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Exploring the Tension between Current Cosmic Microwave Background and Cosmic Shear Data

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Abstract: This paper provides a snapshot of the formal $S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$ tension between Planck 2015 and the Kilo Degree Survey of 450 deg^2 of imaging data (KiDS-450) or the Canada France Hawaii Lensing Survey (CFHTLenS). We find that the Cosmic Microwave Bckground (CMB) and cosmic shear datasets are in tension in the standard Λ Cold Dark Matter (ΛCDM) model, and that adding massive neutrinos does not relieve the tension. If we include an additional scaling parameter on the CMB lensing amplitude A_{lens}, we find that this can put in agreement the Planck 2015 with the cosmic shear data. A_{lens} is a phenomenological parameter that is found to be more than 2σ higher than the expected value in the Planck 2015 data, suggesting an higher amount of lensing in the power spectra, not supported by the trispectrum analysis.

Keywords: Cosmic Microwave Bckground (CMB); S8 tension; cosmological parameters

1. Introduction

There is a long history of potential tension between low redshift probes of mass clustering and the Cosmic Microwave Background (CMB), and ongoing speculation that this may be evidence for new physics. Cosmology is at an exciting time. The best CMB cosmology experiment for a few years, Planck, has just released its final conclusions [1,2] [hereafter Planck 2018]. Meanwhile, some of the first constraints from the new generation of cosmic shear experiments starting to come out, fromt he Kilo Degree Survey of 450 deg^2 of imaging data (KiDS-450) [3–5] and the Dark Energy Survey (DES) [6,7], as well as existing results from the Canada France Hawaii Lensing Survey (CFHTLenS) [8–10]. The newest likelihoods from these surveys have not yet been released; so, in anticipation, we take stock of the current formal constraints using the current best public likelihoods from each of the Planck and KiDS collaborations, as well as the version of CFHTLenS, currently the default in the most popular cosmology code CosmoMC.

The Planck 2018 results appear to have corroborated the expectations of the standard ΛCDM cosmological model. Despite the impressive agreement, some hints for deviations from the standard scenario have been confirmed with this release—for example, some internal inconsistencies like the tension between the constraints obtained by considering the high and low multipoles of Planck, already present in the previous data release [2,11,12], or the hints at more than two standard deviations for new physics, like the A_{lens} anomaly, i.e., the amplitude of the gravitational lensing in the angular power spectra different from one, or the curvature of the Universe different from zero, or modified gravity (MG). Moreover, there are the tensions between Planck and some other cosmological probes, like the direct measurements of the Hubble constant [13–15] at more than 3σ, and the tension in the σ_8-Ω_m plane with cosmic shear experiments at more than 2σ [3–5,8–10].

In the literature, several solutions (see for example [16–24]) have been proposed for solving the tension in the σ_8-Ω_m plane. In this paper, we will revisit it using different extended cosmological models. We will consider the cosmic shear datasets both using the original angular scales and using conservative cuts, and we use the current latest publicly available likelihood from Planck [25], which we refer to as Planck 2015 throughout.

The paper is organized in the following way: in Section 2, we will present the codes, the method and the datasets we will use for the analysis; in Section 3, we will show our results in different cosmological scenarios, and, finally, in Section 4, we will present our conclusions.

2. Method

We analyze the cosmological data by considering the six cosmological parameters of the Standard ΛCDM model, namely the baryon energy density $\Omega_b h^2$, the cold dark matter energy density $\Omega_c h^2$,the ratio between the sound horizon and the angular diameter distance at decoupling θ_s, the reionization optical depth τ, the spectral index of the scalar perturbations n_S and the amplitude of the primordial power spectrum A_S.

In a second step, we add one more parameter at a time, i.e., the total neutrino mass Σm_ν, and the lensing amplitude A_{lens} in order to find a way to relieve the S_8 tension.

All the parameters of our analysis are explored within the range of the conservative flat priors reported in Table 1.

Table 1. Flat priors on the cosmological parameters assumed in this work.

