

Therefore, now we want to check the robustness of these results further increasing the number of parameters, in addition to curvature.

Di Valentino et al., arXiv:2003.04935

Constraints at 68% cl.

10 parameters: replacing Alens with curvature

Parameters	Planck	Planck +R19	Planck +F20	Planck +BAO	Planck + Pantheon
$\Omega_b h^2$	0.02253 ± 0.00019	$0.02253^{+0.00020}_{-0.00016}$	$0.02255^{+0.00019}_{-0.00017}$	0.02243 ± 0.00016	0.02255 ± 0.00018
$\Omega_c h^2$	0.1183 ± 0.0016	$0.1187^{+0.0015}_{-0.0018}$	0.1184 ± 0.0015	0.1198 ± 0.0014	0.1186 ± 0.0015
$100\theta_{MC}$	1.04099 ± 0.00035	$1.04103^{+0.00034}_{-0.00031}$	1.04105 ± 0.00034	1.04095 ± 0.00032	1.04107 ± 0.00034
τ	0.0473 ± 0.0083	$0.052^{+0.009}_{-0.011}$	0.0491 ± 0.0079	0.0563 ± 0.0081	0.0506 ± 0.0082
Σm_ν [eV]	$0.43^{+0.16}_{-0.37}$	< 0.513	$0.28^{+0.11}_{-0.23}$	< 0.194	< 0.420
w	$-1.6^{+1.0}_{-0.8}$	$-2.11^{+0.35}_{-0.77}$	-2.14 ± 0.46	$-1.038^{+0.098}_{-0.088}$	$-1.27^{+0.14}_{-0.09}$
Ω_k	$-0.074^{+0.058}_{-0.025}$	$-0.0192^{+0.0036}_{-0.0099}$	$-0.0263^{+0.0060}_{-0.0077}$	$0.0003^{+0.0027}_{-0.0037}$	$-0.029^{+0.011}_{-0.010}$
$\ln(10^{10}A_s)$	3.025 ± 0.018	$3.037^{+0.016}_{-0.026}$	3.030 ± 0.017	3.049 ± 0.017	3.034 ± 0.017
n_s	0.9689 ± 0.0054	$0.9686^{+0.0056}_{-0.0050}$	0.9693 ± 0.0051	0.9648 ± 0.0048	0.9685 ± 0.0051
α_S	-0.0005 ± 0.0067	-0.0012 ± 0.0066	-0.0010 ± 0.0068	-0.0054 ± 0.0068	-0.0023 ± 0.0065
H_0[km/s/Mpc]	53^{+6}_{-16}	73.8 ± 1.4	69.3 ± 2.0	$68.6^{+1.5}_{-1.8}$	60.5 ± 2.5
σ_8	$0.74^{+0.08}_{-0.16}$	0.932 ± 0.040	0.900 ± 0.039	0.821 ± 0.027	$0.812^{+0.031}_{-0.018}$
S_8	$0.989^{+0.095}_{-0.063}$	0.874 ± 0.032	$0.900^{+0.034}_{-0.031}$	0.826 ± 0.016	0.927 ± 0.037
Age[Gyr]	$16.10^{+0.92}_{-0.80}$	$14.90^{+0.72}_{-0.32}$	$15.22^{+0.054}_{-0.038}$	13.77 ± 0.10	14.98 ± 0.39
Ω_m	$0.61^{+0.21}_{-0.34}$	$0.264^{+0.010}_{-0.013}$	$0.300^{+0.017}_{-0.020}$	0.305 ± 0.016	$0.393^{+0.030}_{-0.036}$
$\Delta\chi^2_{bestfit}$	0.0	0.62	0.88	14.77	1037.82

