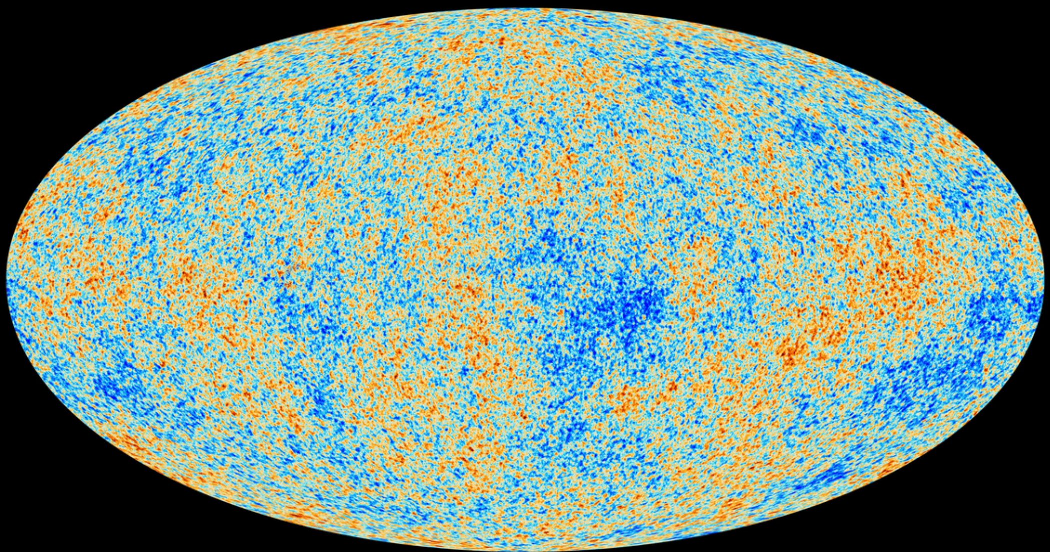
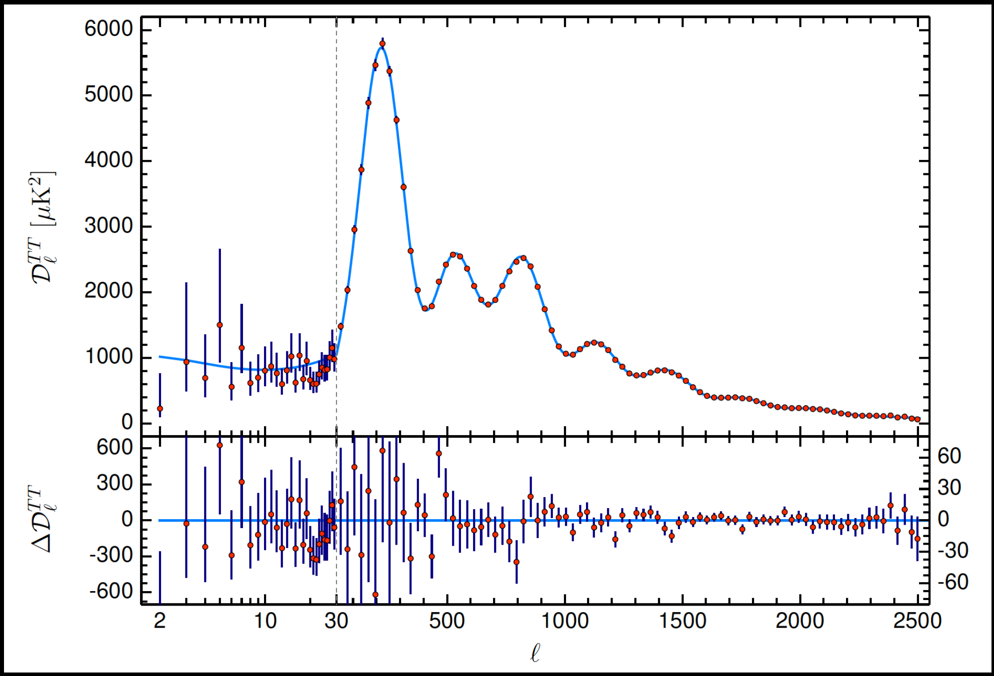
Cosmic Discordances

May 29th, 2020
Cortona Young

Eleonora Di Valentino
University of Manchester

Introduction to CMB





Planck collaboration, 2018

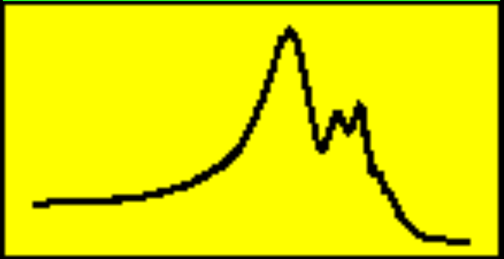
An important tool of research in cosmology is the angular power spectrum of CMB temperature anisotropies.

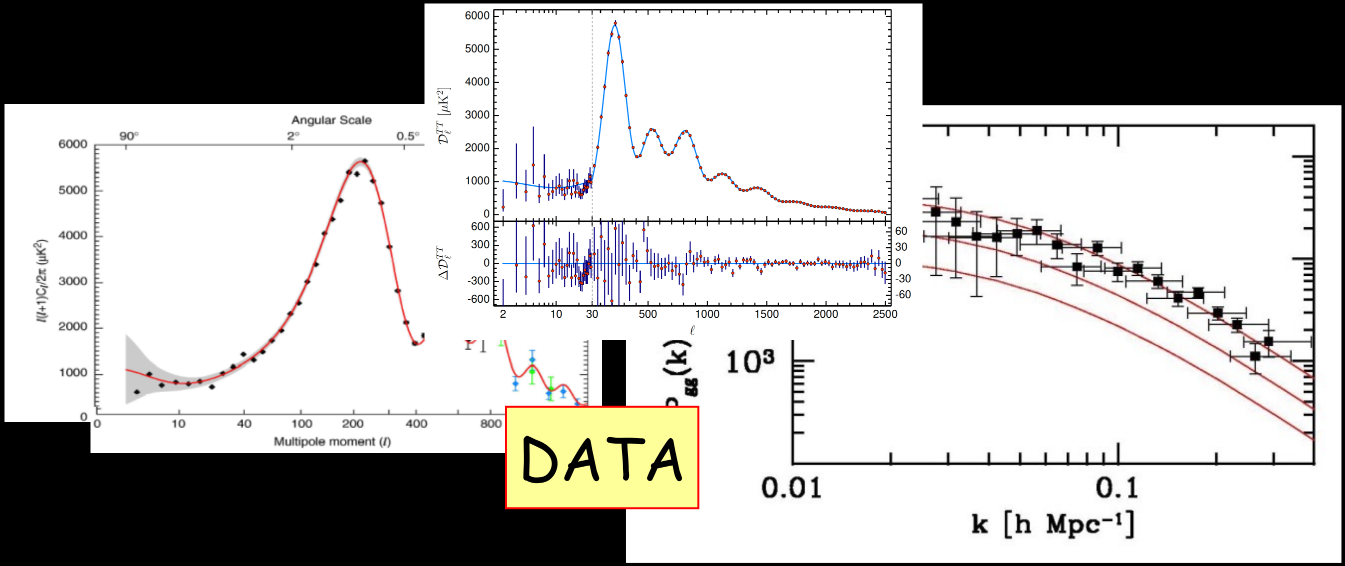
$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$

Introduction to CMB

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

Theoretical model





PARAMETER
CONSTRAINTS

CMB constraints

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

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

2018 Planck results are perfectly in agreement with the standard ΛCDM cosmological model.

Warning!

Since the Planck constraints are model dependent, therefore changing the cosmological scenario we can end with different conclusions.

In fact, anomalies and tensions between Planck and other cosmological probes are present well above the 3 standard deviations. These discrepancies, already hinted in previous Planck data releases, have persisted and strengthened despite several years of accurate analyses.

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.

Warning!

Our current understanding of the structure and evolution of the Universe is primarily based on three ingredients:

- 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).

At the moment, their physical evidence comes solely from cosmology without strong theoretical motivations.

Warning!

The model that has now practically been selected as the "standard" cosmological model is the Lambda Cold Dark Matter (ΛCDM) model, that is based on the choice of three, very specific, solutions:

- 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.

It is important to note that these choices are mostly motivated by computational simplicity, i.e., the theoretical predictions under LCDM for several observables are, in general, easier to compute and include fewer free parameters than most other solutions. The 6 parameter ΛCDM model (that is not motivated by any fundamental theory) can be rightly considered, at best, as a first-order approximation to a more realistic scenario that still needs to be fully explored.

With the increase in experimental sensitivity, observational evidence for deviations from ΛCDM is, therefore, expected.

The most famous and persisting anomalies and tensions of the CMB are:

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

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The H0 tension at more than 4σ

The cosmological constraints obtained from Planck are assuming a cosmological model and are therefore model dependent. Moreover these bounds are also affected by the degeneracy between the parameters that induce similar effects on the observables. Therefore the Planck constraints can change when modifying the assumptions of the underlying cosmological model.

$H0 = 67.27 \pm 0.60$ km/s/Mpc in ΛCDM

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

The last local measurement of the Hubble constant given by the SH0ES collaboration and obtained using Hubble Space Telescope observations of 70 long-period Cepheids in the Large Magellanic Cloud is in tension at 4.4σ with Planck assuming ΛCDM.

$H0 = 74.03 \pm 1.42$ km/s/Mpc

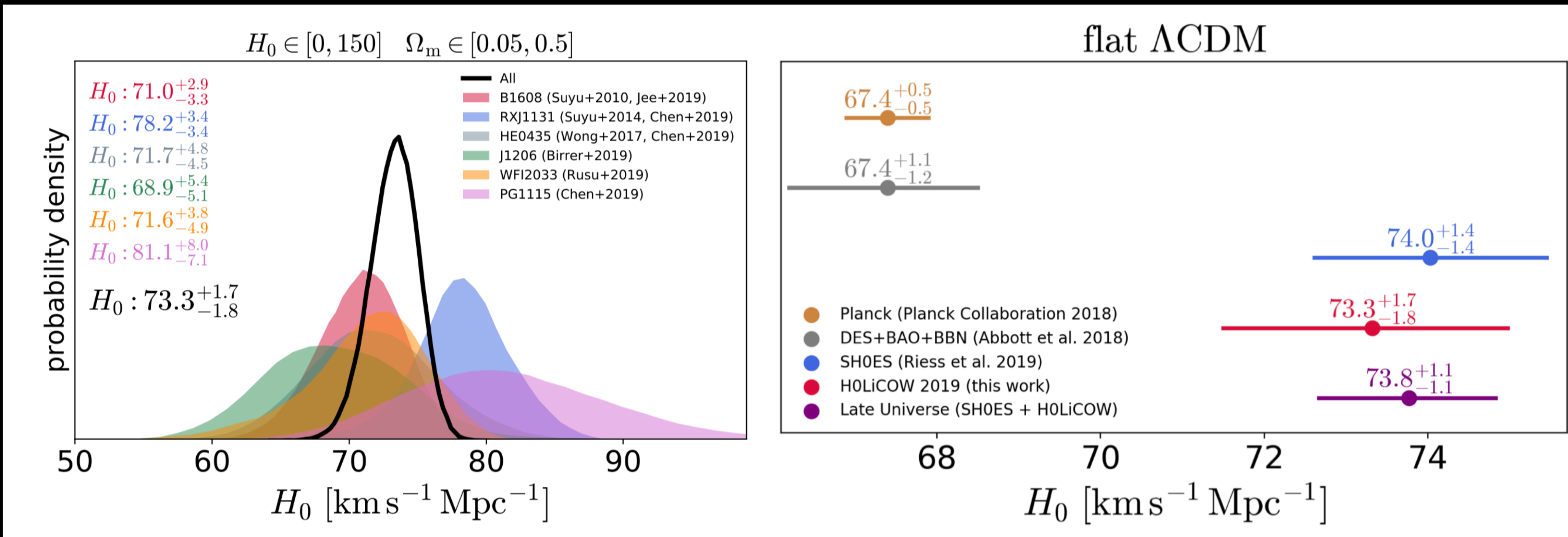
Riess et al. arXiv:1903.07603 [astro-ph.CO]

The H0 tension at more than 5σ

CMB: H0 = 67.27 ± 0.60 km/s/Mpc in ΛCDM

BAO+Pantheon+BBN+$\theta_{MC,\ Planck}$: H0 = 67.9 ± 0.8 km/s/Mpc

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



Wong et al. arXiv:1907.04869v1

SH0ES: H0 = 74.03 ± 1.42 km/s/Mpc

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

Strong Lensing: measurement of the time delays of multiple images of quasar systems caused by the strong gravitational lensing from a foreground galaxy:

- H0liCOW collaboration H0 = 73.3 $^{+1.7}_{-1.8}$ km/s/Mpc Wong et al. arXiv:1907.04869v1
- STRIDES team H0 = 74.2 $^{+2.7}_{-3.0}$ km/s/Mpc Shajib et al. arXiv:1910.06306

Since the Planck constraints are model dependent, we can try to expand the cosmological scenario and see which extensions work in solving the tensions between the cosmological probes.

For example, the most famous extensions for solving the H0 tension are:

→ the neutrino effective number
→ the dark energy equation of state

The Neutrino effective number

The expected value is Neff = 3.046, if we assume standard electroweak interactions and three active massless neutrinos. If we measure a Neff > 3.046, we are in presence of extra radiation.

If we compare the Planck 2015 constraint on Neff at 68% cl

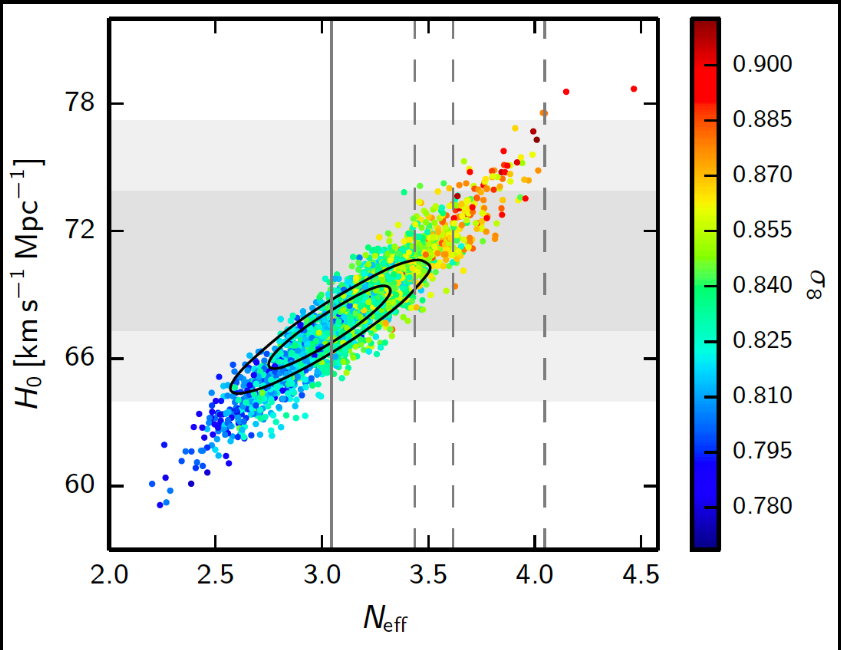
$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck}\ \text{TT+lowP},$$
$$N_{\rm eff} = 3.15 \pm 0.23 \quad \textit{Planck}\ \text{TT+lowP+BAO},$$

with the new Planck 2018 bound,

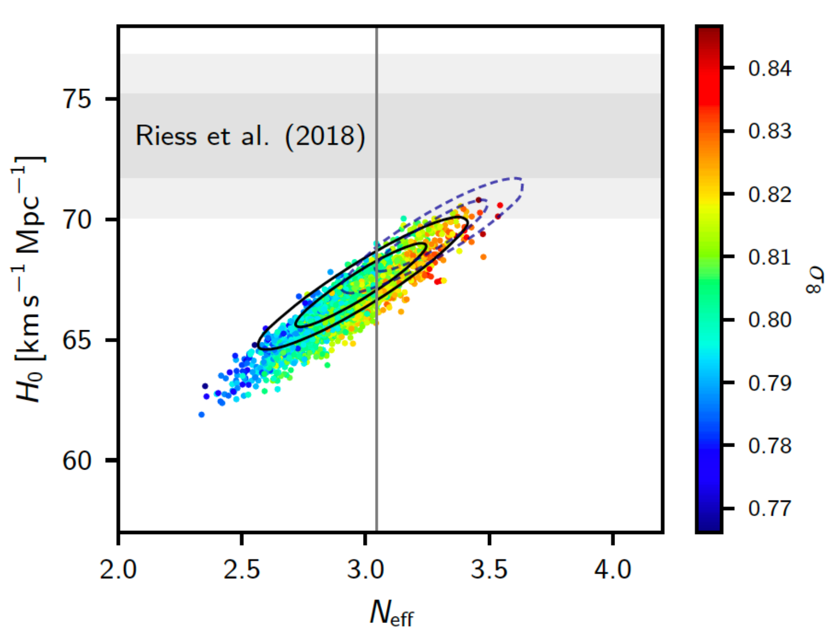
$$N_{\rm eff} = 2.92^{+0.36}_{-0.37} \quad (95\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE}),$$

we see that the neutrino effective number is now very well constrained.

H0 passes from 68.0 ± 2.8 km/s/Mpc (2015) to 66.4 ± 1.4 km/s/Mpc (2018), and the tension with R19 increases from 2.1σ to 3.8σ also varying Neff.



Planck collaboration, 2015



Planck collaboration, 2018

The Dark energy equation of state

Changing the dark energy equation of state w, we are changing the expansion rate of the Universe:

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

w introduces a geometrical degeneracy with the Hubble constant that will be unconstrained using the CMB data only, resulting in agreement with Riess+19.

We have in 2018 $w = -1.58^{+0.52}_{-0.41}$ with $H0 > 69.9$ km/s/Mpc at 95% c.l.