Parameter	Prior
$\Omega_b h^2$	$[0.013, 0.033]$
$\Omega_c h^2$	$[0.001, 0.99]$
θ_s	$[0.5, 10]$
τ	$[0.01, 0.8]$
n_S	$[0.7, 1.3]$
$logA$	$[1.7, 5.0]$
Σm_ν	$[0, 5]$
A_{lens}	$[0, 10]$

We constrain the parameters by analyzing the full range of the 2015 Planck temperature power spectrum ($2 \leq \ell \leq 2500$) together with the low multipole polarization data ($2 \leq \ell \leq 29$) [25], and we call this combination "Planck TT". To understand the impact of the polarization data on our results, we repeat the analysis by including the Planck high multipoles polarization data [25], and we refer to this combination as "Planck TTTEEE". At the time of writing, only the Planck 2015 data is publicly available, even though preprint papers of the final data have been released. Therefore, in this analysis, we use the Planck 2015 data. However, given the similarities between the 2015 and the final Planck constraints, we do not expect the conclusions of this paper to change qualitatively with the new likelihood.

We compare these constraints with those obtained with the cosmic shear data from the Canada France Hawaii Lensing Survey (CFHTLenS) [8,9], with the original cut, that we call 'CFHTLenS', and with the conservative cut as described in [23], which we call 'CFHTLenS-linear-cut' (The default WL.ini in CosmoMC is CFHTLenS-linear-cut, i.e., CFHTLENS_6bin_ultra_conservative.dataset, while the original cut CFHTLenS is CFHTLENS_6bin.dataset). The CFHTLenS in CosmoMC does not include the baryonic feedback and the photo-z errors, while the CFHTLenS-linear-cut to the data is free from much of the systematics. For the latest measurements, see the discussion in Ref. [10] and the release at [26]. Moreover, we consider the Kilo Degree Survey of 450 deg^2 of imaging data (KiDS-450) [3–5], also in this case with the original cut, which we call 'KiDS', and with the conservative cuts as described in [27], which we call 'KiDS-linear-cut'. We note that the KiDS data has recently been re-analysed by Ref. [28], who modify the covariance matrix and bin positions to correct approximations made in the original release. These changes reduce the tension with Planck by increasing the clustering amplitude measured by cosmic shear by up to half a sigma. In the absence of an official update to the KiDS data, we have chosen to stick with the publicly available version provided by the KiDS team.

Finally, we consider a combination of data including a Gaussian prior on H_0 (i.e., $H_0 = 73.24 \pm 1.75\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ [14]), referred as "R16"; the baryon acoustic oscillation data from 6dFGS [29], SDSS-MGS [30], BOSSLOWZ [31] and CMASS-DR11 [31] surveys as was done in [32], called "BAO"; and the Joint light-curve analysis (JLA) sample of Supernovae Type Ia comprising 740 luminosity distance measurements in the redshift interval $z \in [0.01, 1.30]$ [33], referred as "JLA".

In order to analyze these datasets statistically exploring the different cosmological scenarios, we have used the publicly available Monte-Carlo Markov Chain package cosmomc [34], with a convergence diagnostic based on the Gelman and Rubin statistic. It implements an efficient sampling of the posterior distribution using the fast/slow parameter decorrelations [35], including also the support for the Planck data release 2015 Likelihood Code [25] (see [36]). Finally, we make use of the modified `cosmomc` modules and associated data files for weak lensing tomography cosmology fitting with KiDS [3,37] (see [38]).