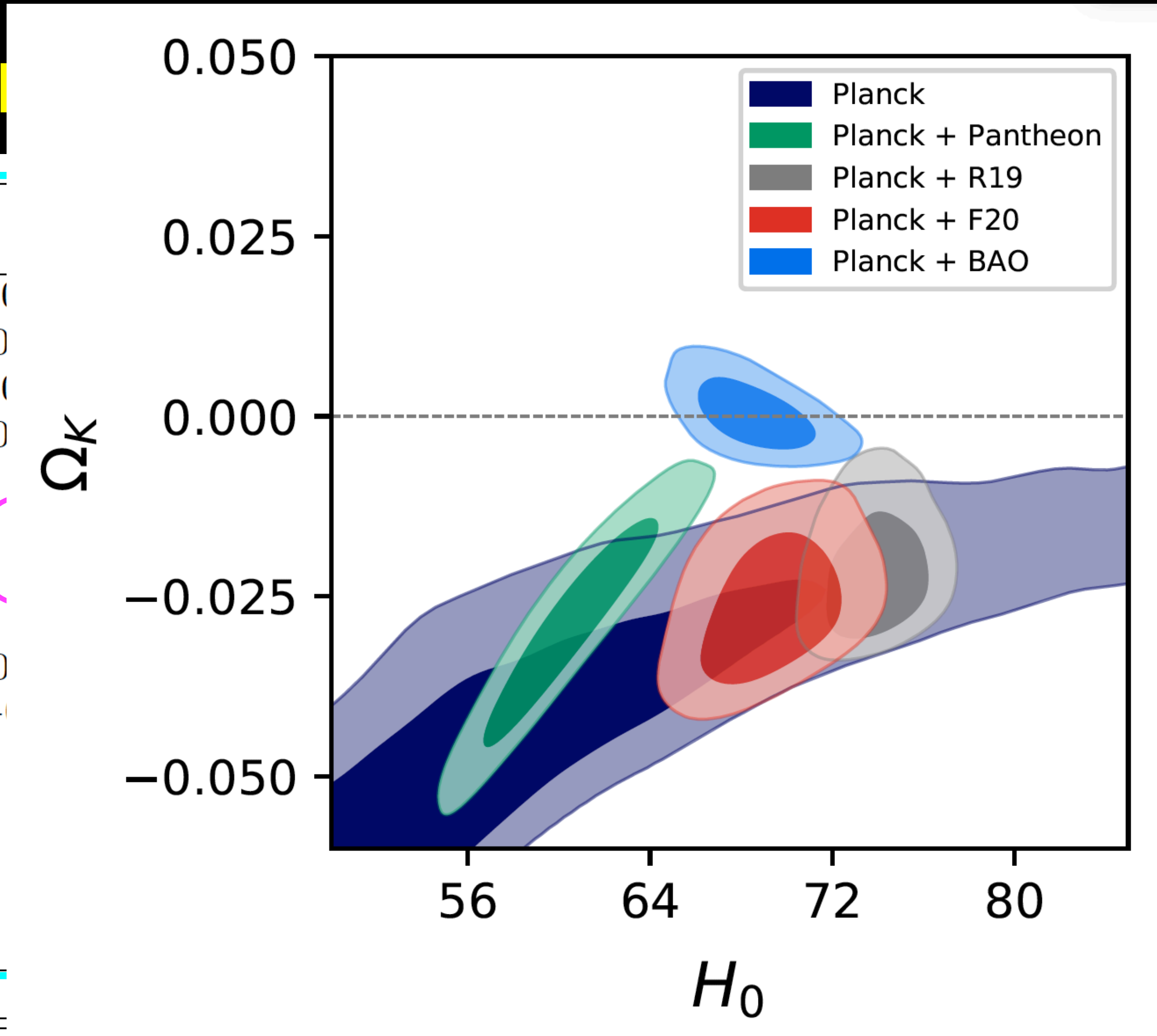
A combined analysis of the recent Planck angular power spectra with different luminosity distance measurements is in strong disagreement (at more than 99% C.L.) with the two main expectations of the standard LCDM model, i.e., a flat universe and a cosmological constant.

Di Valentino et al., arXiv:2003.04935

Constraints at 68% cl.