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

Anyway, there exist models that expect an effective energy density with a phantom equation of state without showing the problems before.

More specific extensions for solving the H0 tension are:

- Interacting dark sector (Di Valentino et al. arXiv:1704.08342, Kumar and Nunes arXiv:1702.02143 , Yang et al. arXiv:1805.08252, Yang et al. arXiv:1809.06883, Yang et al. arXiv:1906.11697, Martinelli et al. arXiv:1902.10694, Di Valentino et al. arXiv:1908.04281, Di Valentino et al. arXiv:1910.09853, etc…)
- Parker Vacuum Metamorphosis (Di Valentino et al., PRD97 (2018) no.4, 043528)
- Vacuum Dynamics (Sola Peracaula et al. arXiv:1705.06723)
- Early dark Energy (Poulin et al. arXiv:1811.04083)
- Uber-gravity (Khosravi et al. arXiv:1710.09366)
- Bulk viscosity (Yang et al. arXiv:1906.04162)
- Decaying dark matter (Pandey et al. arXiv:1902.10636, Vattis et al. arXiv:1903.06220, etc..)
- Metastable Dark Energy (Li et al. arXiv:1904.03790)
- Many many others… (Colgain et al. arXiv:1807.07451, Nunes arXiv:1802.02281, Agrawal et al. arXiv:1904.01016, Yang et al. arXiv:1907.05344, Martinelli and Tutusaus arXiv:1906.09189, Adhikari and Huterer arXiv:1905.02278, Gelmini et al. arXiv:1906.10136, Colgain et al. arXiv:1905.02555, Pan et al. 1907.12551, Knox and Millea arXiv:1908.03663, Benevento et al. arXiv:2002.11701, D'agostino et al. arXiv:2002.06381, etc..)

IDE can solve the H0 tension

In the standard cosmological framework, the dark matter is assumed to be collisionless. In practice this means that one arbitrarily sets the dark matter interactions to zero when predicting the angular power spectrum of the CMB.

In particular, dark matter and dark energy are described as separate fluids not sharing interactions beyond gravitational ones. However, from a microphysical perspective it is hard to imagine how non-gravitational DM-DE interactions can be avoided, unless forbidden by a fundamental symmetry. This has motivated a large number of studies based on models where DM and DE share interactions other than gravitational.

IDE can solve the H0 tension

If we consider the interacting dark energy scenario characterised by a modification to the usual conservation equations, with the introduction of an interaction:

$$\nabla_\mu T^\mu_{(dm)\nu} = Q u_\nu^{(dm)}/a,$$

$$\nabla_\mu T^\mu_{(de)\nu} = -Q u_\nu^{(dm)}/a.$$

four-velocity of the Dark Matter fluid

Dark matter and Dark Energy energy-momentum tensor

Interaction rate

$$Q = \xi \mathcal{H} \rho_{de}$$

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

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

Planck 2018

In this scenario of IDE the tension on H0 between the Planck satellite and R19 is completely solved. The coupling could affect the value of the present matter energy density Ω_m. Therefore, if within an interacting model Ω_m is smaller (because for negative ξ the dark matter density will decay into the dark energy one), a larger value of H0 would be required in order to satisfy the peaks structure of CMB observations, which accurately determine the value of $\Omega_m h^2$.

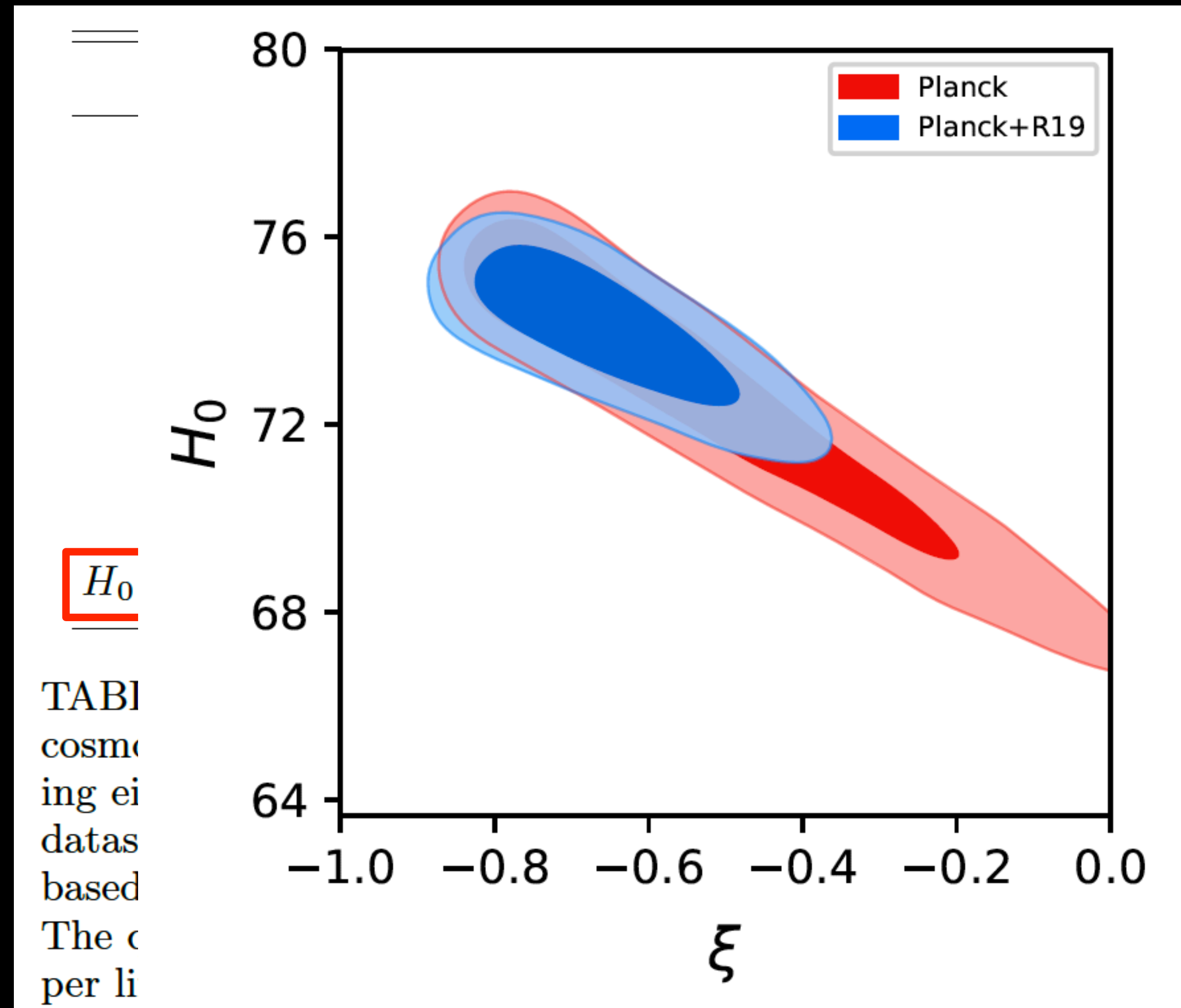
Parameter	*Planck*	*Planck+R19*
$\Omega_b h^2$	0.02239 ± 0.00015	0.02239 ± 0.00015
$\Omega_c h^2$	< 0.105	< 0.0615
n_s	0.9655 ± 0.0043	0.9656 ± 0.0044
$100\theta_s$	$1.0458^{+0.0033}_{-0.0021}$	1.0470 ± 0.0015
τ	0.0541 ± 0.0076	0.0534 ± 0.0080
ξ	$-0.54^{+0.12}_{-0.28}$	$-0.66^{+0.09}_{-0.13}$
$H_0\,[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$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

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

Di Valentino et al. arXiv:1908.04281

Planck 2018

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



Di Valentino et al. arXiv:1908.04281

Constraints at 68% cl.

Planck 2018

Parameters	Planck	Planck +R19	Planck +lensing	Planck +BAO	Planck + Pantheon
$\Omega_b h^2$	0.02239 ± 0.00015	0.02239 ± 0.00015	0.02241 ± 0.00014	0.02236 ± 0.00014	0.02235 ± 0.00015
$\Omega_c h^2$	< 0.0634	$0.031^{+0.013}_{-0.023}$	< 0.0675	$0.095^{+0.022}_{-0.008}$	$0.103^{+0.013}_{-0.007}$
$100\theta_{\rm MC}$	$1.0458^{+0.0033}_{-0.0021}$	1.0470 ± 0.0015	$1.0456^{+0.0031}_{-0.0024}$	$1.0424^{+0.0006}_{-0.0013}$	$1.04185^{+0.00049}_{-0.00078}$
τ	0.0541 ± 0.0076	0.0534 ± 0.0080	0.0526 ± 0.0074	0.0540 ± 0.0076	0.0540 ± 0.0076
n_s	0.9655 ± 0.0043	0.9656 ± 0.0044	0.9663 ± 0.0040	0.9647 ± 0.0040	0.9643 ± 0.0042
$ln(10^{10} A_s)$	3.044 ± 0.016	3.042 ± 0.017	$3.039^{+0.013}_{-0.015}$	3.044 ± 0.016	3.044 ± 0.016
ξ	$-0.54^{+0.12}_{-0.28}$	$-0.66^{+0.09}_{-0.13}$	$-0.51^{+0.12}_{-0.29}$	$\boxed{-0.22^{+0.21}_{-0.05}}$	$-0.15^{+0.12}_{-0.06}$
H_0[km/s/Mpc]	$72.8^{+3.0}_{+1.5}$	$74.0^{+1.2}_{-1.0}$	$72.8^{+3.0}_{+1.6}$	$\boxed{69.4^{+0.9}_{-1.5}}$	$68.6^{+0.8}_{-1.0}$
σ_8	$2.3^{+0.4}_{-1.4}$	$2.71^{+0.05}_{-1.3}$	$2.2^{+0.4}_{-1.4}$	$1.05^{+0.03}_{-0.24}$	$0.95^{+0.04}_{-0.12}$
S_8	$1.30^{+0.17}_{-0.44}$	$1.44^{+0.17}_{-0.34}$	$1.30^{+0.15}_{-0.42}$	$0.93^{+0.03}_{-0.10}$	$0.892^{+0.028}_{-0.054}$

The addition of low-redshift measurements, as BAO data, still hints to the presence of a coupling, albeit at a lower statistical significance.
Also for this data sets the Hubble constant values is larger than that obtained in the case of a pure LCDM scenario, enough to bring the H0 tension well below the 3σ from 4.4σ.

Di Valentino et al. Phys. Rev. D 101, 063502

Planck 2018

In other words, the tension between Planck+BAO and R19 could be due to a statistical fluctuation in this case.

Moreover, BAO data is extracted under the assumption of ΛCDM, and the modified scenario of interacting dark energy could affect the result.
In fact, the full procedure which leads to the BAO constraints carried out by the different collaborations might be not necessarily valid in extended DE models.
For instance, the BOSS collaboration advises caution when using their BAO measurements (both the pre- and post reconstruction measurements) in more exotic dark energy cosmologies.

BAO constraints themselves might need to be revised in a non-trivial manner when applied to constrain extended dark energy cosmologies.

Di Valentino et al. Phys. Rev. D 101, 063502

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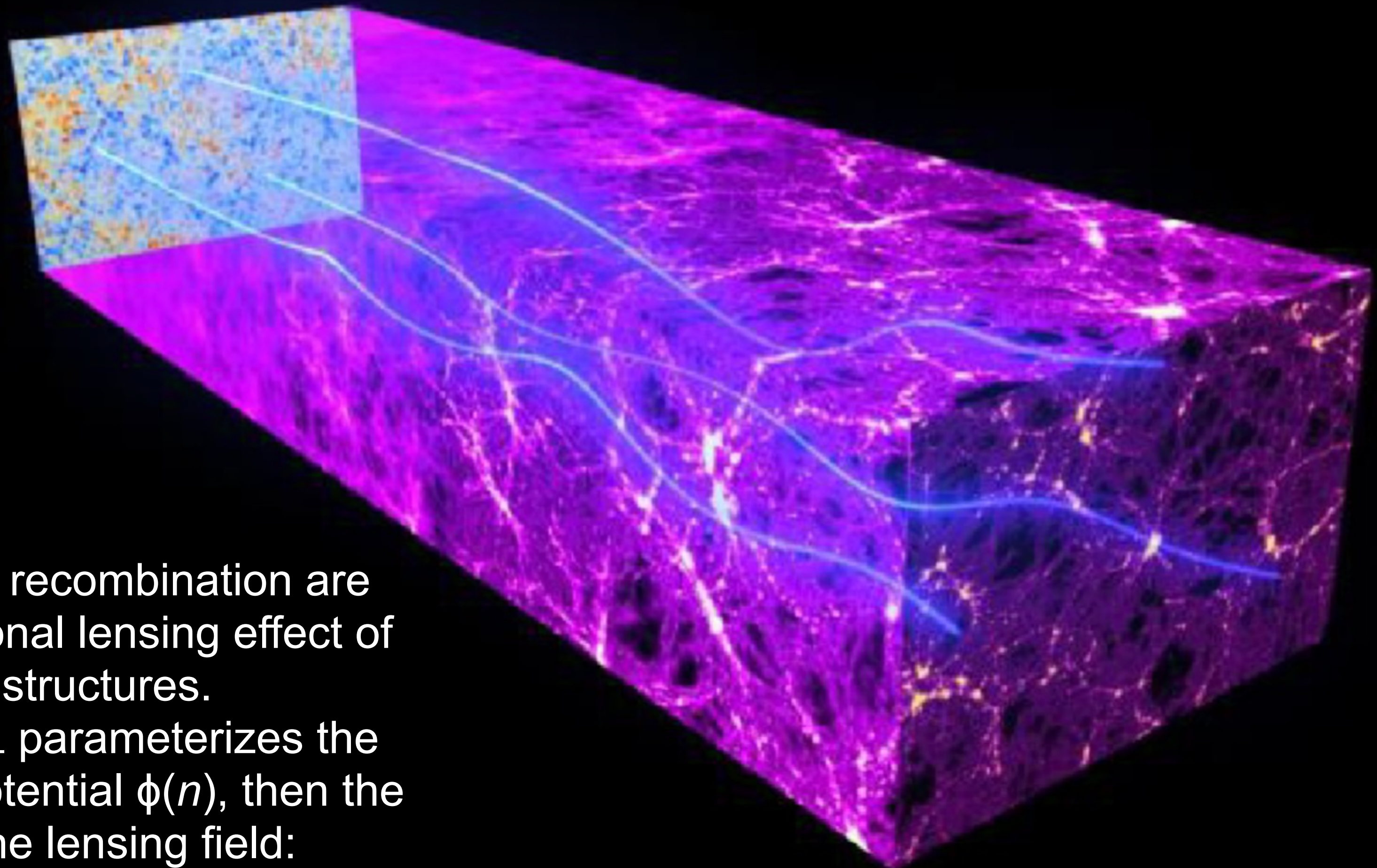
- H0 with local measurements
- A_L internal anomaly
- S8 with cosmic shear data
- Ωκ different from zero

A_L internal anomaly



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

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

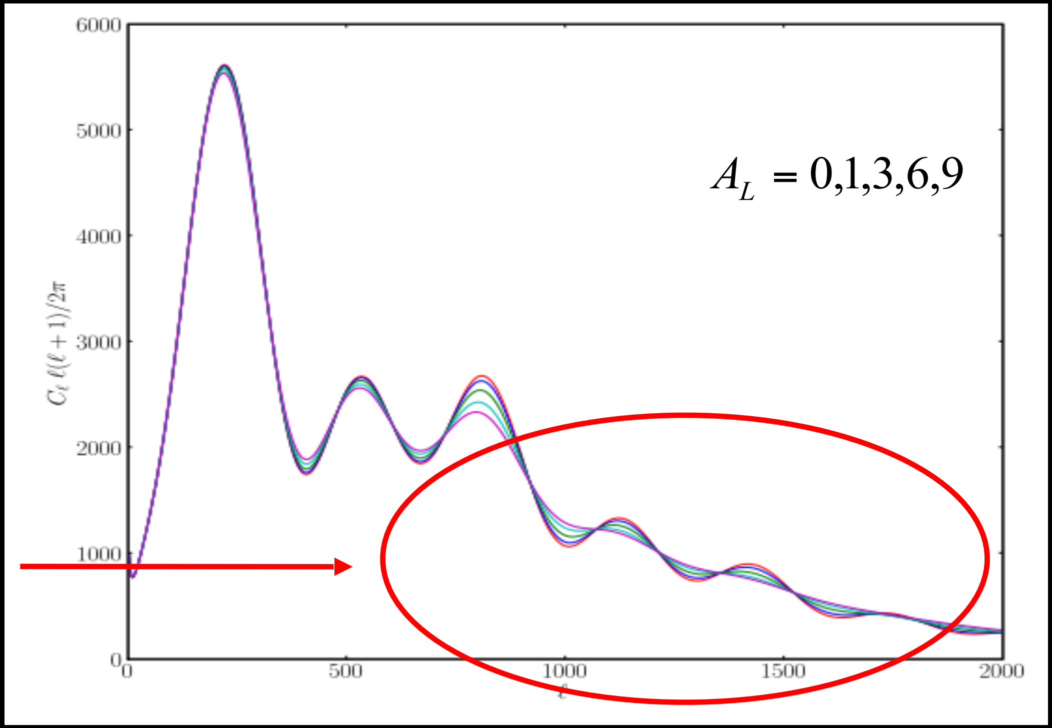
The gravitational lensing deflects the photon path by a quantity defined by the gradient of the lensing potential $\phi(n)$, integrated along the line of sight n, remapping the temperature field.