3. Results

3.1. Standard Cosmological Model

In Table A1 and in Figure 1, we show the constraints for σ_8 and Ω_m for Planck and the cosmic shear experiments considered in this work, i.e., KiDS and CFHTLenS, for the original and the conservative scale cut, assuming the standard ΛCDM model. The conservative cut is used to mitigate the uncertainty over the nonlinear modeling scheme. Moreover, we compute the combination $S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$, reported in Figure 2, in order to quantify the tension between the datasets in the 2D dimensions, and we compare the full combination of datasets KiDS + BAO + JLA + R16 with Planck. In fact, if we compare the constraints on σ_8 and Ω_m, reported in Table A1, from the Planck satellite with KiDS or CFHTLenS, they seem perfectly in agreement. However, we can see from the Figures 1 and 2 that Planck TTTEEE is in disagreement with both CFHTLenS and KiDS, in agreement with each other, at more than 3σ and 2σ, respectively, while the tension disappears if we consider the conservative cuts for both the experiments. However, when combining KiDS with all the other cosmological probes considered here, namely BAO + JLA + R16, also for the conservative cut, the tension with Planck appears again at more than 2σ. The tension T in unit of σ can be quantified looking at the S_8 constraints in Figure 2 and Table A1 and computing:

$$T = \frac{S_{8,i} - S_{8,j}}{\sqrt{\sigma^2_{S_{8,i}} + \sigma^2_{S_{8,j}}}}\,. \tag{1}$$

While this tension between Planck and the cosmic shear experiments can be due to the presence of systematics in one or all the experiments, it is interesting to investigate if, by changing the assumed cosmological model, this tension can be mitigated or solved completely because the constraints obtained are always model dependent.

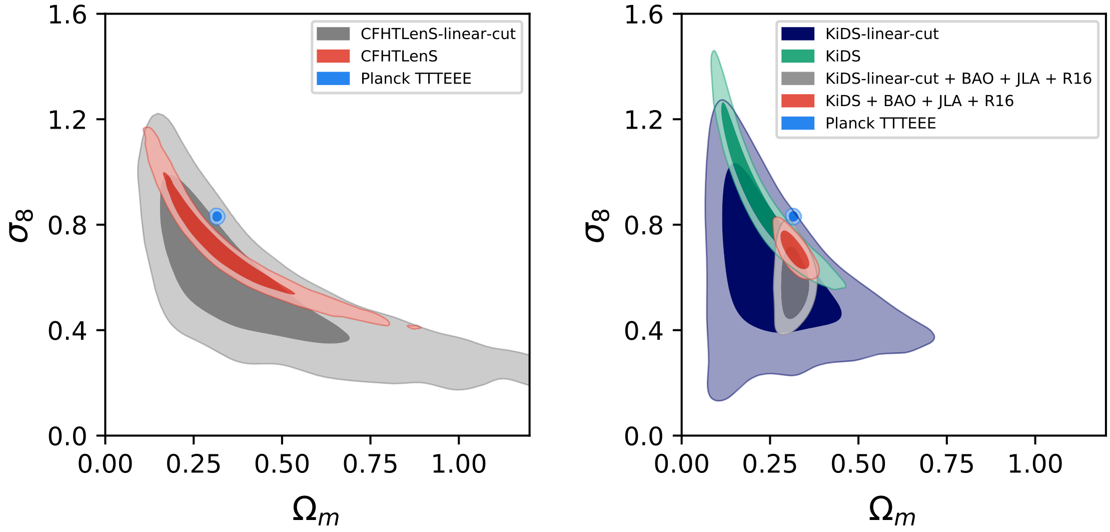

Figure 1. Constraints at 68% and 95% confidence levels on the σ_8 vs. Ω_m plane for several combination of datasets in the ΛCDM scenario. In both the cases, Planck is in tension at more than 2σ with the cosmic shear experiments with the original cut, while is in agreement considering their conservative cut.