10 para… curvature

Parameters	Planck + Pantheon
$\Omega_b h^2$	0.02255 ± 0.00018
$\Omega_c h^2$	0.1186 ± 0.0015
$100\theta_{MC}$	1.04107 ± 0.00034
τ	0.0506 ± 0.0082
Σm_ν [eV]	< 0.420
w	$-1.27^{+0.14}_{-0.09}$
Ω_k	$-0.029^{+0.011}_{-0.010}$
$\ln(10^{10} A_s)$	3.034 ± 0.017
n_s	0.9685 ± 0.0051
α_S	-0.0023 ± 0.0065
H_0[km/s/Mpc]	60.5 ± 2.5
σ_8	$0.812^{+0.031}_{-0.018}$
S_8	0.927 ± 0.037
Age[Gyr]	14.98 ± 0.39
Ω_m	$0.393^{+0.030}_{-0.036}$
$\Delta\chi^2_{bestfit}$	1037.82



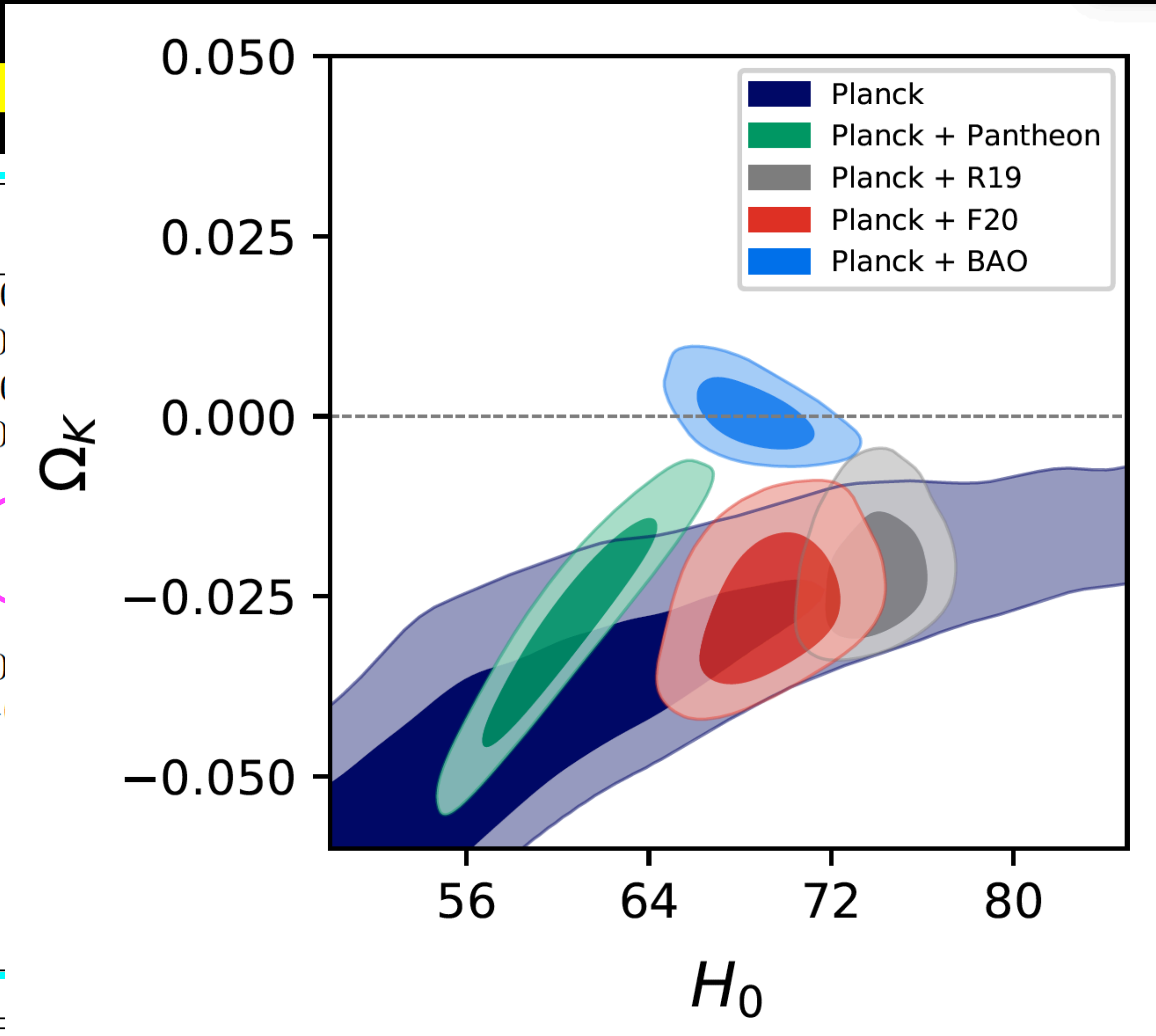
The confidence levels from Planck are clearly below the $\Omega_k = 0$ line that describes a flat universe. On the other hand, the Planck data are now in perfect agreement with the Pantheon, R19, and F20 (Freedman et al. arXiv:2002.01550) measurements, while they are still in strong tension with the BAO measurements, so their combination should be considered with some caution.