A_L internal anomaly

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 internal anomaly

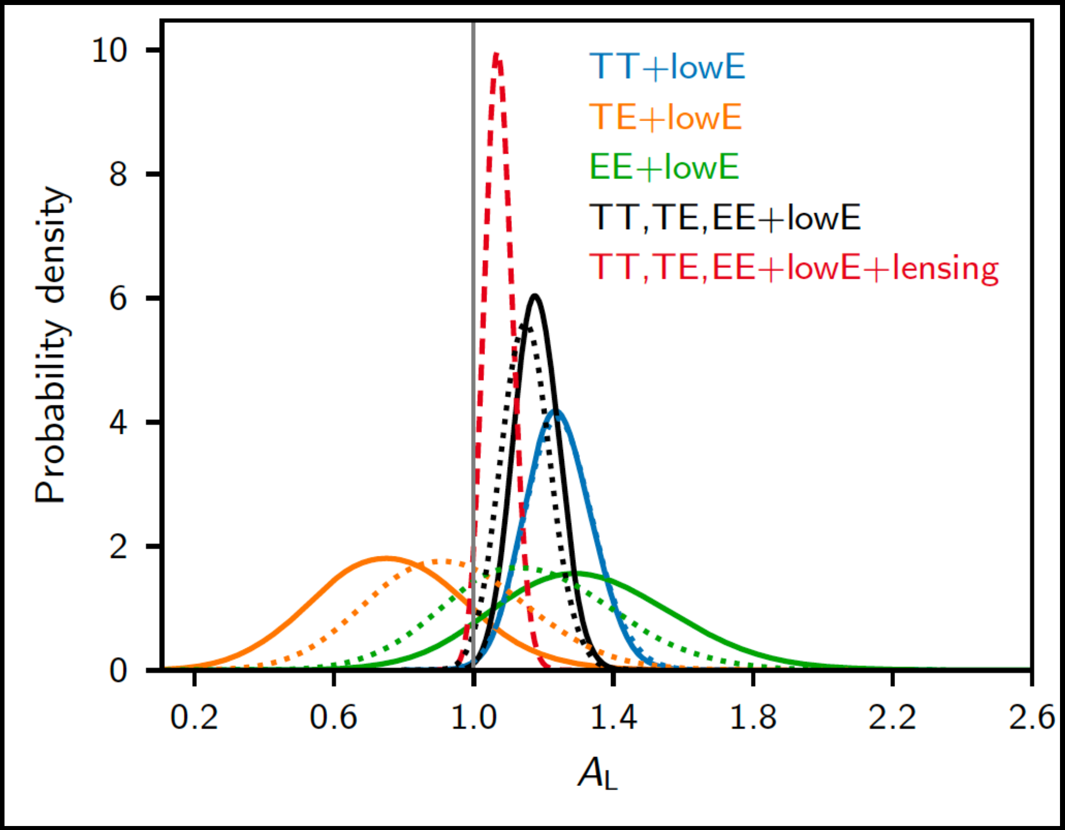
The Planck lensing-reconstruction power spectrum is consistent with the amplitude expected for LCDM models that fit the CMB spectra, so the Planck lensing measurement is compatible with AL = 1.

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.

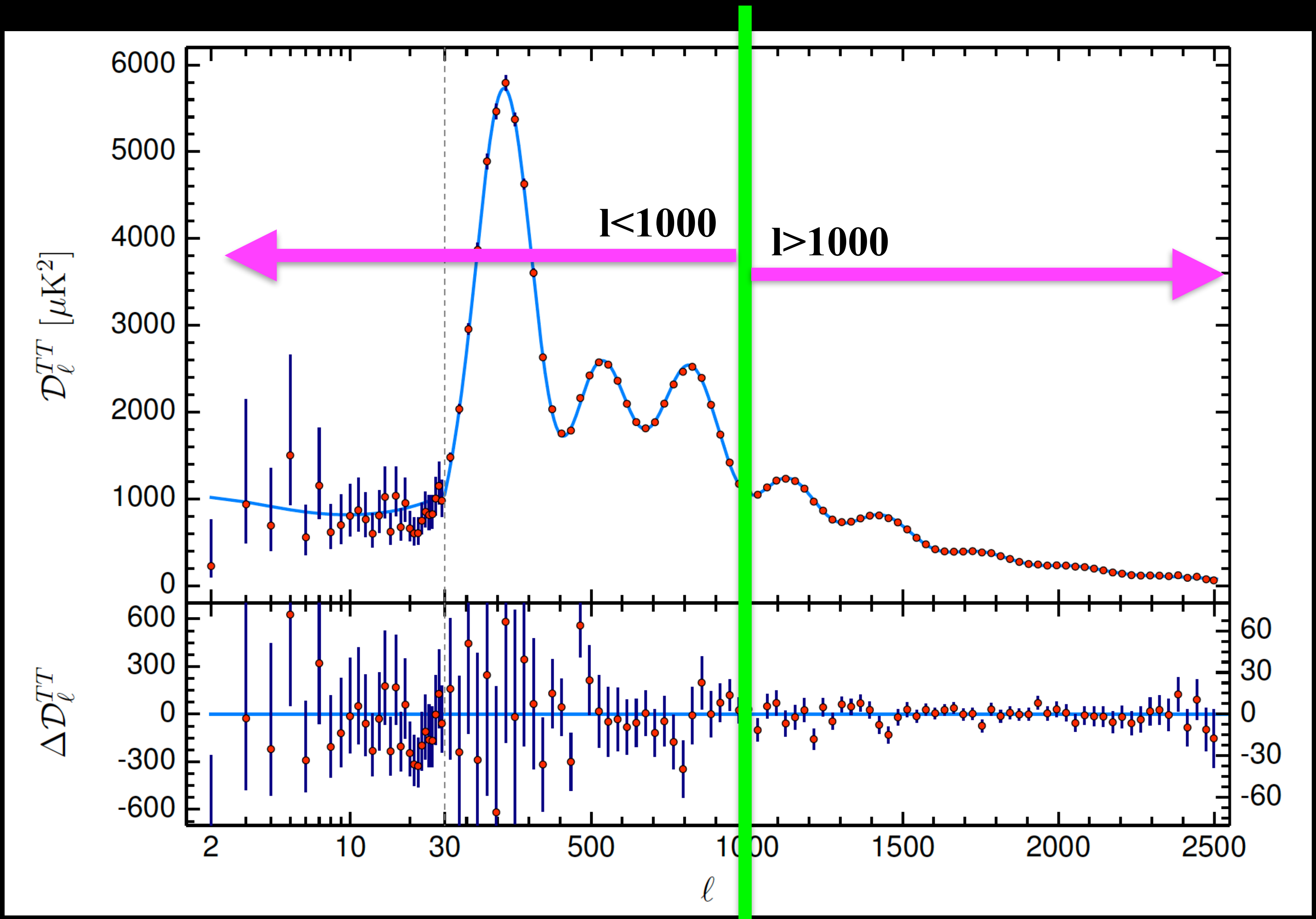
Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]



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

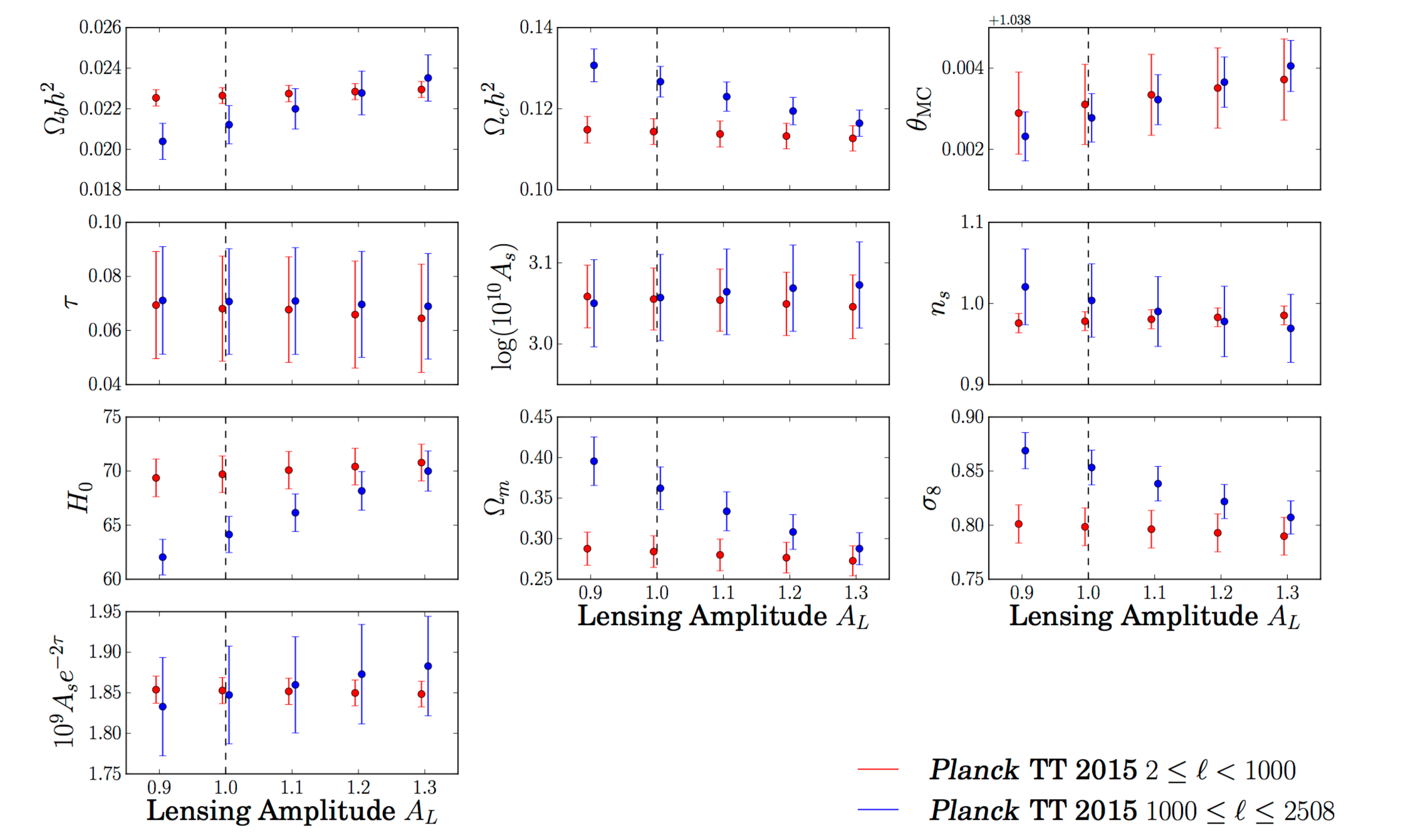
$$A_L = 1.180 \pm 0.065 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT,TE,EE{+}lowE}),$$

A_L internal anomaly



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

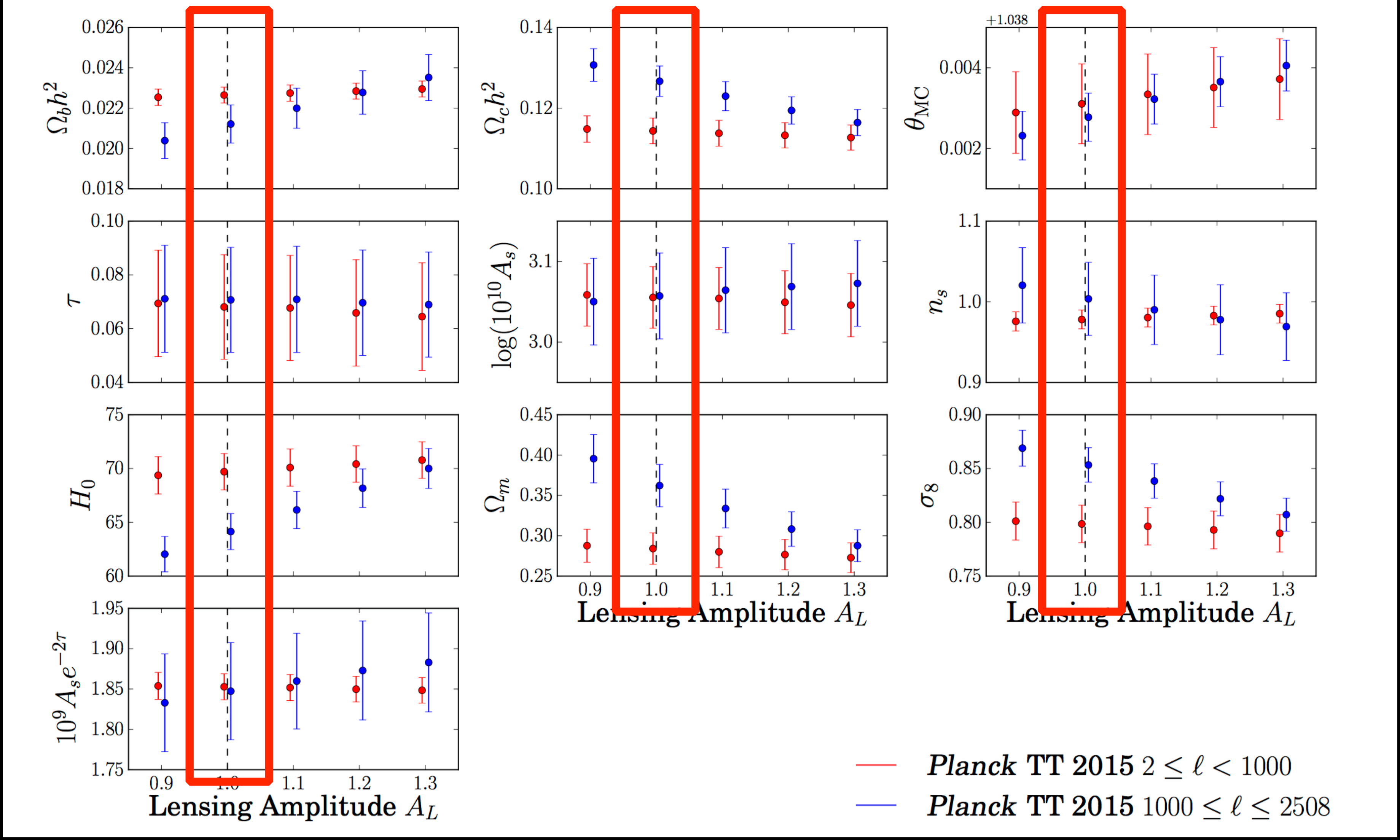
A_L internal anomaly



Marginalized 68.3% confidence ΛCDM parameter constraints from fits to the l < 1000 and l ≥ 1000 Planck TT 2015 spectra, fixing AL at different values.

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

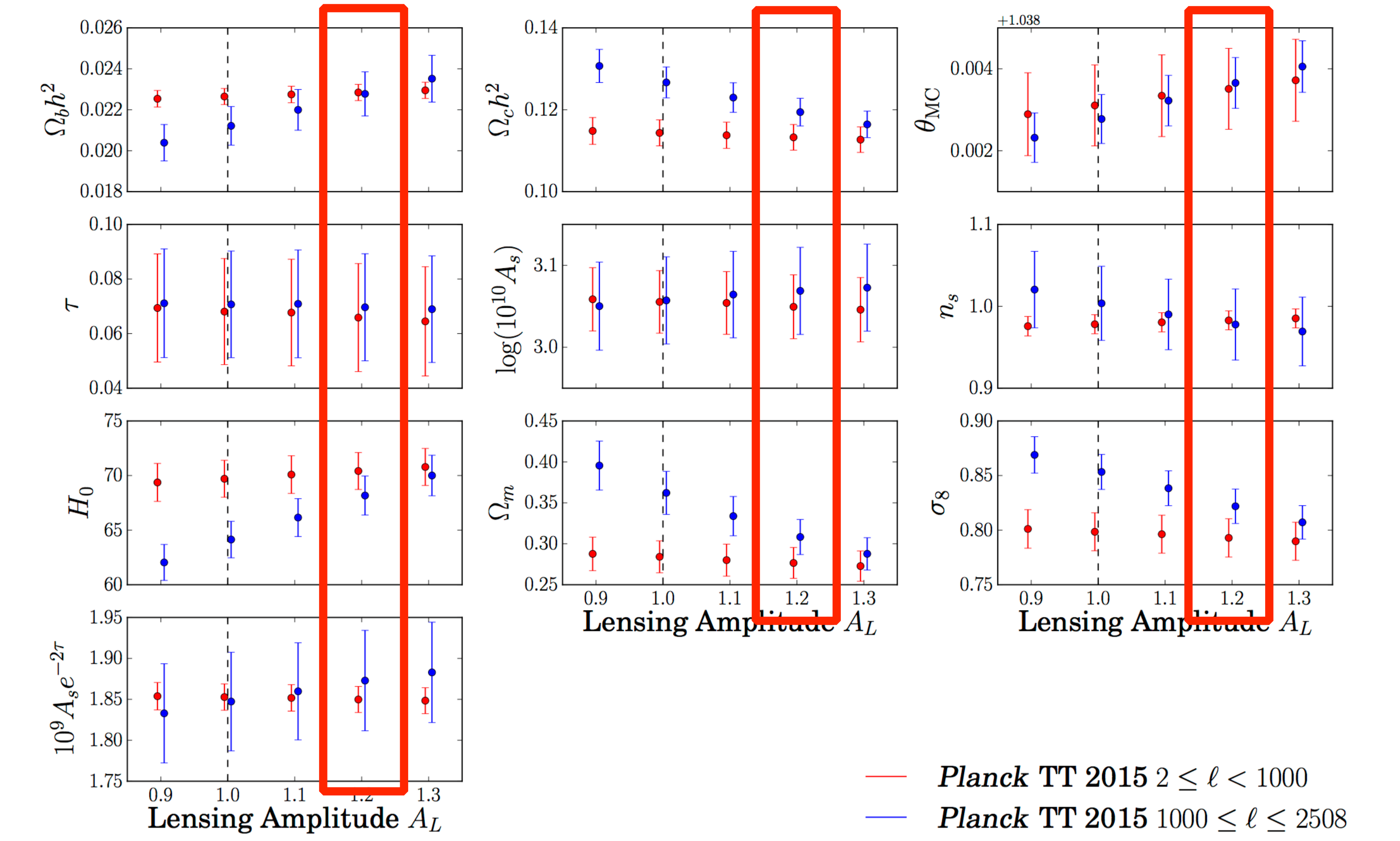
A_L internal anomaly



Tension at more than 2σ level is apparent 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 internal anomaly