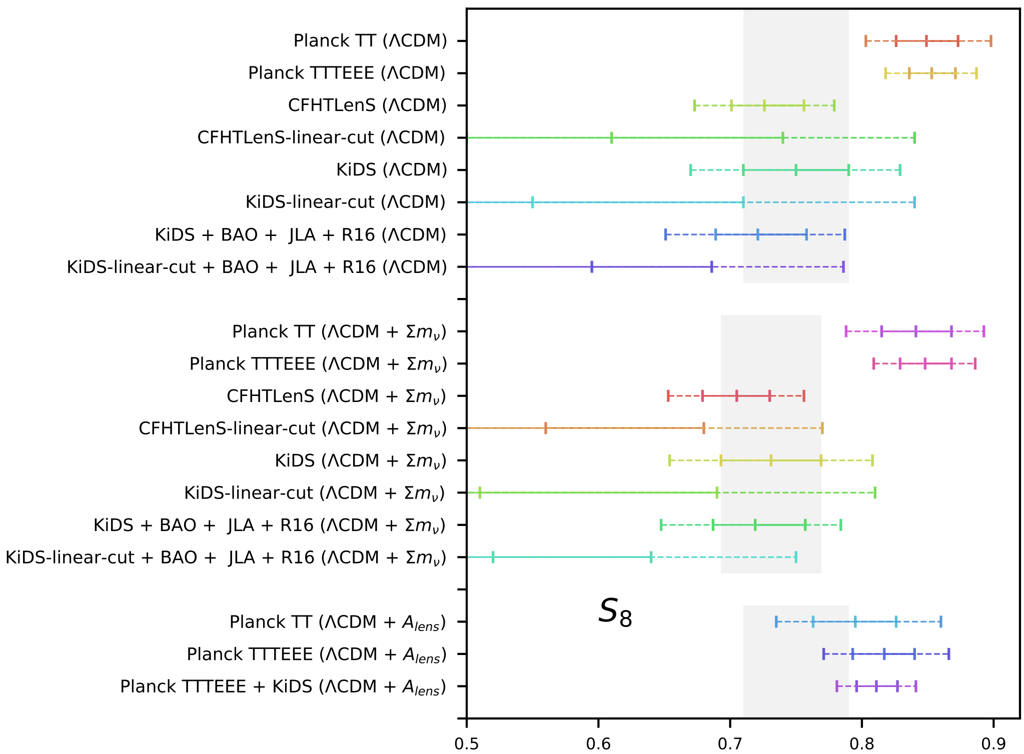

Figure 2. Constraints at 68% (solid) and 95% (dashed) on S_8 for several combination of datasets and models considered in this work. The gray band corresponds to the KiDS bounds in each cosmological scenario.

3.2. Massive Neutrinos

In Table A2 and in Figure 3, we show the constraints for σ_8, Ω_m and S_8 for Planck, KiDS and CFHTLenS, for both the original and the conservative scale cuts, assuming the ΛCDM + Σm_ν model.

Also in this case, if we compare the constraints on σ_8 and Ω_m, reported in Table A2, from the Planck satellite with KiDS or CFHTLenSt, they seem perfectly in agreement. Usually, massive neutrinos are included in the analysis to try to solve the tension between Planck and the cosmic shear experiments because, when introduced, the σ_8 bound shifts towards lower values [22,39–42]. However, we can see from the Figure 3 that Planck TTTEEE is in disagreement with both CFHTLenS and KiDS even when varying massive neutrinos, at more than 3σ and 2σ respectively. Also in this case, the tension is reduced if we consider the conservative cuts for both the experiments. Moreover, also in this case, when considering conservative KiDS + BAO + JLA + R16, the tension with Planck is restored at more than 2σ, as we can see looking at the S_8 constraints in Figure 2 and Table A2.