Di Valentino et al., arXiv:2003.04935

Constraints at 68% cl.

10 para curvature

Parameters			Planck + Pantheon
$\Omega_b h^2$	0.(	016	0.02255 ± 0.00018
$\Omega_c h^2$	0	14	0.1186 ± 0.0015
$100\theta_{MC}$	1.(	032	1.04107 ± 0.00034
τ	0	81	0.0506 ± 0.0082
Σm_ν [eV]			< 0.420
w		8 8	$-1.27^{+0.14}_{-0.09}$
Ω_k		7 7	$-0.029^{+0.011}_{-0.010}$
$\ln(10^{10} A_s)$		7	3.034 ± 0.017
n_s	0	48	0.9685 ± 0.0051
α_S	−(	068	-0.0023 ± 0.0065
H_0[km/s/Mpc]			60.5 ± 2.5
σ_8		7	$0.812^{+0.031}_{-0.018}$
S_8		6	0.927 ± 0.037
Age[Gyr]		)	14.98 ± 0.39
Ω_m		6	$0.393^{+0.030}_{-0.036}$
$\Delta\chi^2_{bestfit}$			1037.82



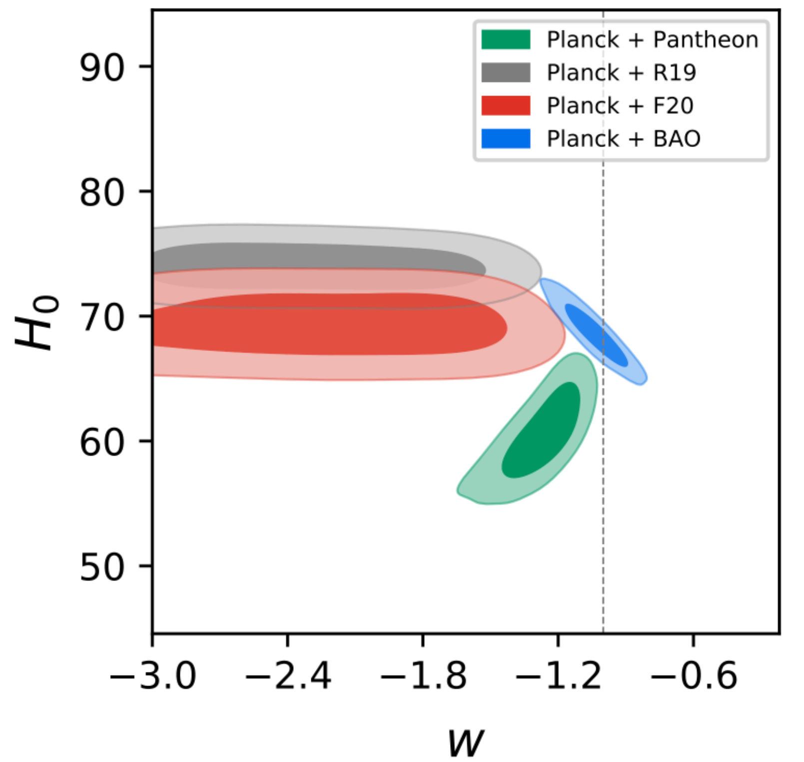
Moreover, all the 95% confidence regions from the Planck+Pantheon, Planck+F20, and Planck+R19 datasets are well below the $\Omega_k = 0$ line. This clearly shows that the recent claims of a closed universe as being incompatible with luminosity distance measurements are simply due to the assumption of a cosmological constant.

Di Valentino et al., arXiv:2003.04935

Constraints at 68% cl.