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

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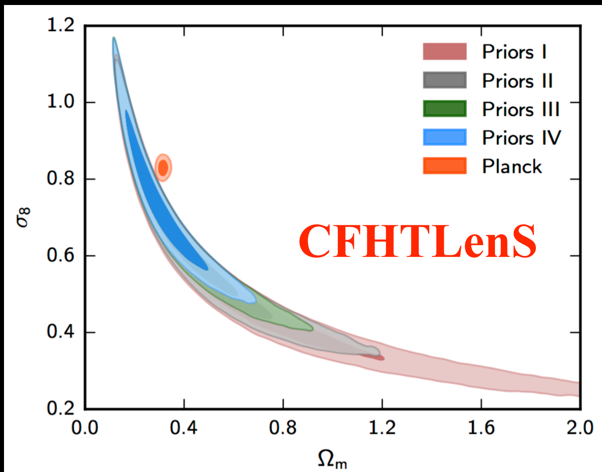
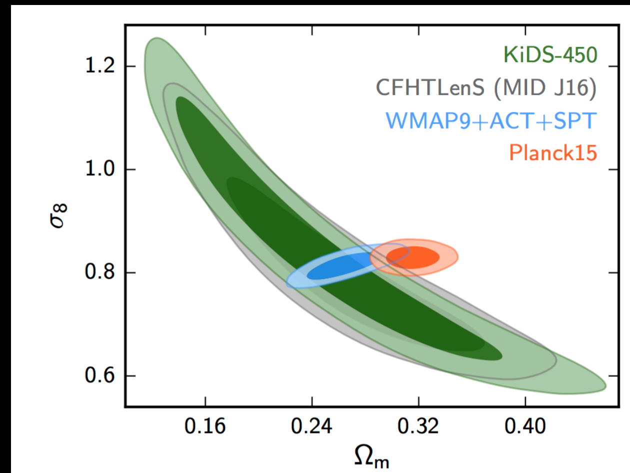
The S8 tension

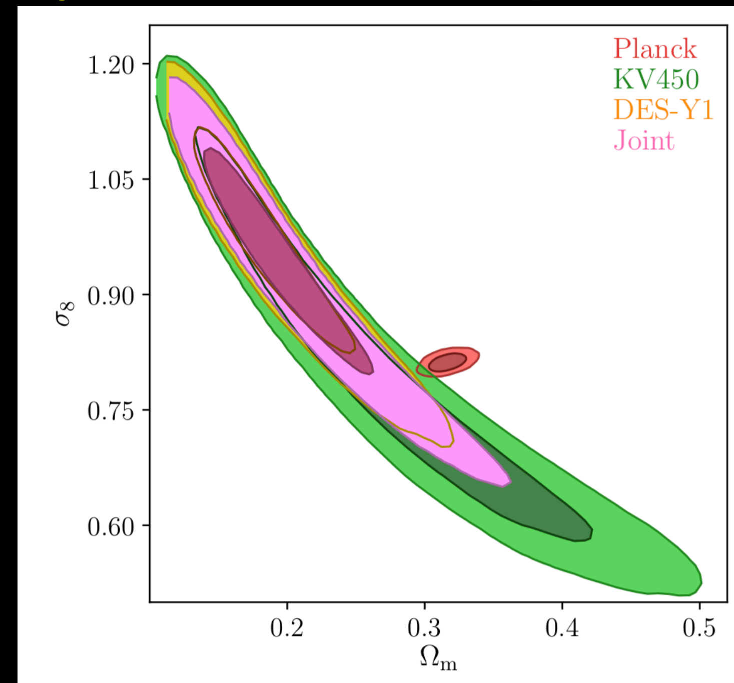


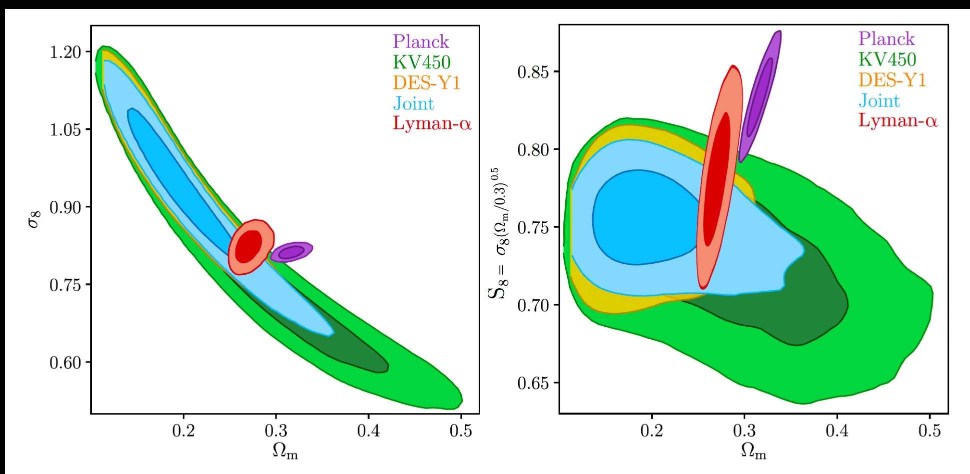
Joudaki et al, arXiv:1601.05786



Hildebrandt et al., arXiv:1606.05338.

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





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

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

A tension on S8 at 3.2σ is present between the Planck data in the ΛCDM scenario and KiDS+VIKING-450 and DES-Y1 combined together.

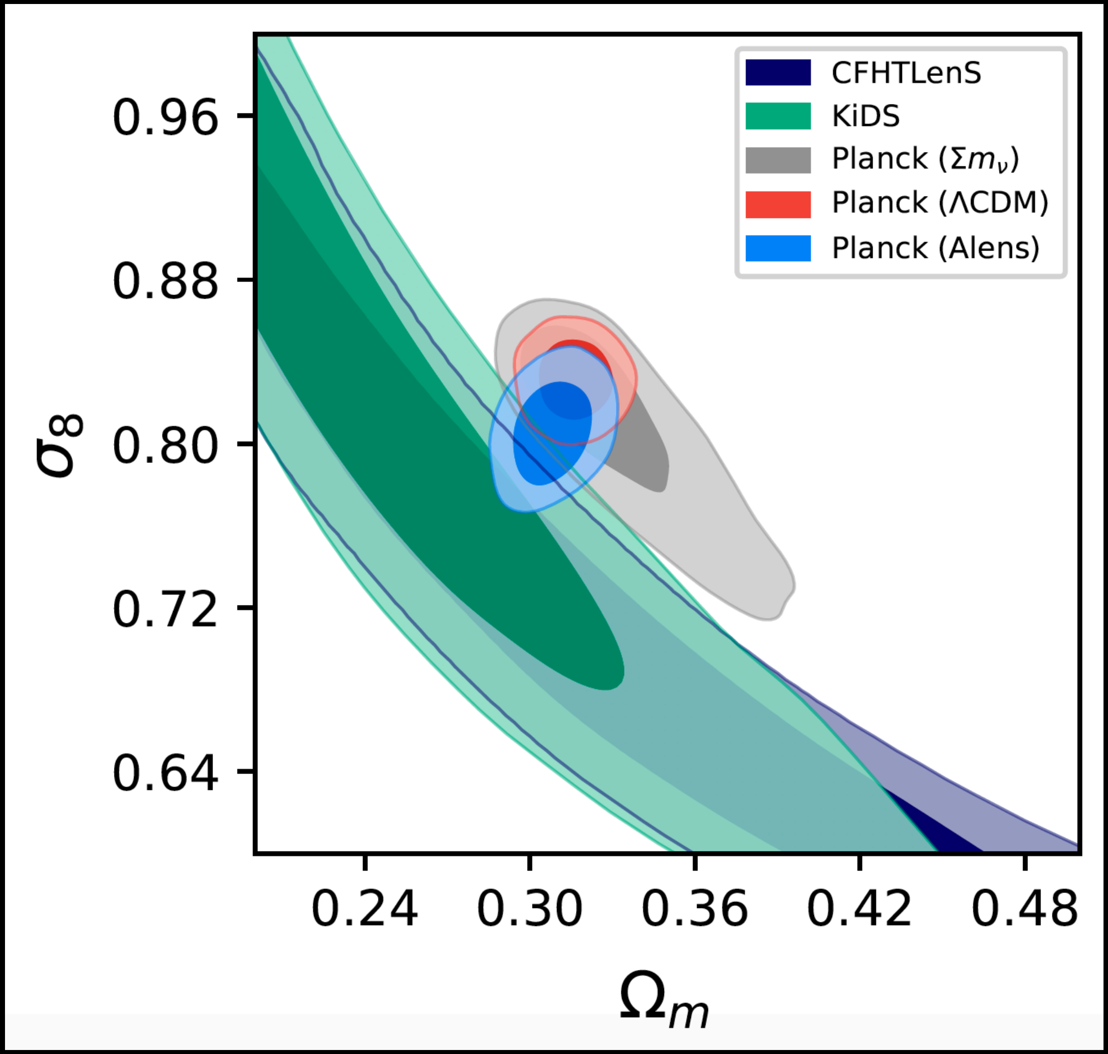
The S8 tension

This is mainly due to the anomalous value of A_L.

We find that the CMB and cosmic shear datasets, in tension in the standard LCDM model, are still in tension adding massive neutrinos.

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

A_L is a phenomenological parameter that is found to be more than 2σ higher than the expected value in the Planck 2015 data, suggesting a higher amount of lensing in the power spectra, not supported by the trispectrum analysis.



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

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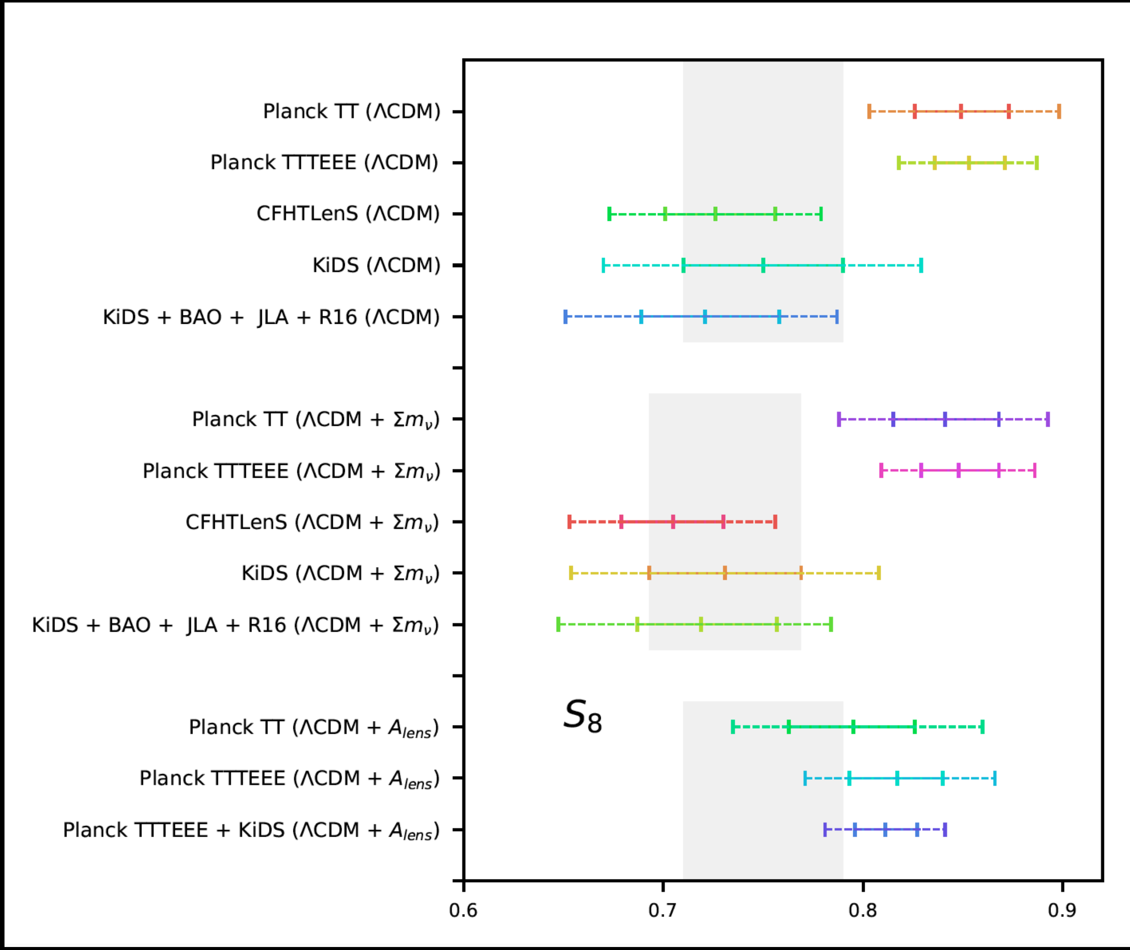


Di Valentino and Bridle, Symmetry 10 (2018) no.11, 585

The most famous and persisting anomalies and tensions of the CMB are:

- $H0$ with local measurements
- A_L internal anomaly
- $S8$ with cosmic shear data
- $\Omega\kappa$ different from zero

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

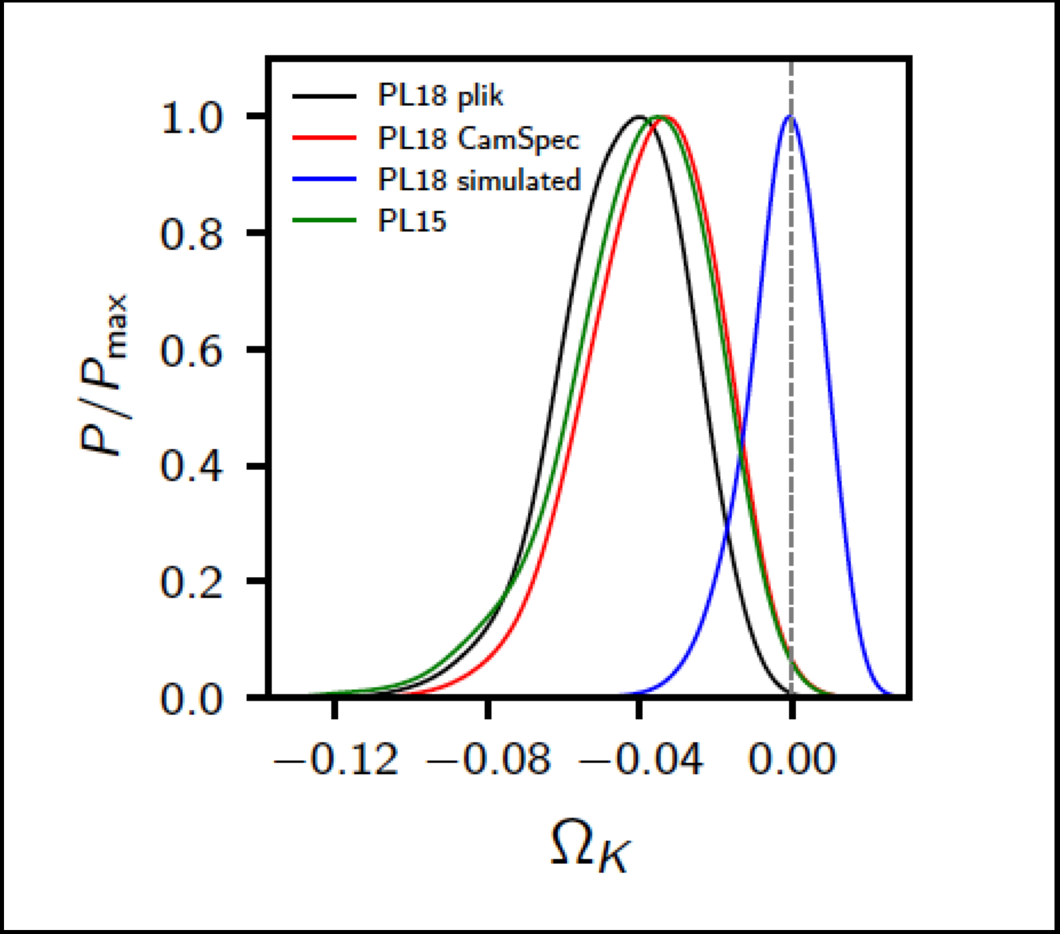
$$\Omega_K = -0.044^{+0.018}_{-0.015} \quad (68\,\%, \textit{Planck}\ \text{TT,TE,EE+lowE}),$$

a detection of curvature at about 3.4σ.