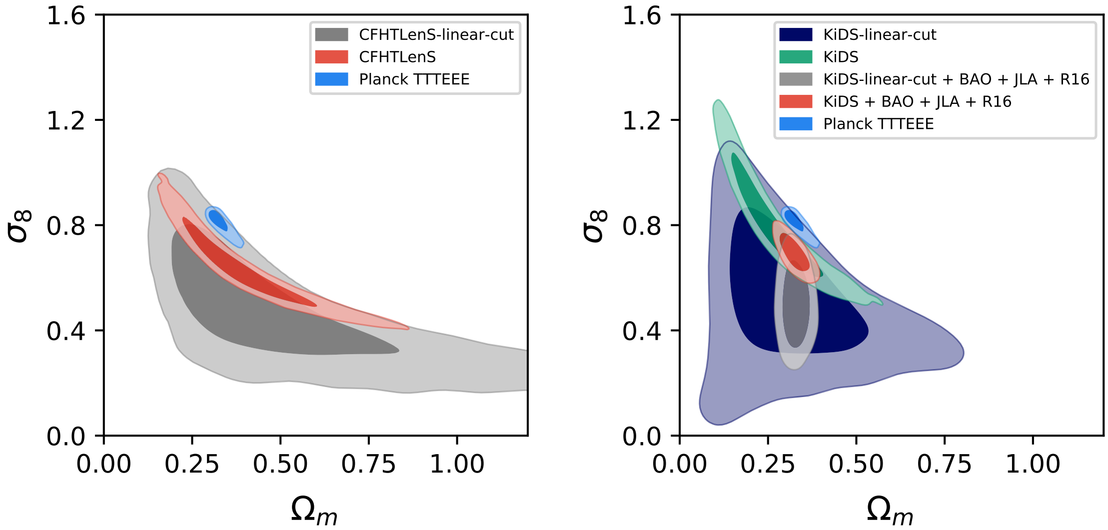

Figure 3. Constraints at 68% and 95% confidence levels on the σ_8 vs. Ω_m plane for several combination of datasets in the ΛCDM + Σm_ν model. In both of the cases, Planck is still in tension at more than 2σ with the cosmic shear experiments with the original cut, while is in agreement considering their conservative cut.

3.3. The Lensing Amplitude

In Table A3 and in Figure 4, we show the constraints for σ_8, Ω_m and S_8 for Planck assuming the ΛCDM + A_{lens} model. In this case, we compare the results with the constraints obtained for the parameters listed before for the cosmic shear experiments in the ΛCDM case because the A_{lens} parameter is just an effective parameter, with no physical meaning, that simply rescales the the lensing amplitude in the CMB spectra, and it is used for testing theoretical assumptions and systematics. See Ref. [43]. We consider here this A_{lens} parameter because this extension of the ΛCDM model is different from the expected value at more than 2σ, for the Planck dataset used in this work [32], and has been very recently confirmed with more statistical significance in the new Planck release [2]. This indication for a wrong amount of lensing in the CMB power spectra is not confirmed by the lensing reconstruction data, i.e., the trispectrum analysis, and is very robust (see Ref. [41,44,45]). Future CMB data will help in understanding this parameter, as shown in Ref. [46], while, in Refs. [2,24], it has been shown that a possible explanation for the A_{lens} parameter is the degeneracy with the MG parameters. Another possibility is that A_{lens} takes into account unresolved systematics. Further possible theoretical explanations have been analyzed in Refs. [47–50]. Moreover, varying A_{lens} is considered in the literature a possible conservative way of using the Planck data marginalizing over the systematics in the data because an incorrect amount of lensing can bias some correlated parameters like massive neutrinos [22,41,44,45,51]. In addition, when A_{lens} is varying, it is possible to solve the tension between the constraints coming from the high and low multipoles of Planck [2,11,12].

A consequence of varying A_{lens} in our work is that Planck TTTEEE is now perfectly in agreement with KiDS or CFHTLenS, in both the scale cuts, as we can see in Figure 4 in the σ_8-Ω_m plane, or by looking at the S_8 constraints in Figure 2. Also in this case, the agreement improves in a significant way if we consider the conservative cuts for both the experiments, but, looking at the plots, is still within the 68% c.l. also with the original cut and when considering KiDS + BAO + JLA + R16.