10 parameters: replacing Alens with curvature

Parameters	Planck	Planck +	Planck	Planck	Planck + Pantheon
$\Omega_b h^2$	0.02253 ± 0.00019	0.0225		16	0.02255 ± 0.00018
$\Omega_c h^2$	0.1183 ± 0.0016	0.118		4	0.1186 ± 0.0015
$100\theta_{MC}$	1.04099 ± 0.00035	1.0410		32	1.04107 ± 0.00034
τ	0.0473 ± 0.0083	0.05		1	0.0506 ± 0.0082
Σm_ν [eV]	$0.43^{+0.16}_{-0.37}$	$<$			< 0.420
w	$-1.6^{+1.0}_{-0.8}$	$-2.$			$-1.27^{+0.14}_{-0.09}$
Ω_k	$-0.074^{+0.058}_{-0.025}$	-0.01			$-0.029^{+0.011}_{-0.010}$
$\ln(10^{10} A_s)$	3.025 ± 0.018	3.03			3.034 ± 0.017
n_s	0.9689 ± 0.0054	0.968		8	0.9685 ± 0.0051
α_S	-0.0005 ± 0.0067	-0.001		68	-0.0023 ± 0.0065
H_0[km/s/Mpc]	53^{+6}_{-16}	73.8			60.5 ± 2.5
σ_8	$0.74^{+0.08}_{-0.16}$	0.932			$0.812^{+0.031}_{-0.018}$
S_8	$0.989^{+0.095}_{-0.063}$	0.874			0.927 ± 0.037
Age[Gyr]	$16.10^{+0.92}_{-0.80}$	14.9			14.98 ± 0.39
Ω_m	$0.61^{+0.21}_{-0.34}$	0.26			$0.393^{+0.030}_{-0.036}$
$\Delta\chi^2_{bestfit}$	0.0	0.62	0.88	14.77	1037.82