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

Curvature of the universe

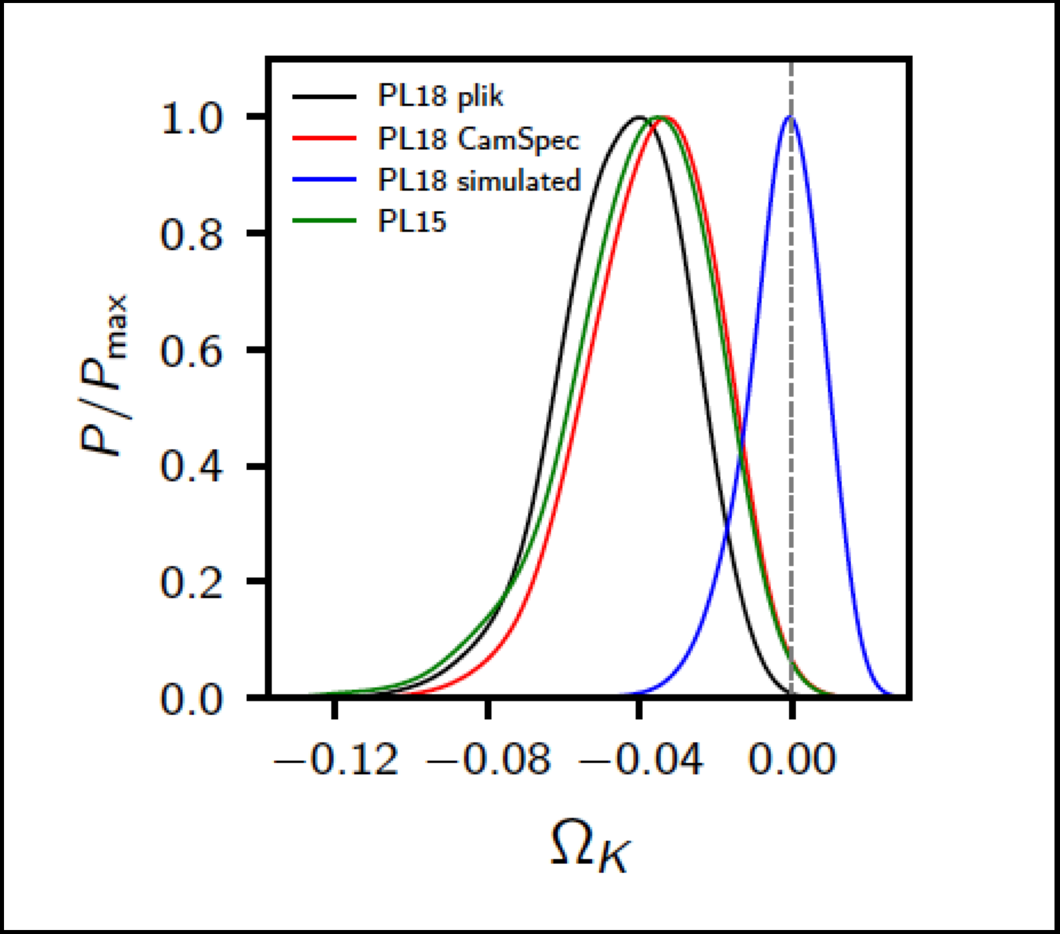
Can Planck provide an unbiased and reliable estimate of the curvature of the Universe?
This may not be the case since a "geometrical degeneracy" is present with Ωm.
When precise CMB measurements at arc-minute angular scales are included, since gravitational lensing depends on the matter density, its 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)

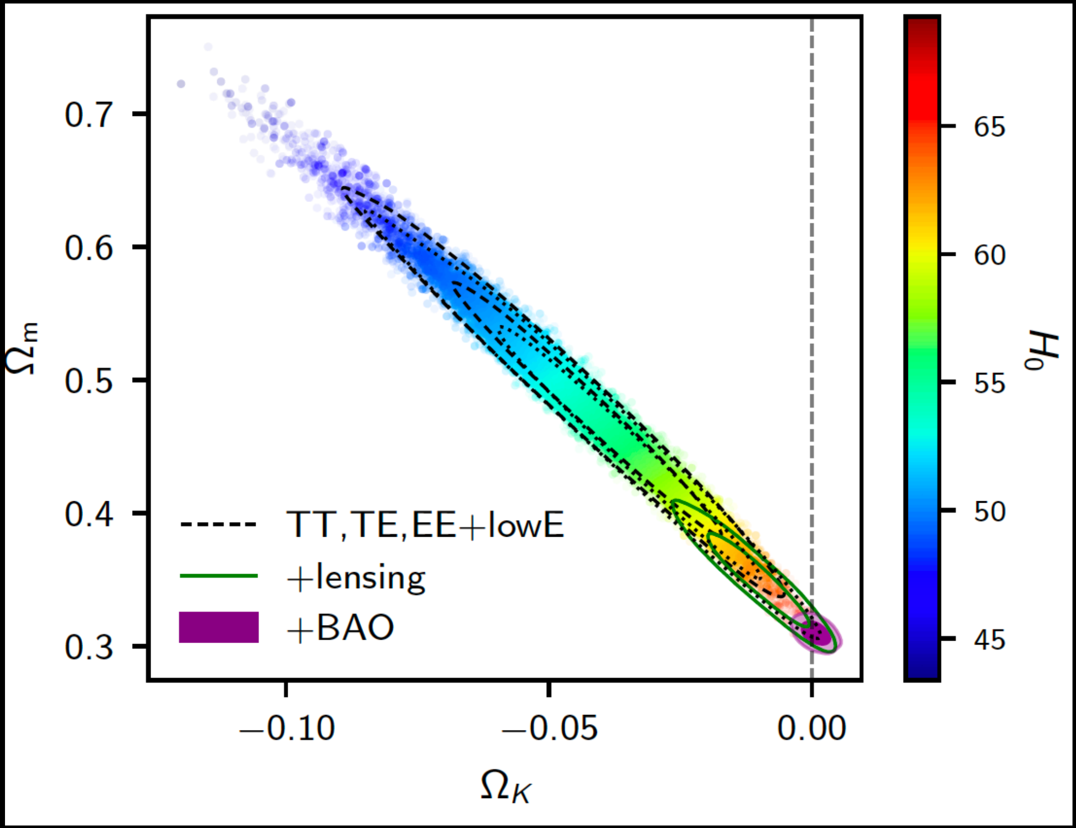
Curvature of the universe

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)

Curvature of the universe



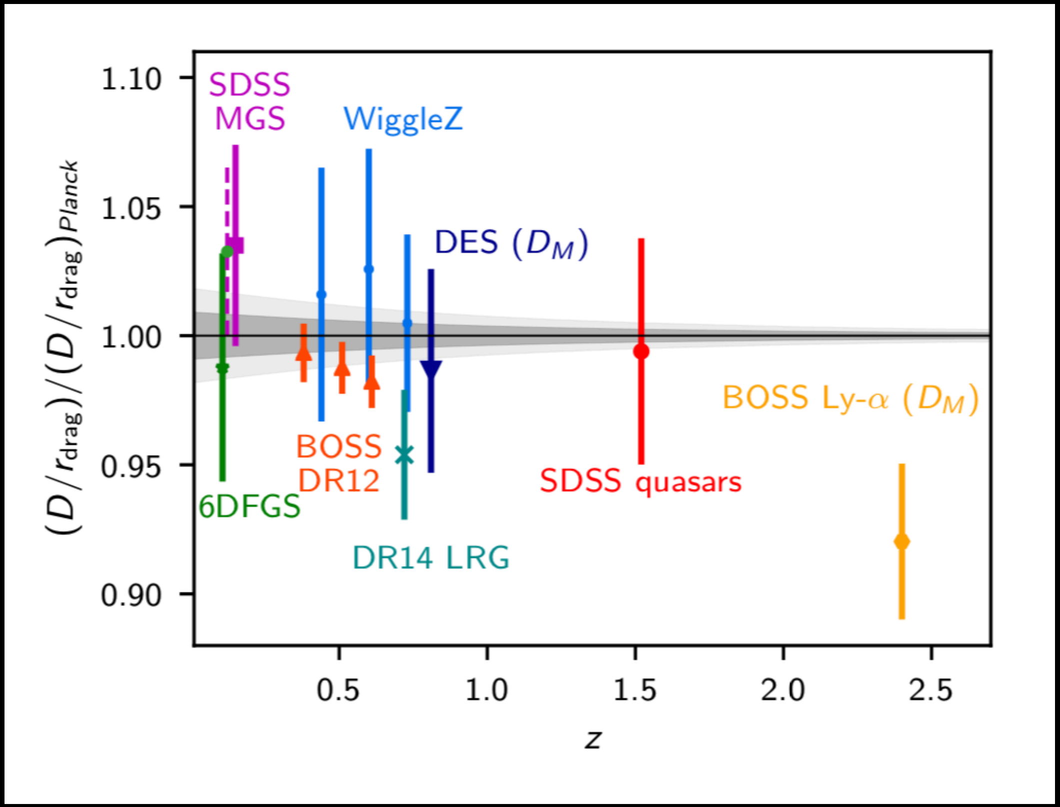
Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

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, ie they must plausibly arise from the same cosmological model.

Curvature of the universe

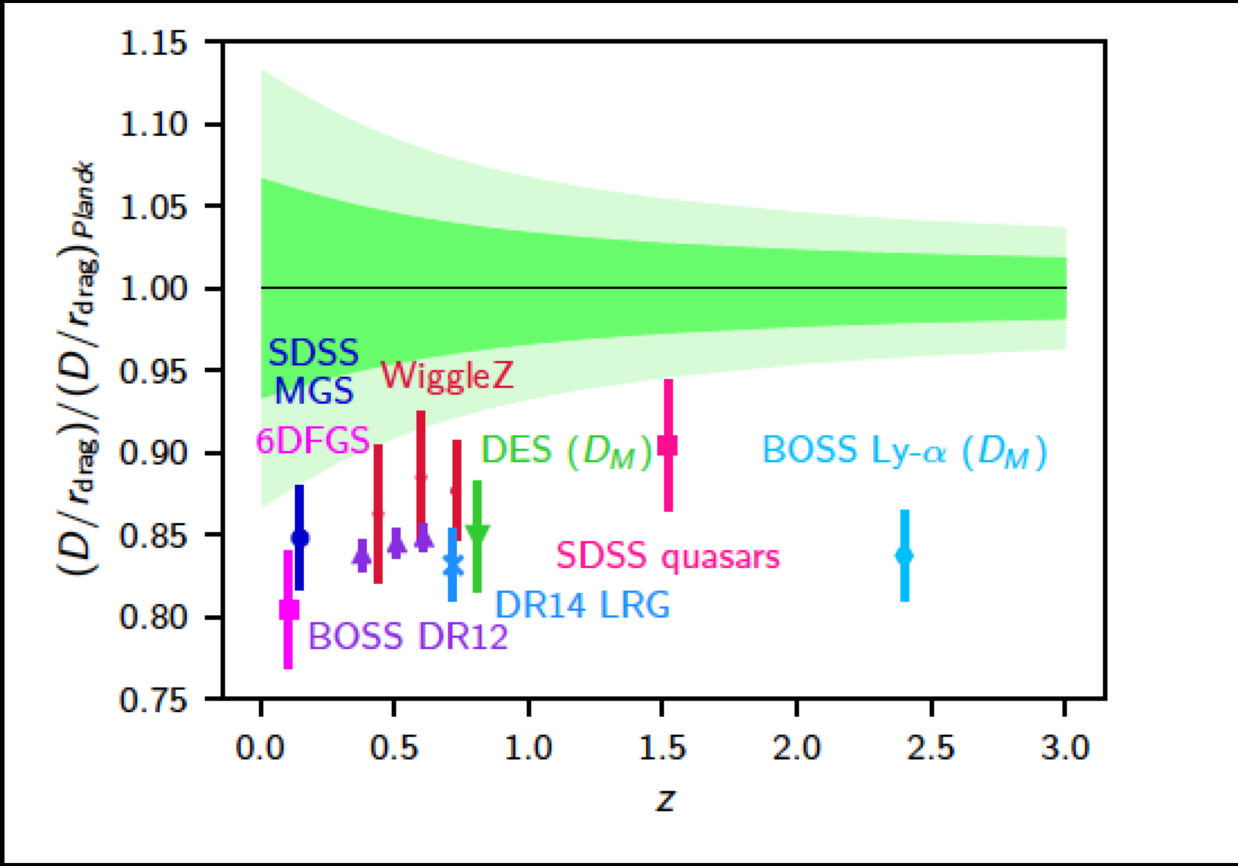


Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

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…

Curvature of the universe



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!

Curvature of the universe

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
$H(r_{d,fid}/r_d)$ (km s^{-1} Mpc^{-1})	0.38	81.5 ± 1.9	71.6 ± 3.3	2.6σ
$H(r_{d,fid}/r_d)$ (km s^{-1} Mpc^{-1})	0.51	90.5 ± 1.97	78.9 ± 3.1	3.1σ
$H(r_{d,fid}/r_d)$ (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)

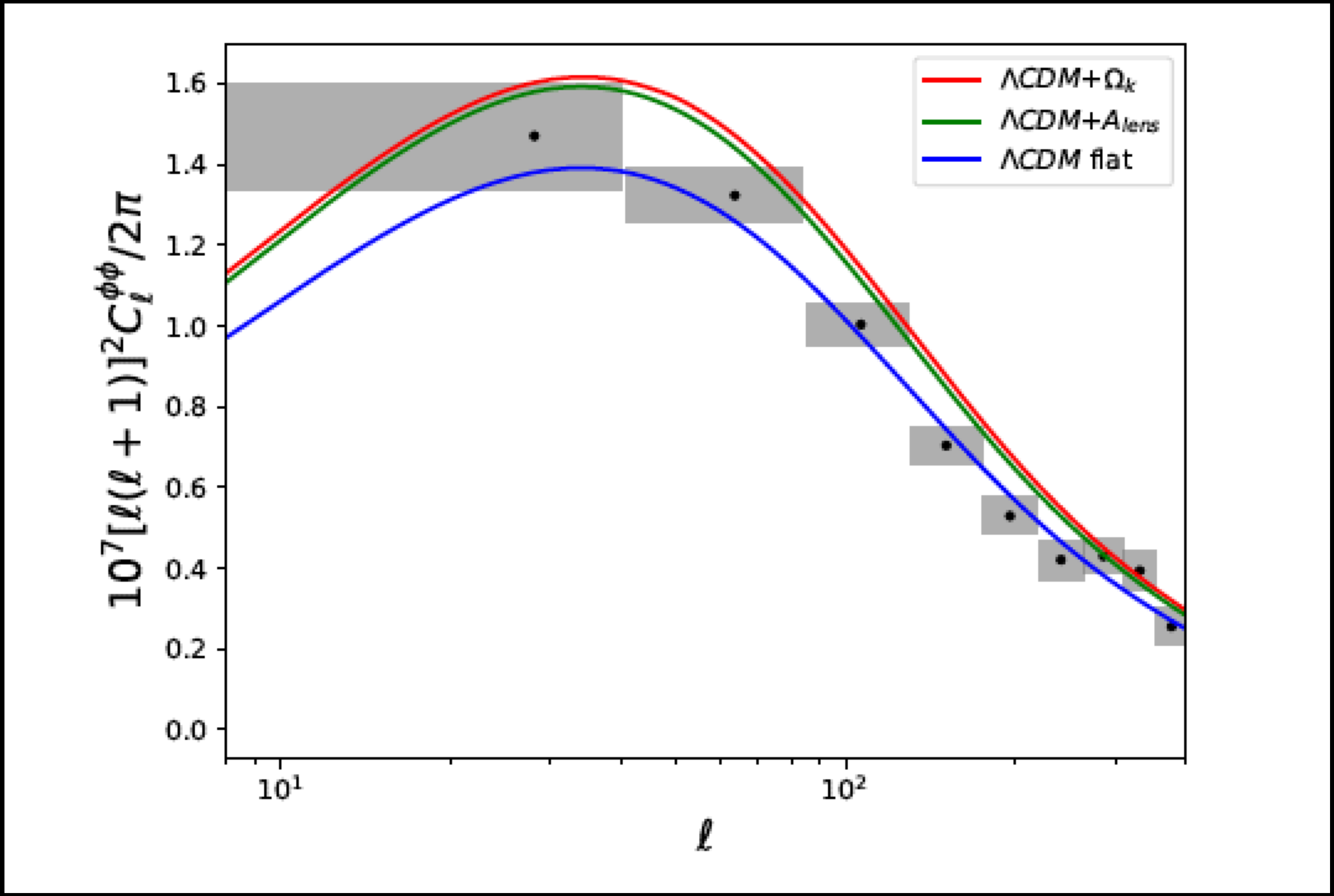
In the Table we have the constraints on DM and H(z) from the recent analysis of BOSS DR12 data and the corresponding constraints obtained indirectly from Planck, assuming a ΛCDM model with curvature.

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.