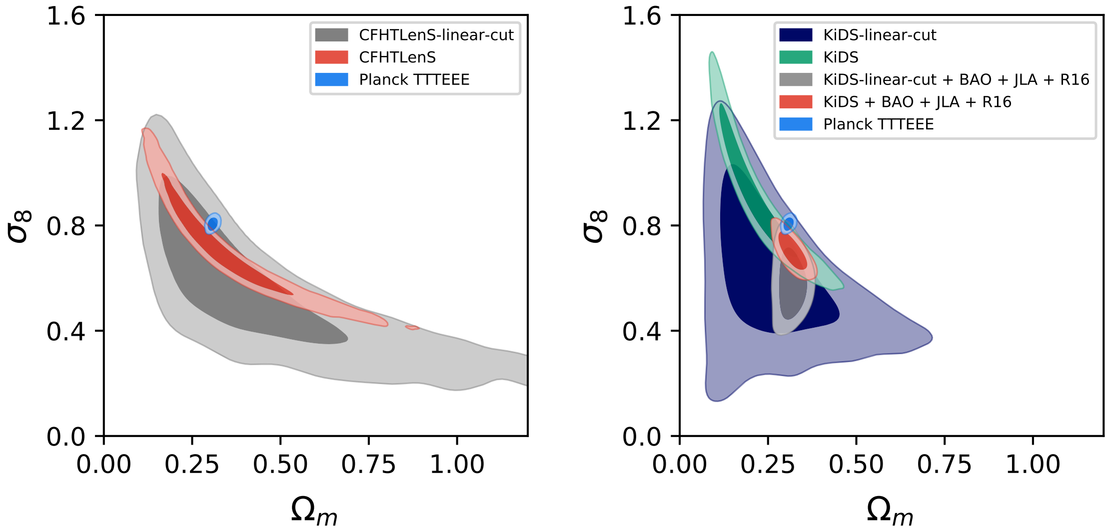

Figure 4. Constraints at 68% and 95% confidence levels on the σ_8 vs. Ω_m plane for several combination of datasets in the ΛCDM + A_{lens} model. In both of the plots, Planck shifts in agreement with the cosmic shear experiments within 2σ.

4. Conclusions

We have investigated the matter fluctuation amplitude (S_8) tension between the latest publicly available cosmic shear experiment (KiDS) likelihood and the latest publicly available CMB dataset in the standard cosmological model ΛCDM. We have also shown results using the most commonly used CFHTLenS dataset. We show results for both the original and the conservative (linear theory only) cut for both cosmic shear experiments. We find that there is a tension using original (nonlinear) scales for cosmic shear, but this disappears on using the conservative cut.

We considered extensions to ΛCDM to try to resolve the tension. We find that massive neutrinos do not relieve the tension because they change the σ_8 constraint in the right direction, simultaneously with the Ω_m value in the wrong one, as discussed in [41]. However, allowing a rescaling of the CMB lensing amplitude A_{lens} does resolve the tension. A_{lens} is a phenomenological parameter that is found to be more than 2σ higher than the expected value in the Planck 2015 data, suggesting an higher amount of lensing in the power spectra, not supported by the trispectrum analysis. We found that this incorrect amount of lensing can be responsible for the tension between the Planck and the cosmic shear data.

We already discuss the possibility of having systematics in Planck, which could be described by the A_{lens} parameter that we considered in this analysis. There are also known systematics in the weak lensing experiments we considered, which could change our conclusions. For example, see the long list in Ref. [52] for CFHTLenS, where however the authors show that the approximations used in the analysis have a negligible impact on the cosmological parameter constraints, or see the re-analysis of the KiDS data done by Ref. [28], which improves the agreement with Planck of half a sigma. We await with interest the new likelihoods from Planck 2018 and the Dark Energy Survey [6,7] to update our work.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

In this appendix, we show the constraints on cosmological parameters from the different analyses performed in this paper.

Table A1. 68% credible intervals for cosmological parameters for several data combination in the ΛCDM model.