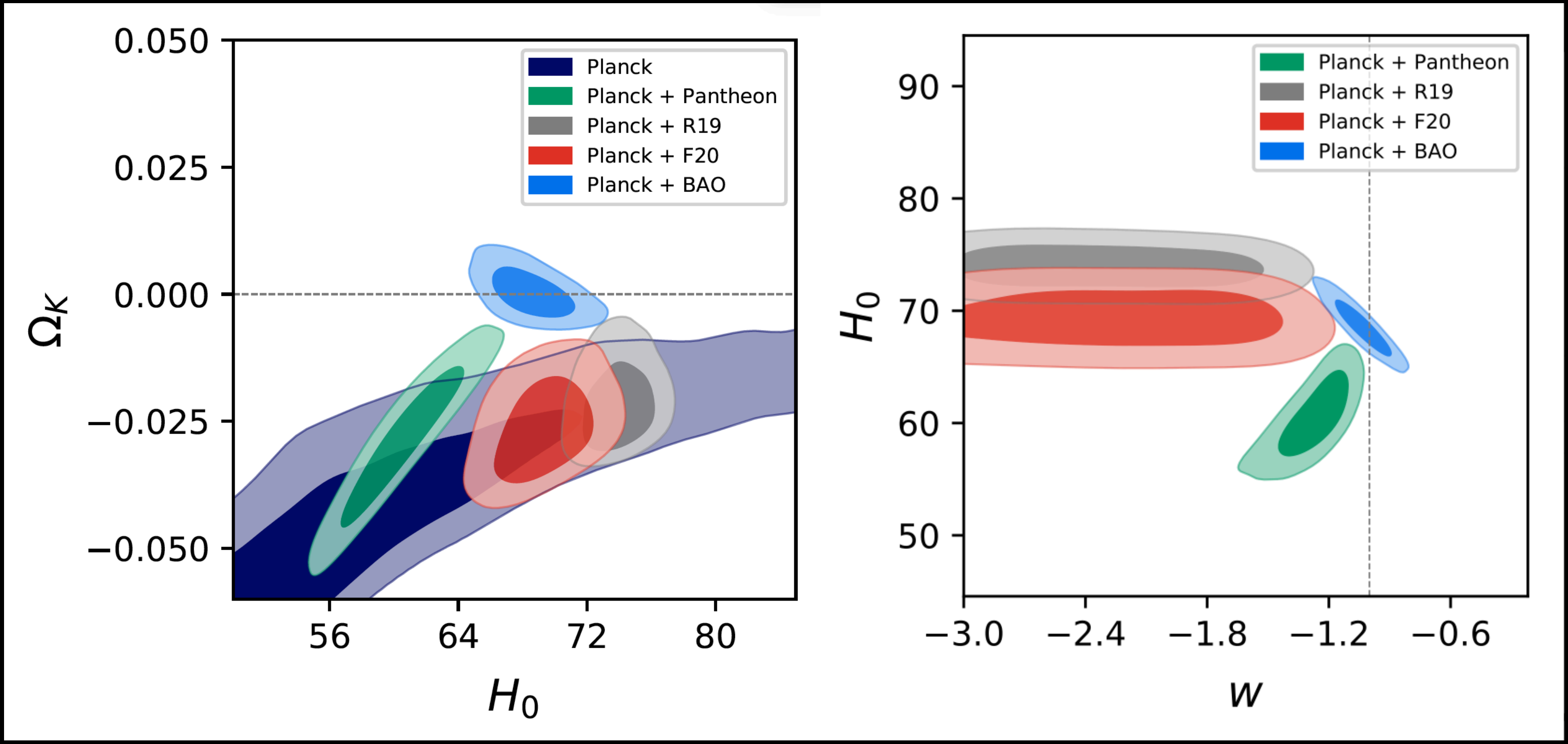


Indeed, all the three datasets, combined with Planck, exclude a cosmological constant, clearly preferring a value of w < −1, but their Hubble constant values that are in tension between themselves.

Di Valentino et al., arXiv:2003.04935

Constraints at 68% cl.

Cosmic Discordance



In practice, Planck+Pantheon, Planck+R19, and Planck+F20
all exclude both
a cosmological constant and a flat universe at more than 99% C.L.

Di Valentino et al., arXiv:2003.04935

Conclusions

Anomalies and tensions between model dependent observations at early cosmological time and direct observations at late cosmological time are stressing the robustness of the ΛCDM model.

We have an indication for a closed universe by Planck at about 3.4σ, that can explain the Alens anomaly, but this increases all the other cosmological tensions.

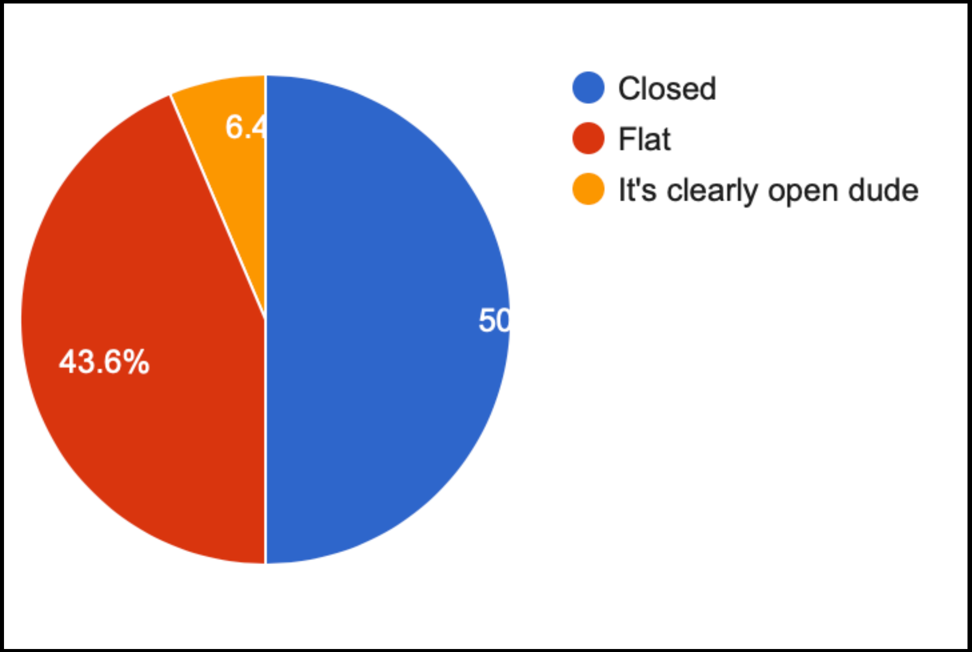
When combining Planck with luminosity distance cosmologies, we can rule out a cosmological constant AND a spatially flat universe. It is interesting to note that if a closed universe increases the fine-tuning of the theory, the removal of a cosmological constant, on the other hand, reduces it. It is, therefore difficult to decide whether a phantom closed model is less or more theoretically convoluted than ΛCDM.