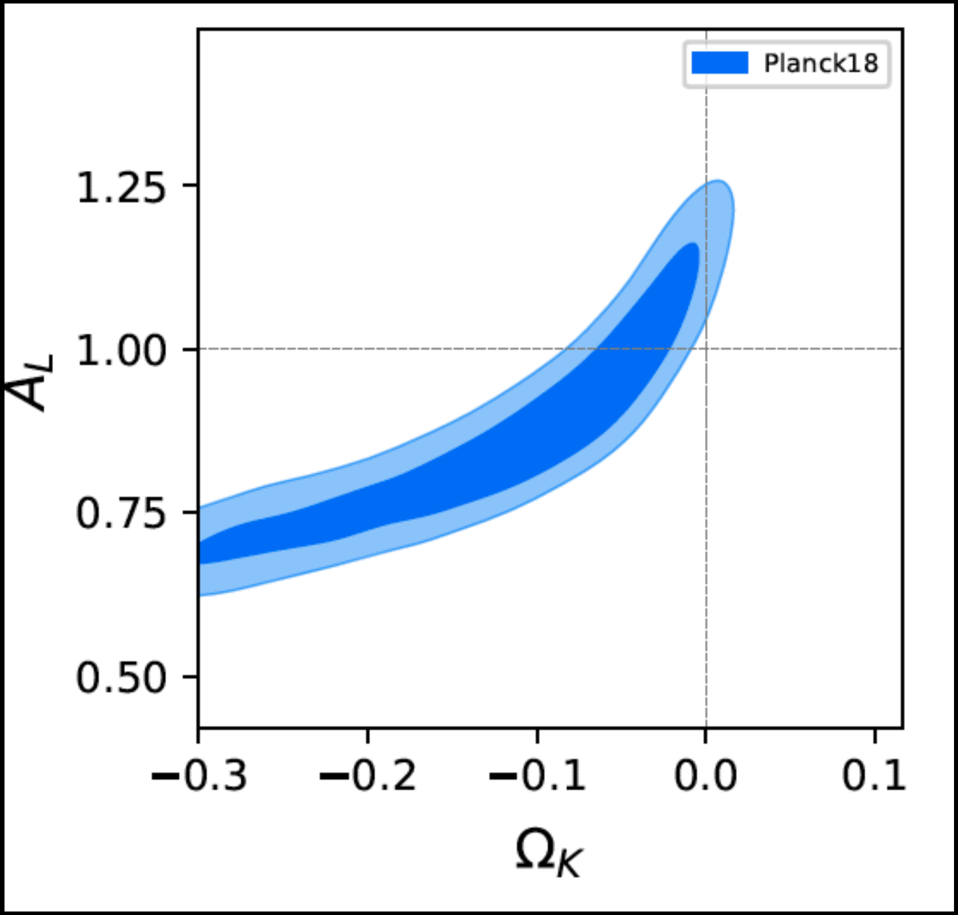
Curvature of the universe

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)

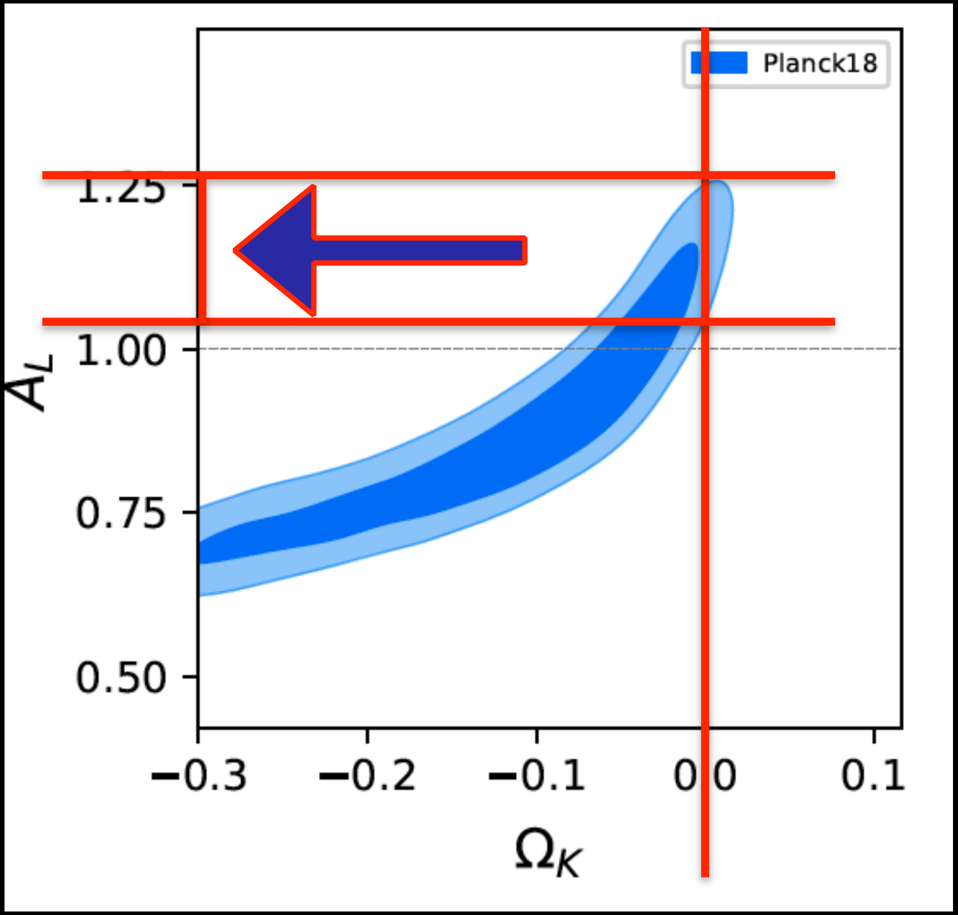
Curvature can explain A_L



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. Note that a model with $\Omega_K < 0$ is slightly preferred with respect to a flat model with $AL > 1$, because closed models better fit the low-multipole data.

Curvature can explain A_L



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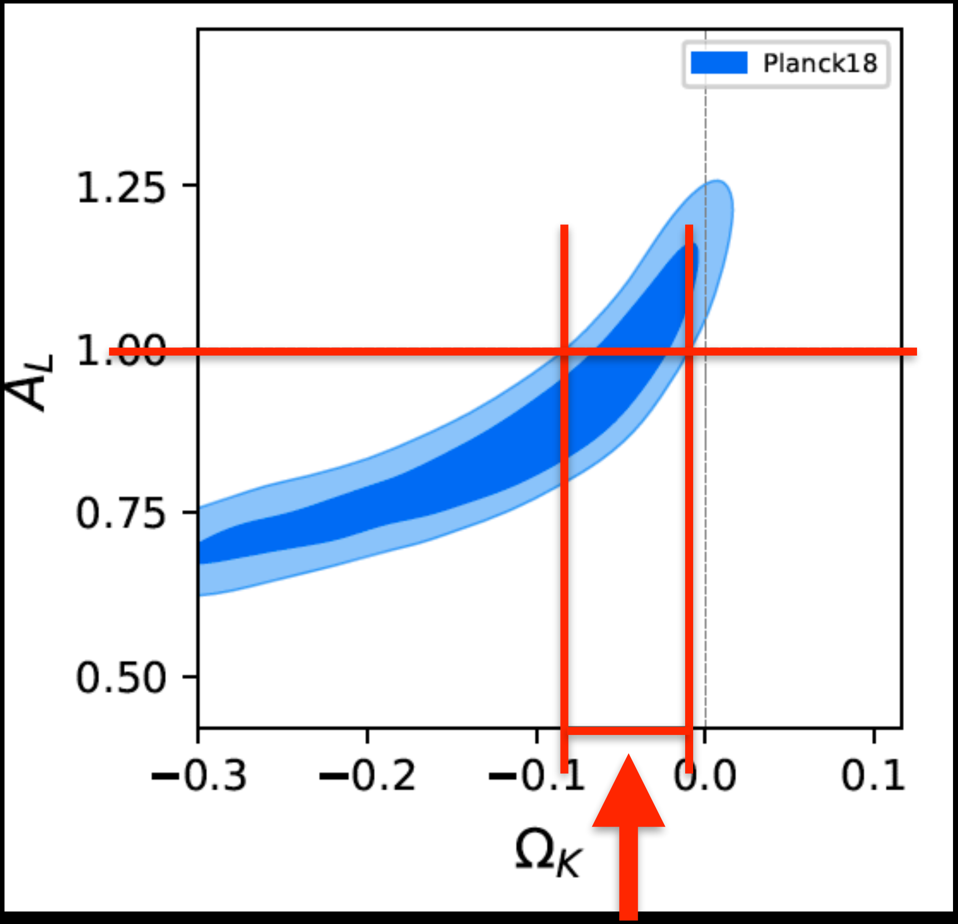

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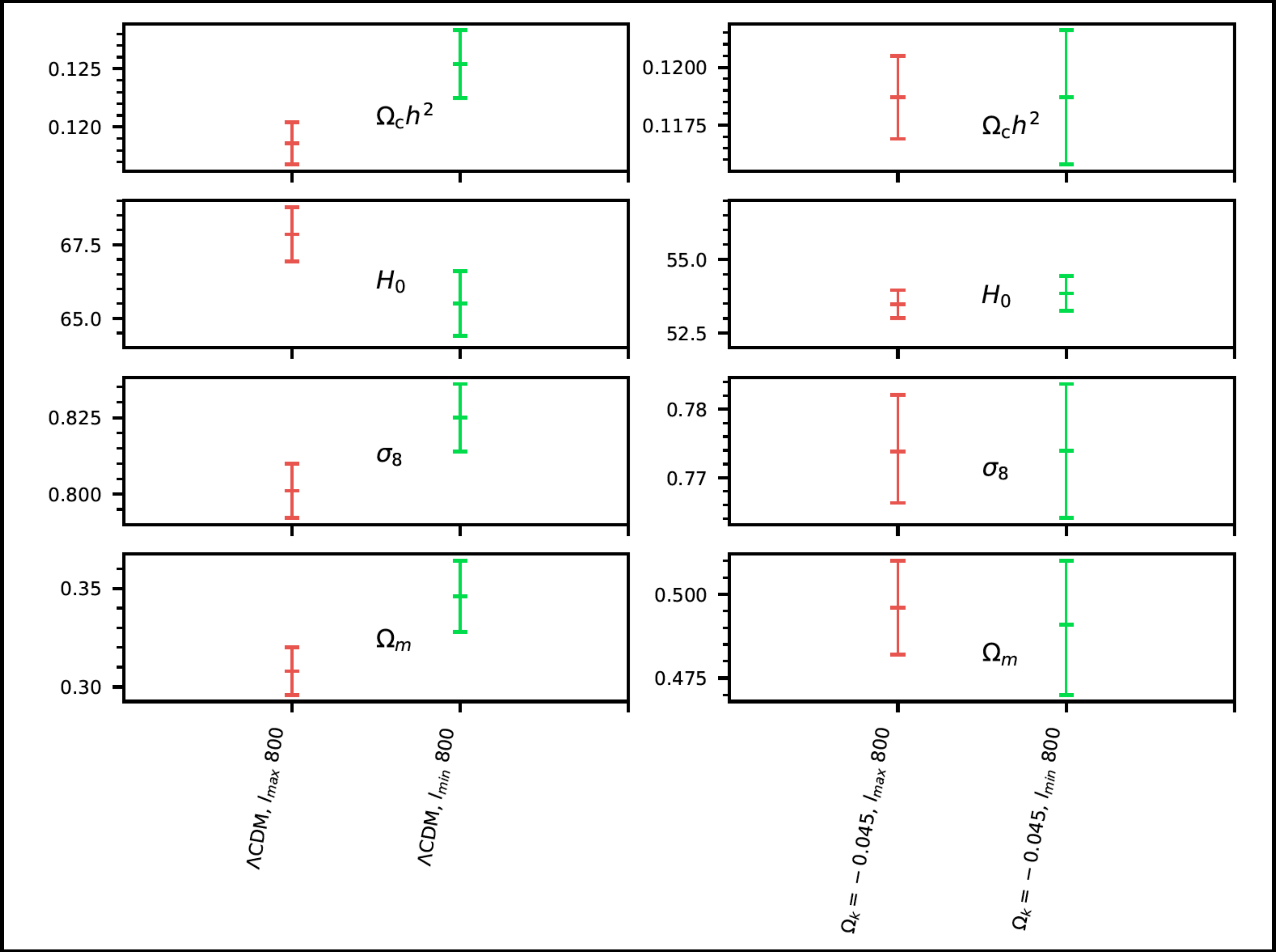
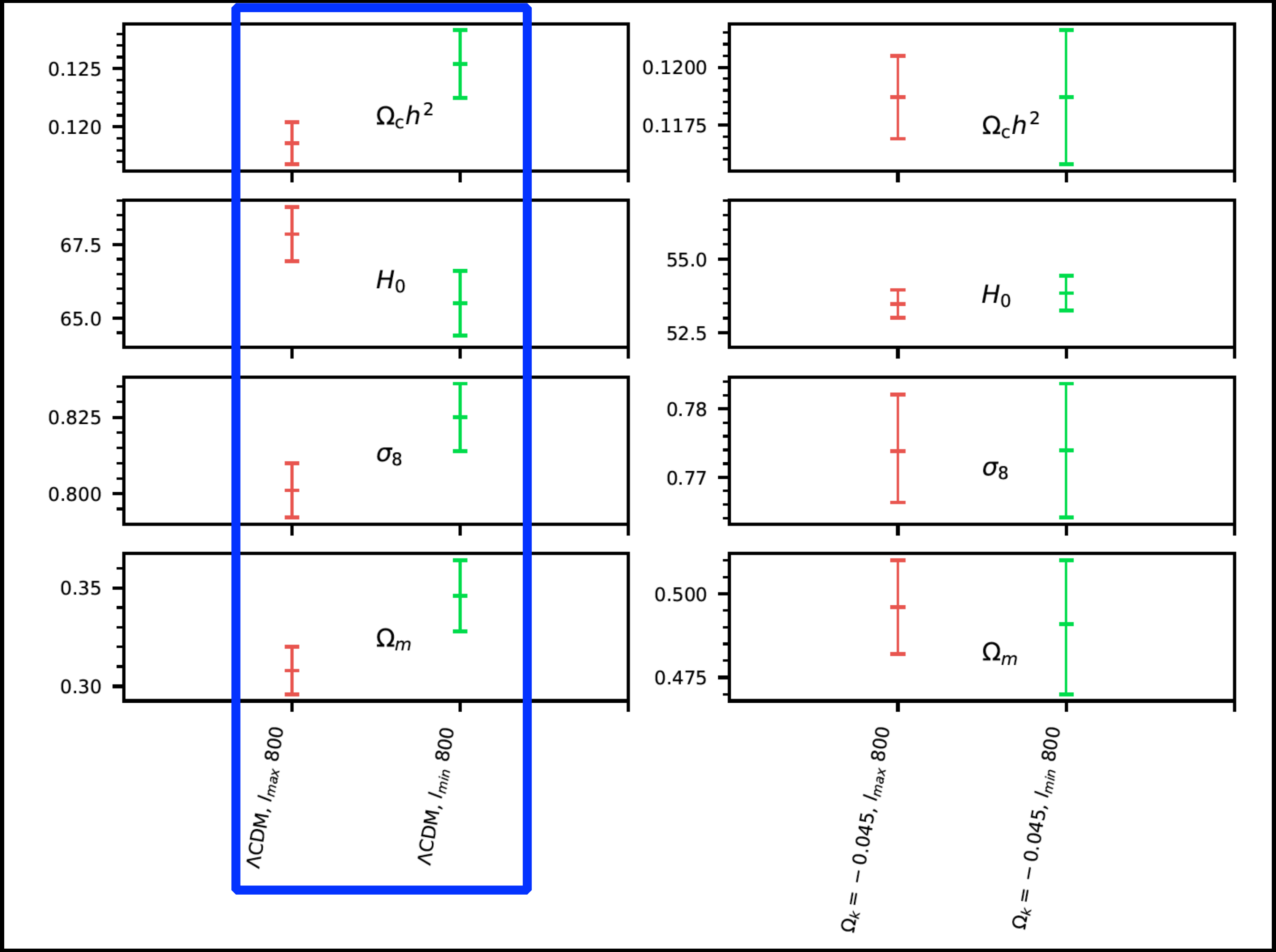
Curvature can explain internal tension



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)

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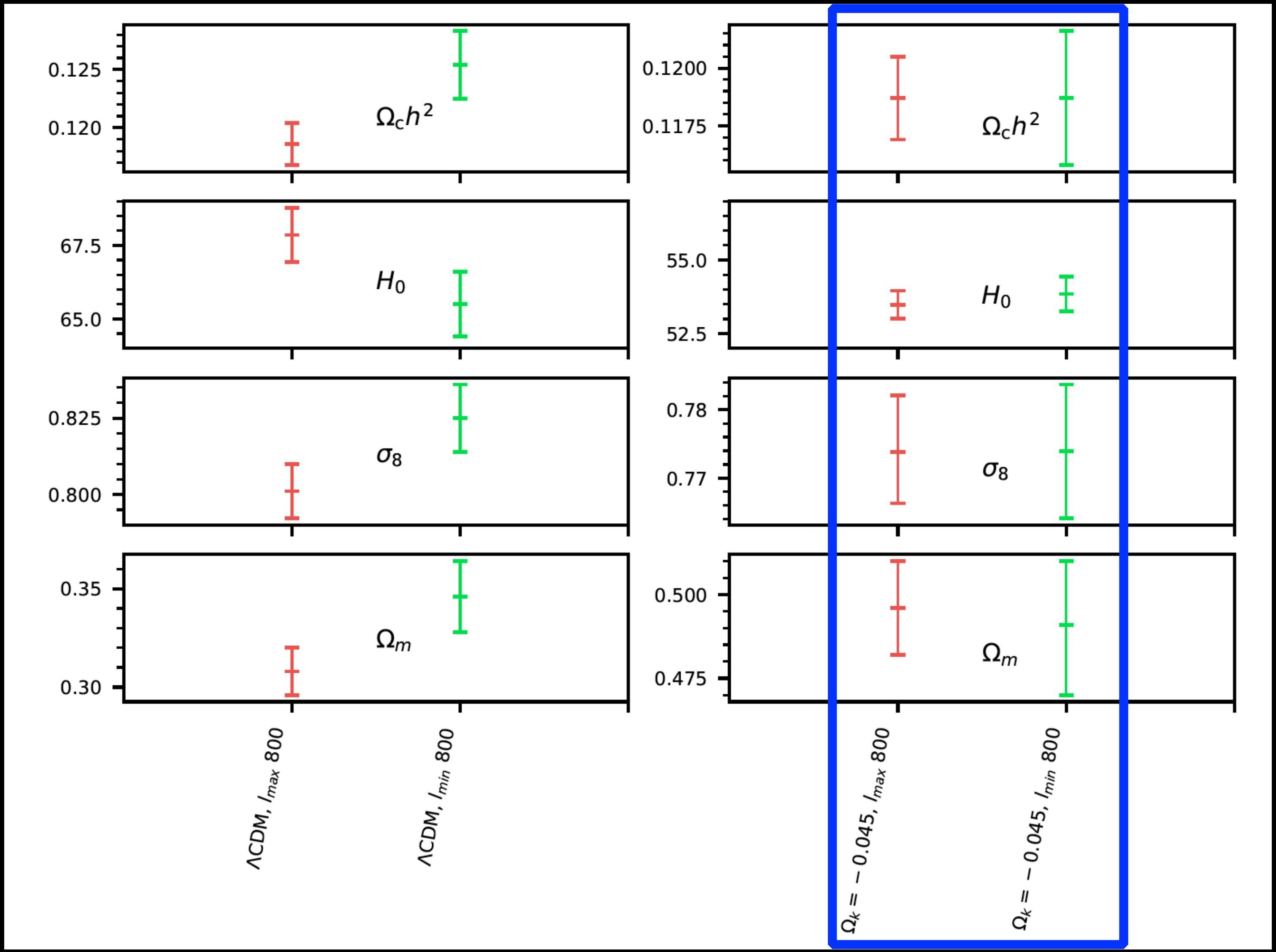

Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

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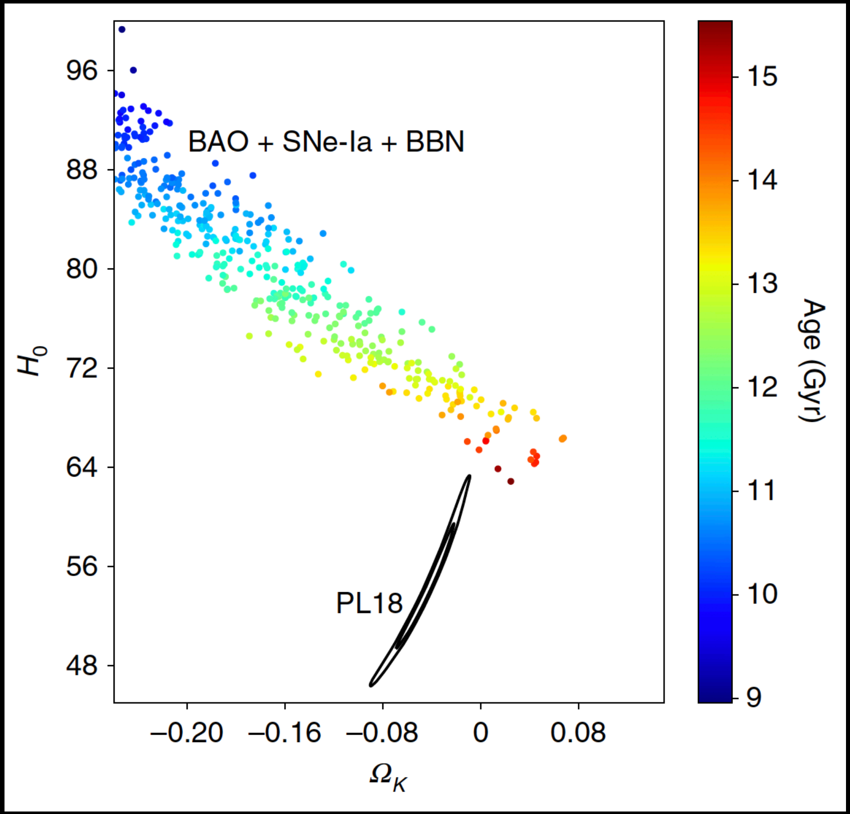
Curvature of the universe



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.