The new ACT-DR4 results are thickening the mystery introducing further tensions.

This picture calls for a more conservative approach when discussing cosmological bounds on the parameters, and the necessity of further data and investigations to fully confirm a flat universe.

What is the shape of the Universe?

ARXIV POLL: 94 ANSWERS



Vagnozzi, Di Valentino, et al., arXiv:2010.02230 [astro-ph.CO]

Advertisement!

Working group composed of more than 100 people from all over the world:

Eleonora Di Valentino, Luis A. Anchordoqui,
Ozgur Akarsu, Yacine Ali-Haimoud, Luca Amendola, Nikki Arendse, Marika Asgari, Mario Ballardini, Spiros Basilakos,
Elia Battistelli, Micol Benetti, Simon Birrer, François R. Bouchet, Marco Bruni, Erminia Calabrese, David Camarena,
Salvatore Capozziello, Angela Chen, Jens Chluba, Anton Chudaykin, Eoin Ó Colgáin, Francis-Yan Cyr-Racine,
Paolo de Bernardis, Javier de Cruz Pérez, Jacques Delabrouille, Jo Dunkley, Celia Escamilla-Rivera, Agnès Ferté,
Fabio Finelli, Wendy Freedman, Noemi Frusciante, Elena Giusarma, Adrià Gómez-Valent, Julien Guy, Will Handley,
Ian Harrison, Luke Hart, Alan Heavens, Hendrik Hildebrandt, Daniel Holz, Dragan Huterer, Mikhail M. Ivanov, Shahab Joudaki,
Marc Kamionkowski, Tanvi Karwal, Lloyd Knox, Suresh Kumar, Luca Lamagna, Julien Lesgourgues, Matteo Lucca,
Valerio Marra, Silvia Masi, Sabino Matarrese, Arindam Mazumdar, Alessandro Melchiorri, Olga Mena,
Laura Mersini-Houghton, Vivian Miranda, Cristian Moreno-Pulido, David F. Mota, Jessica Muir, Ankan Mukherjee,
Florian Niedermann, Alessio Notari, Rafael C. Nunes, Francesco Pace, Andronikos Paliathanasis, Antonella Palmese,
Supriya Pan, Daniela Paoletti, Valeria Pettorino, Francesco Piacentini, Vivian Poulin, Marco Raveri, Adam G. Riess,
Vincenzo Salzano, Emmanuel N. Saridakis, Anjan A. Sen, Arman Shafieloo, Anowar J. Shajib, Joseph Silk,
Alessandra Silvestri, Martin S. Sloth, Tristan L. Smith, Joan Solà, Carsten van de Bruck, Licia Verde, Luca Visinelli,
Benjamin D. Wandelt, Deng Wang, Jian-Min Wang, Anil K. Yadav, Weiqiang Yang.

4 Snowmass 2021 LoIs:

- Cosmology Intertwined I: Perspectives for the Next Decade
- Cosmology Intertwined II: The Hubble Constant Tension
- Cosmology Intertwined III: $f\sigma8$ and S8
- Cosmology Intertwined IV: The Age of the Universe and its Curvature

We will have a first draft of the white paper covering all these topics by March.
Please let me know if you are interested in joining the working group sending an email to
eleonora.di-valentino@durham.ac.uk