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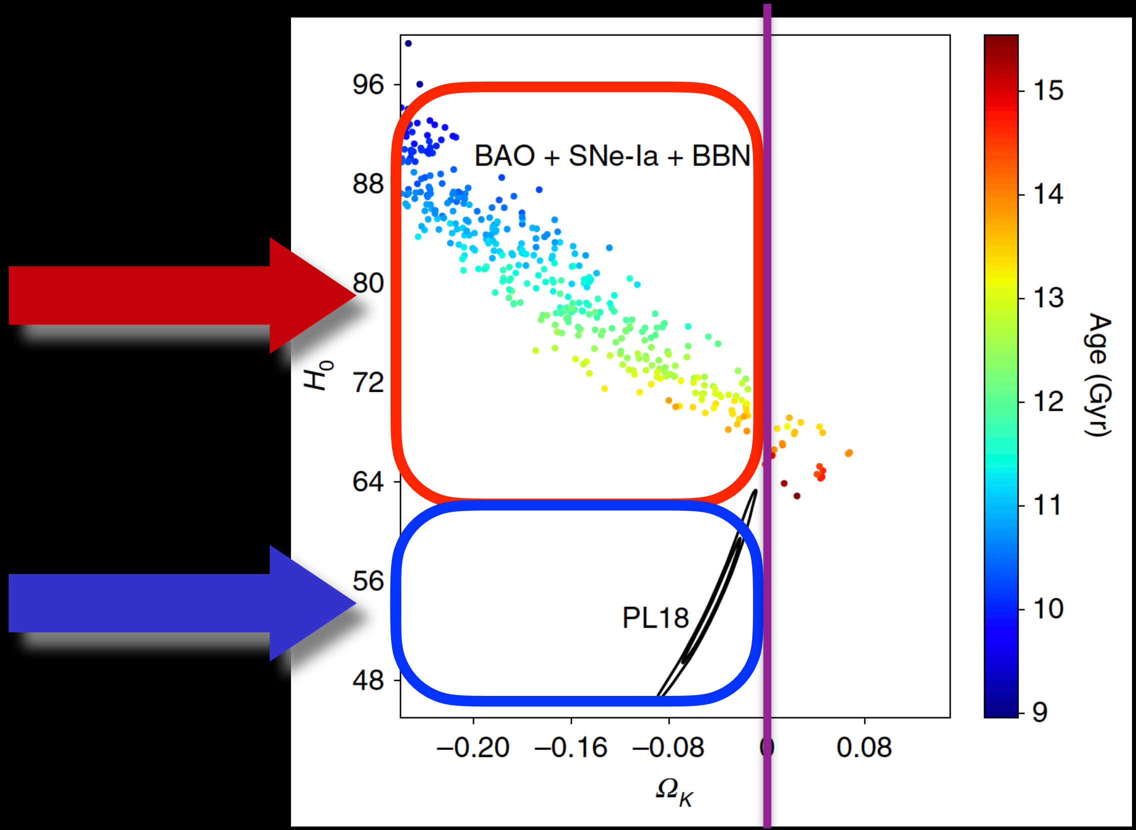

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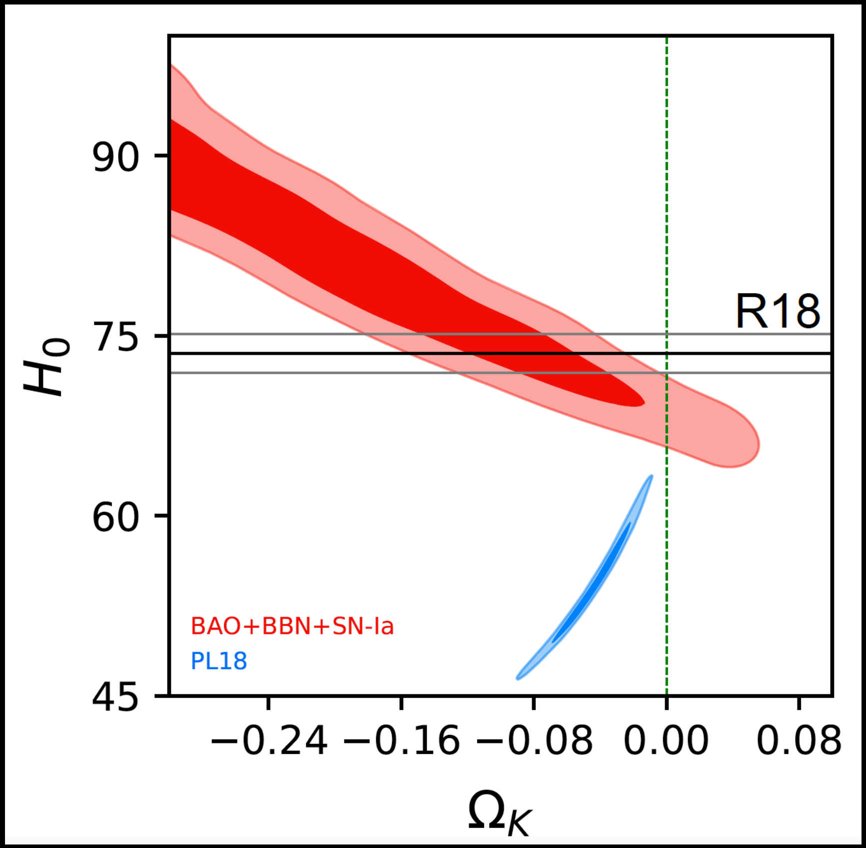
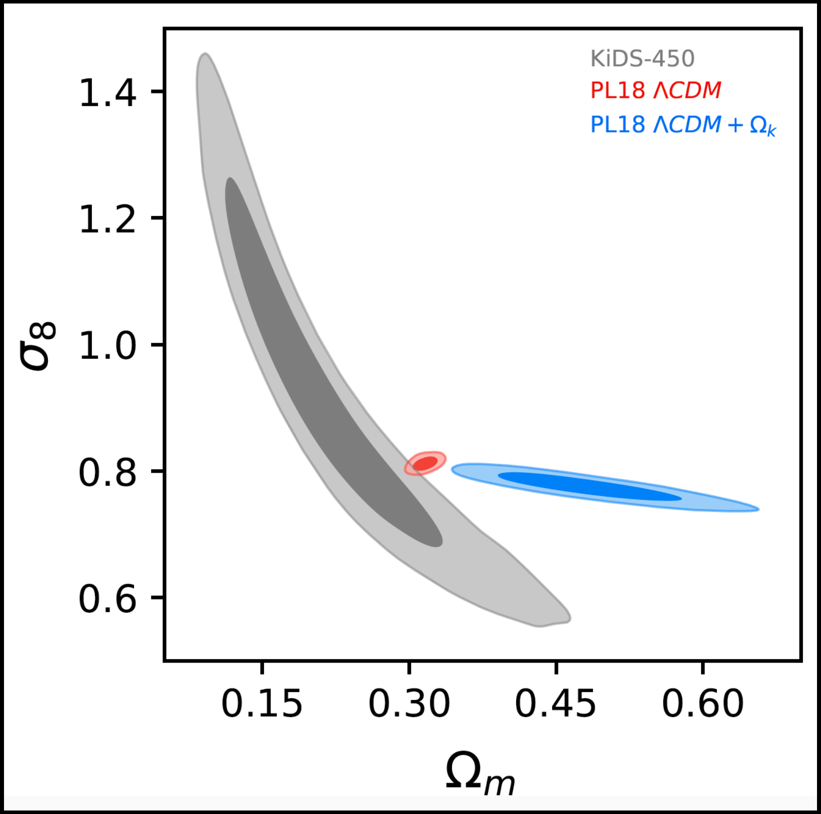


Di Valentino, Melchiorri and Silk, Nature Astronomy (2019)

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.

arXiv.org > astro-ph > arXiv:2002.06892

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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.

Plik is the official likelihood, tested and chosen by the Planck collaboration, while CamSpec is the likelihood used for crosschecking, not publicly available. The prior is flat and uniform on omegak as for all the other parameters.

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. Martine
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
B. Partridge[39], G. Patanchon[2], H. V. Peiris[22], F. Perrotta[78]
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*

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

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. Impro
many parameters, with residual modelling uncertainties estimated
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 ne
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 spati
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 radiati... 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

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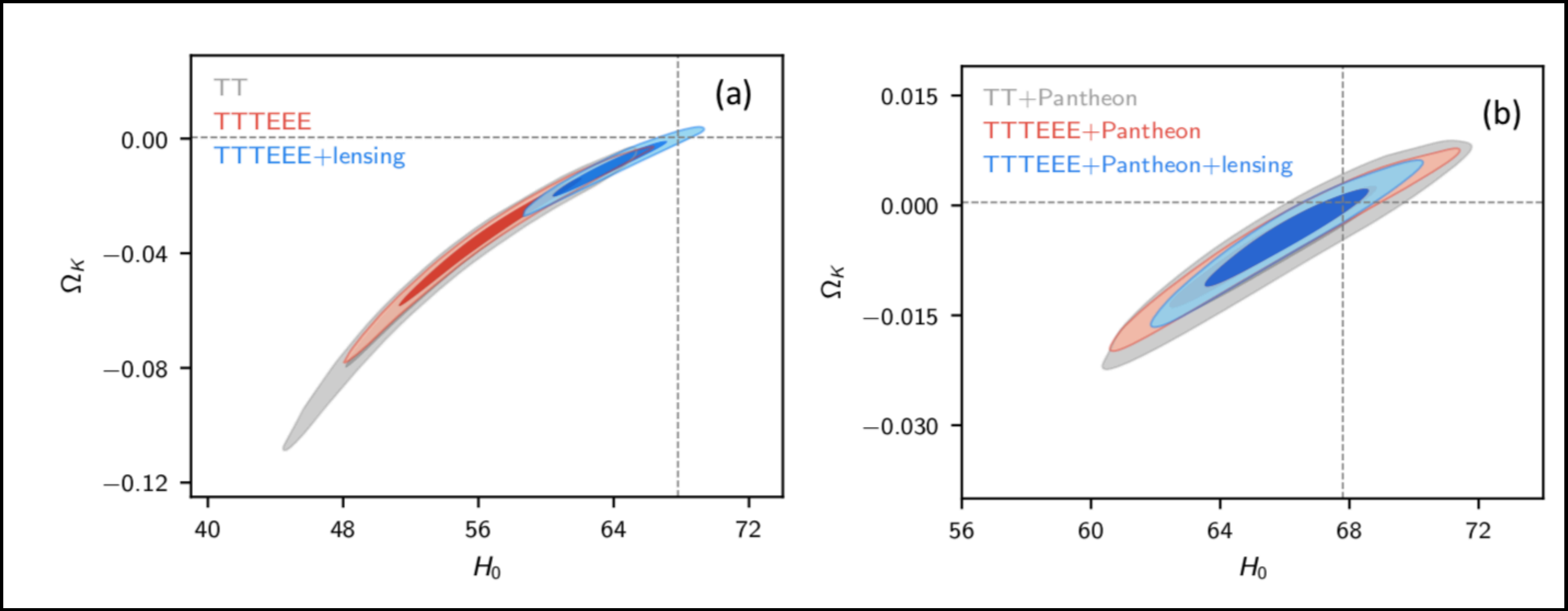


Efstathiou and Gratton, arXiv:2002.06892

Major objections raised in the paper are:

- Use of the Plik likelihood instead of CamSpec, not publicly available.
- Uniform prior on omegak instead of a prior peaked in zero, as predicted by inflation.
- Use of the low multipoles (ell<30) data showing an amplitude suppression as predicted by a closed universe.
- Possible statistical fluctuation.
- Possible systematics in Planck.
- 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.

Constraints at 68% cl.

10 parameters: including 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: including 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

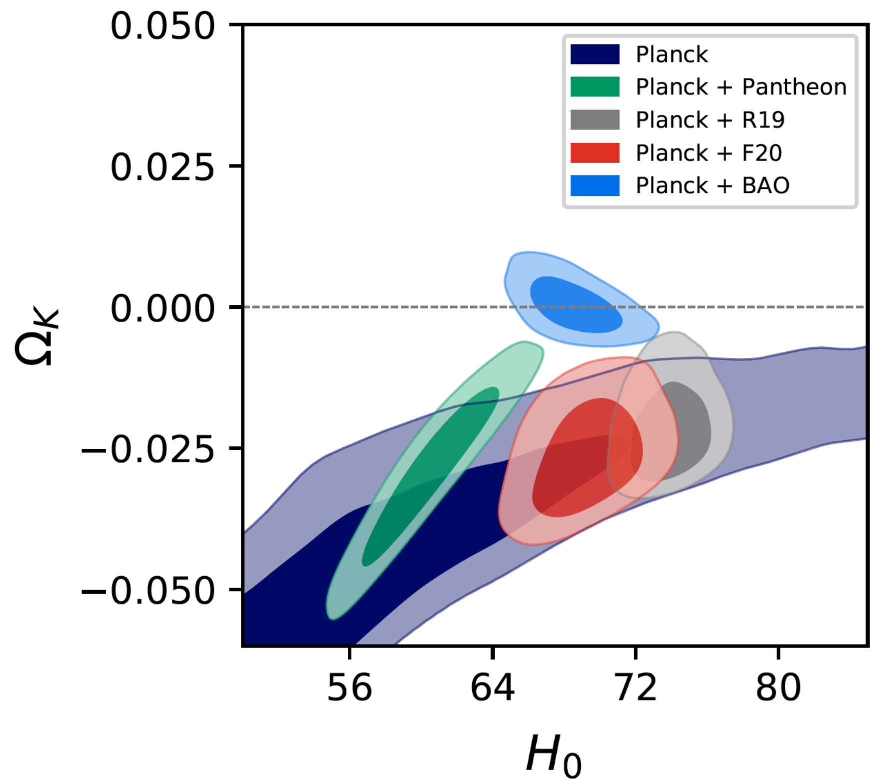
A combined analysis of the recent Planck angular power spectra with different luminosity distance measurements is in strong disagreement (at more than 99% C.L.) with the two main expectations of the standard LCDM model, i.e., a flat universe and a cosmological constant.

Di Valentino et al., arXiv:2003.04935

Constraints at 68% cl.

10 parameters: including curvature

Parameters	Planck	Planck	Planck	Planck	Planck + Pantheon
$\Omega_b h^2$	0.02253 ± 0.00019			016	0.02255 ± 0.00018
$\Omega_c h^2$	0.1183 ± 0.0016			14	0.1186 ± 0.0015
$100\theta_{MC}$	1.04099 ± 0.00035			032	1.04107 ± 0.00034
τ	0.0473 ± 0.0083			81	0.0506 ± 0.0082
Σm_ν [eV]	$0.43^{+0.16}_{-0.37}$				< 0.420
w	$-1.6^{+1.0}_{-0.8}$			98 38	$-1.27^{+0.14}_{-0.09}$
Ω_k	$-0.074^{+0.058}_{-0.025}$			27 37	$-0.029^{+0.011}_{-0.010}$
$\ln(10^{10}A_s)$	3.025 ± 0.018			17	3.034 ± 0.017
n_s	0.9689 ± 0.0054			048	0.9685 ± 0.0051
α_S	-0.0005 ± 0.0067			068	-0.0023 ± 0.0065
H_0[km/s/Mpc]	53^{+6}_{-16}				60.5 ± 2.5
σ_8	$0.74^{+0.08}_{-0.16}$			27	$0.812^{+0.031}_{-0.018}$
S_8	$0.989^{+0.095}_{-0.063}$			16	0.927 ± 0.037
Age[Gyr]	$16.10^{+0.92}_{-0.80}$			0	14.98 ± 0.39
Ω_m	$0.61^{+0.21}_{-0.34}$			16	$0.393^{+0.030}_{-0.036}$
$\Delta\chi^2_{bestfit}$	0.0	0.62	0.88	14.77	1037.82



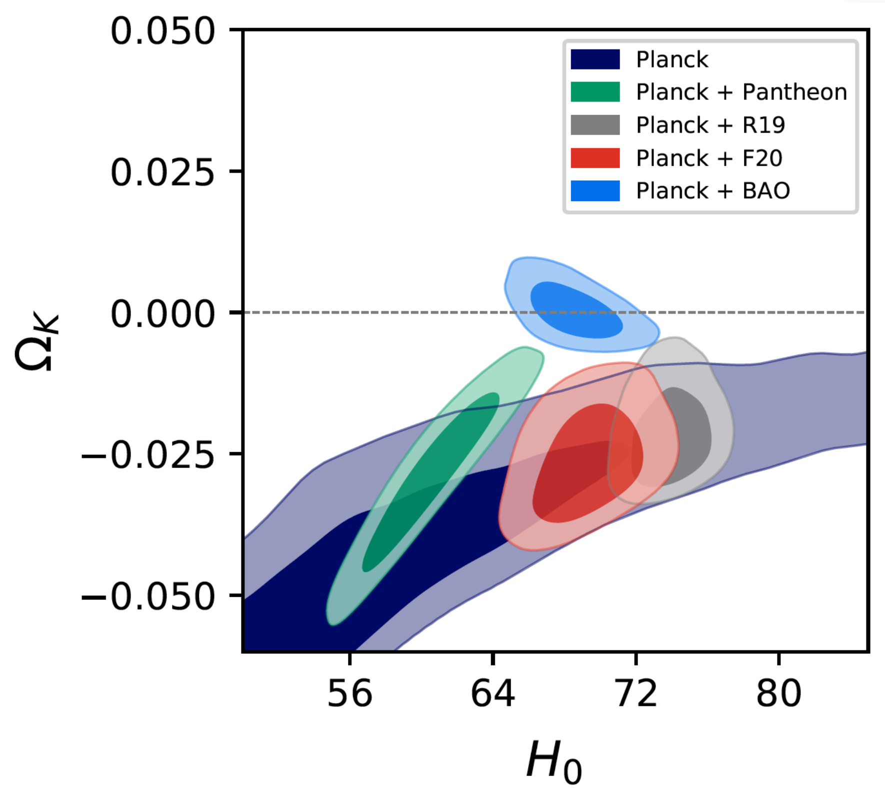
The confidence levels from Planck are clearly below the $\Omega_K = 0$ line that describes a flat universe. On the other hand, the Planck data are now in perfect agreement with the Pantheon, R19, and F20 measurements, while they are still in strong tension with the BAO measurements, so their combination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

Di Valentino et al., arXiv:2003.04935

Constraints at 68% cl.

10 parameters: including curvature

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



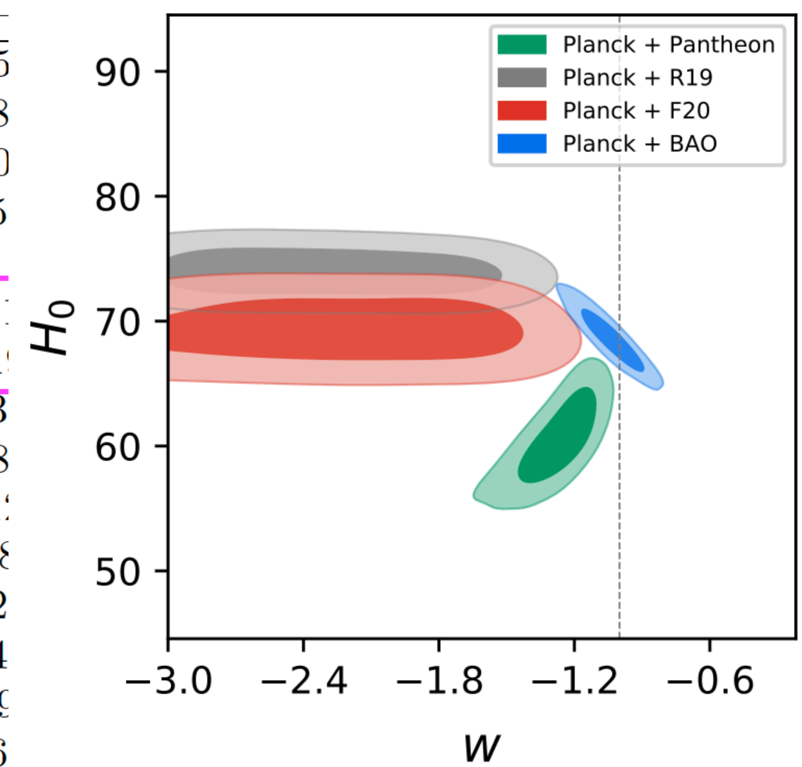
Moreover, all the 95% confidence regions from the Planck+Pantheon, Planck+F20, and Planck+R19 datasets are well below the $\Omega_k = 0$ line. This clearly shows that the recent claims of a closed universe as being incompatible with luminosity distance measurements are simply due to the assumption of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

Di Valentino et al., arXiv:2003.04935

Constraints at 68% cl.

10 parameters: including 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}	$73.$			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]	$16.10^{+0.92}_{-0.80}$	$14.$			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

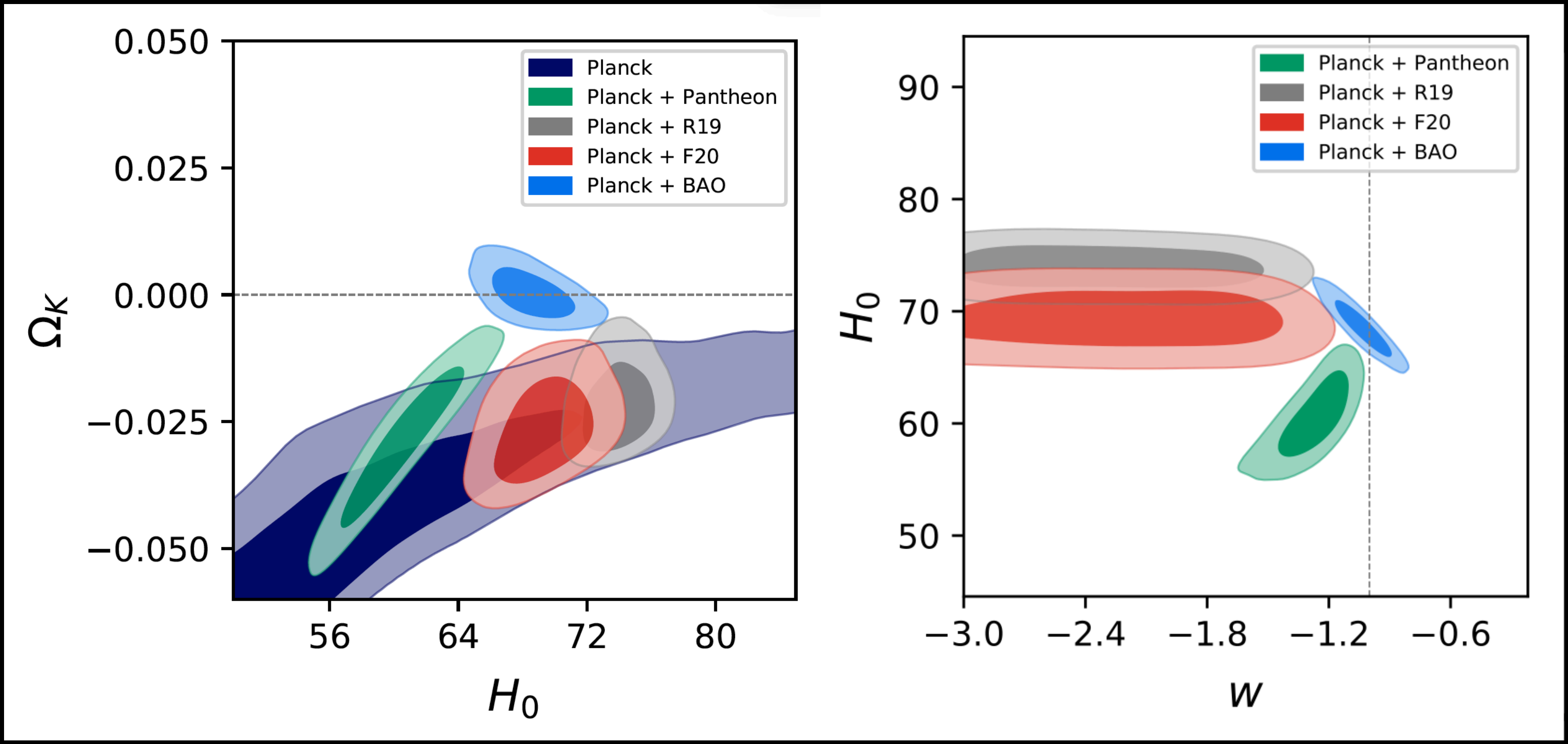


Indeed, all the three datasets, combined with Planck, exclude a cosmological constant, clearly preferring a value of w < –1, but their Hubble constant values that are in tension between themselves.

Di Valentino et al., arXiv:2003.04935

Constraints at 68% cl.

10 parameters: including curvature



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

Summarising

Extended neutrino scenarios seem no more suitable for solving the H0 tension, but the possible solution seems to be in the dark energy sector.

We studied a simple IDE model that relieves the H0 tension hinting for an interaction different from zero at more than 5σ. However, when BAO data are added in the analysis the Hubble constant tension is restored at about 2.5σ.

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.

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

Thank you!

eleonora.divalentino@manchester.ac.uk

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Curvature of the universe

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.

Curvature of the universe

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
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's 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.

Curvature of the universe

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

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

A second 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 lensing amplitude

μ(k, a) modifies the Poisson equation for the Newton's gravitational potential Ψ:

$$k^2\Psi = -4\pi G a^2 \mu(k,a)\rho\Delta$$

η(k,a) takes into account the presence of a non-zero anisotropic stress, with Φ the space curvature:

$$\eta(k,a) = \frac{\Phi}{\Psi}\,.$$

Σ(k, a) modifies the lensing/ Weyl potential Φ+Ψ:

$$-k^2(\Phi+\Psi) \equiv 8\pi G a^2 \Sigma(k,a)\rho\Delta$$

$$\Sigma = \frac{\mu}{2}(1+\eta)\,.$$

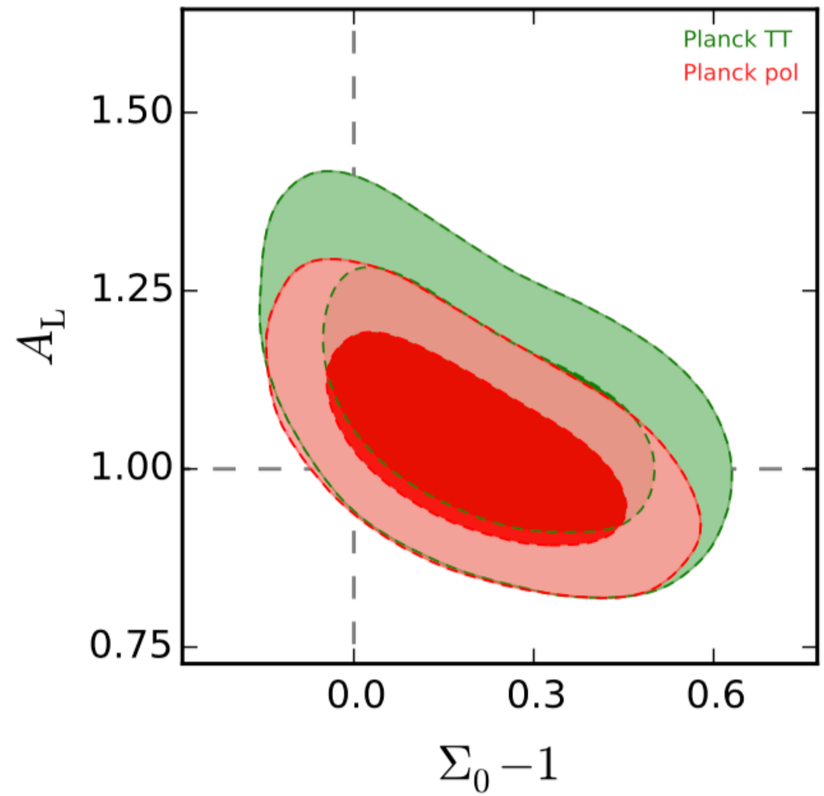


FIG. 2: Constraints at 68% and 95% confidence levels on the $\Sigma_0 - 1$ vs $A_{\rm lens}$ plane from the Planck TT and Planck pol datasets. A strong degeneracy is present between Σ_0 and $A_{\rm lens}$: larger values of $A_{\rm lens}$ are more compatible with the data if Σ_0 is smaller than one.

Di Valentino et al., Phys.Rev. D93 (2016) no.2, 023513

IDE can solve the H0 tension

The evolution equations for the interacting background will be

$$\dot{\rho}_{dm} + 3\mathcal{H}\rho_{dm} = \xi\mathcal{H}\rho_{de},$$

$$\dot{\rho}_{de} + 3\mathcal{H}(1+w)\rho_{de} = -\xi\mathcal{H}\rho_{de}.$$

While the perturbation evolution, within the linear regime and in the synchronous gauge, is given by

$$\dot{\delta}_{dm} = -\left(kv_{dm} + \frac{1}{2}\dot{h}\right) + \xi\mathcal{H}\frac{\rho_{de}}{\rho_{dm}}(\delta_{de} - \delta_{dm}) + \xi\frac{\rho_{de}}{\rho_{dm}}\left(\frac{kv_T}{3} + \frac{\dot{h}}{6}\right),$$

$$\dot{\delta}_{de} = -(1+w)\left(kv_{de} + \frac{1}{2}\dot{h}\right) - 3\mathcal{H}(1-w) \times \left[\delta_{de} + \mathcal{H}(3(1+w)+\xi)\frac{v_{de}}{k}\right] - \xi\left(\frac{kv_T}{3} + \frac{\dot{h}}{6}\right),$$

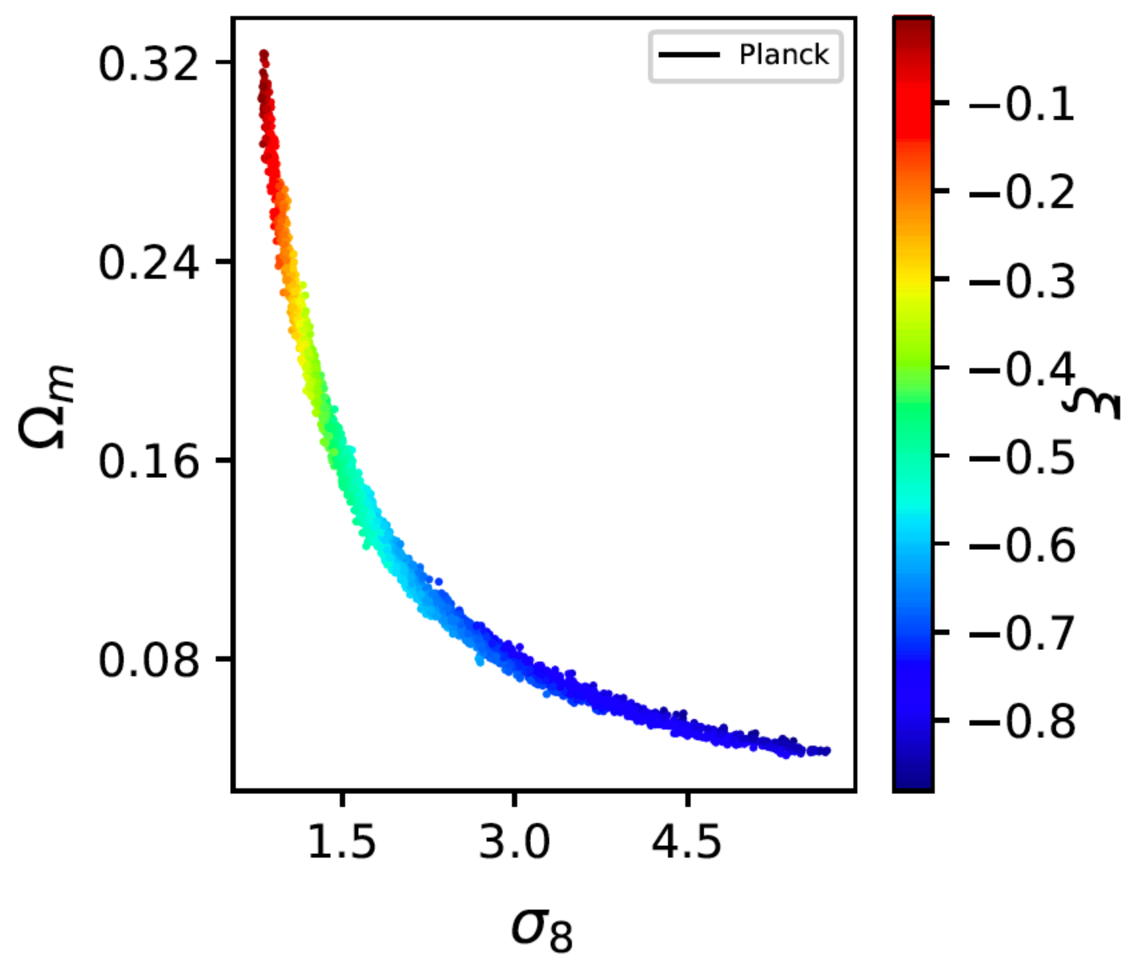
$$\dot{v}_{dm} = -\mathcal{H}v_{dm},$$

$$\dot{v}_{de} = 2\mathcal{H}\left(1 + \frac{\xi}{1+w}\right)v_{de} + \frac{k}{1+w}\delta_{de} - \xi\mathcal{H}\frac{v_{dm}}{1+w},$$

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

IDE

Moreover, we find a shift of the clustering parameter σ_8 towards a higher value, compensated by a lowering of the matter density Ω_m, both with relaxed error bars. The reason is that once a coupling is switched on and Ω_m becomes smaller, the clustering parameter σ_8 must be larger to have a proper normalization of the (lensing and clustering) power spectra.



Di Valentino et al. arXiv:1908.04281