References

- Aghanim et al. [Planck Collaboration], arXiv:1807.06209 [astro-ph.CO];
- Bennett et al. [WMAP collaboration], arXiv:1212.5225 [astro-ph.CO];
- Ade et al. [Planck Collaboration], arXiv:1502.01598 [astro-ph.CO];
- Aghanim et al. [Planck Collaboration], arXiv:1605.02985 [astro-ph.CO];
- Riess et al. arXiv:1604.01424v3;
- Riess et al. arXiv:1801.01120 [astro-ph.SR];
- Riess et al. 2018, ApJ, 861, 126
- Wong et al. arXiv:1907.04869v1
- Riess et al. arXiv:1903.07603 [astro-ph.CO];
- Dhawan et al. Astron.Astrophys. 609 (2018) A72
- Burns et al. [CSP collaboration], Astrophys.J. 869 (2018) no.1, 56
- Joudaki et al, arXiv:1601.05786;
- Hildebrandt et al., arXiv:1606.05338 [astro-ph.CO];
- Mangano et al., Nucl. Phys. B 729, 221 (2005) [hep-ph/0506164];
- Archidiacono et al. Adv.High Energy Phys. 2013 (2013) 191047;
- Calabrese et al., Phys. Rev. D, 77, 123531;
- Di Valentino et al., Phys.Rev. D92 (2015) no.12, 121302, arXiv:1507.06646;
- Di Valentino and Bridle, Symmetry 10 (2018) no.11, 585
- Di Valentino et al., Phys.Lett. B761 (2016) 242-246, arXiv:1606.00634;
- Ross et al., Mon. Not. Roy. Astron. Soc. 449, no. 1, 835 (2015);
- Shajib et al. arXiv:1910.06306
- Freedman et al. ApJ 882, 34 (2019)
- Freedman et al. arXiv:2002.01550
- Yuan et al. arXiv:1908.00993.
- Anderson et al. [BOSS Collaboration], Mon. Not. Roy. Astron. Soc. 441, no. 1, 24 (2014);
- M. Betoule et al. [SDSS Collaboration] Astron. Astrophys 568, A22 (2014);
- Chevallier and Polarski, Int. J. Mod. Phys. D 10, 213 (2001);
- Linder, Phys. Rev. Lett. 90, 091301 (2003);
- Yang et al., PHYS. REV. D 99, 043543 (2019)
- Di Valentino et al. Phys.Rev. D97 (2018) no.4, 043513
- Gavela et al. J. Cosmol. Astropart. Phys. 07 (2009) 034
- Di Valentino et al. Phys.Rev. D96 (2017) no.4, 043503
- Di Valentino et al. Phys.Rev. D98 (2018) no.8, 083523
- Adam et al. [Planck Collaboration], arXiv:1502.01582 [astro-ph.CO];
- Aghanim et al. [Planck Collaboration], arXiv:1507.02704 [astro-ph.CO];
- Aghanim et al. [Planck Collaboration], arXiv:1605.02985 [astro-ph.CO];
- Di Valentino, Melchiorri and Silk, arXiv:1908.01391v1 [astro-ph.CO]
- Di Valentino et al. arXiv:1908.04281
- Di Valentino et al. Phys. Rev. D 101, 063502
- Riess, Nature Reviews Physics (2019)
- Abbott et al. arXiv:1710.05835 [astro-ph.CO]
- Di Valentino et al. Phys.Rev. D98 (2018) no.8, 083523
- Huang et al. arXiv:1908.10883
- Verde et al. Nat. Astr. 3, 891-895 (2019)
- Efstathiou and Gratton, arXiv:2002.06892
- Di Valentino et al., arXiv:2003.04935
- Di Valentino et al., Phys.Rev. D96 (2017) no.2, 023523;
- Heymans et al., Mon. Not. Roy. Astron. Soc. 427, 146 (2012);
- Erben et al., Mon. Not. Roy. Astron. Soc. 433, 2545 (2013) ;
- Beutler et al., Mon. Not. Roy. Astron. Soc. 416, 3017 (2011);
- Asgari et al., arXiv:1910.05336 [astro-ph.CO]
- Di Valentino et al. arXiv: 2005.12587 [astro-ph.CO]
- ACT-DR4 2020, Aiola et al., arXiv:2007.07288 [astro-ph.CO];
- Handley and Lemos, arXiv:2007.08496 [astro-ph.CO].
- Gil-Marín et al., Mon. Not. Roy. Astron. Soc. 460 (2016).