Parameter	Planck TT	CFHTLenS-linear-cut	CFHTLenS	KiDS-linear-cut	KiDS	Planck TT + KiDS	Planck TT + KiDS-linear-cut
Ω_m	0.315 ± 0.013	0.35 ± 0.16	0.44 ± 0.33	0.222 ± 0.088	0.26 ± 0.12	0.2911 ± 0.0083	0.299 ± 0.010
σ_8	0.830 ± 0.015	0.72 ± 0.16	0.58 ± 0.21	0.92 ± 0.20	0.63 ± 0.21	0.8221 ± 0.0062	0.8279 ± 0.0072
S_8	0.849 ± 0.024	0.726 ± 0.027	0.61 ± 0.12	0.750 ± 0.040	0.55 ± 0.15	0.810 ± 0.017	0.827 ± 0.020
	Planck TTTEEE	**Planck TTTEEE + KiDS**	**Planck TTTEEE + KiDS-linear-cut**	**CFHTLenS + KiDS**	**CFHTLenS-linear-cut + KiDS-linear-cut**	**KiDS + BAO + JLA + R16**	**KiDS-linear-cut + BAO + JLA + R16**
Ω_m	0.3162 ± 0.0090	0.3006 ± 0.0065	0.3077 ± 0.0078	0.245 ± 0.085	0.28 ± 0.11	0.319 ± 0.027	0.316 ± 0.026
σ_8	0.831 ± 0.013	0.8282 ± 0.0048	0.8332 ± 0.0054	0.87 ± 0.16	0.73 ± 0.21	0.702 ± 0.048	0.581 ± 0.090
S_8	0.853 ± 0.018	0.829 ± 0.013	0.844 ± 0.016	0.754 ± 0.029	0.651 ± 0.095	0.721 ± 0.035	0.595 ± 0.094

Table A2. 68% credible intervals for cosmological parameters for several data combination in the ΛCDM + Σm_ν model.

Parameter	Planck TT	CFHTLenS	CFHTLenS-linear-cut	KiDS	KiDS-linear-cut	Planck TT + KiDS	Planck TT + KiDS-linear-cut
Ω_m	0.344 ± 0.041	0.41 ± 0.16	0.44 ± 0.55	0.27 ± 0.10	0.31 ± 0.15	0.306 ± 0.027	0.313 ± 0.027
σ_8	0.790 ± 0.051	0.64 ± 0.12	0.47 ± 0.17	0.81 ± 0.17	0.53 ± 0.19	0.799 ± 0.037	0.807 ± 0.037
S_8	0.841 ± 0.026	0.705 ± 0.026	0.56 ± 0.11	0.731 ± 0.039	0.51 ± 0.16	0.805 ± 0.018	0.822 ± 0.024
	Planck TTTEEE	**Planck TTTEEE + KiDS**	**Planck TTTEEE + KiDS-linear-cut**	**CFHTLenS-linear-cut + KiDS-linear-cut**	**KiDS + BAO + JLA + R16**	**KiDS-linear-cut + BAO + JLA + R16**	
Ω_m	0.329 ± 0.023	0.315 ± 0.024	0.318 ± 0.020	0.35 ± 0.15	0.325 ± 0.028	0.328 ± 0.026	
σ_8	0.811 ± 0.033	0.807 ± 0.036	0.817 ± 0.029	0.61 ± 0.17	0.693 ± 0.048	0.50 ± 0.11	
S_8	0.848 ± 0.020	0.824 ± 0.016	0.840 ± 0.017	0.611 ± 0.090	0.719 ± 0.035	0.52 ± 0.11	

Table A3. 68% credible intervals for cosmological parameters for several data combination in the ΛCDM + A_{lens} model.

Parameter	Planck TT	Planck TT + KiDS-linear-cut	Planck TTTEEE	Planck TTTEEE + KiDS	Planck TTTEEE + KiDS-linear-cut
Ω_m	0.295 ± 0.015	0.278 ± 0.012	0.329 ± 0.023	0.2919 ± 0.0074	0.2983 ± 0.0086
σ_8	0.802 ± 0.018	0.8138 ± 0.0094	0.806 ± 0.017	0.8224 ± 0.0056	0.8271 ± 0.0063
S_8	0.795 ± 0.032	0.783 ± 0.026	0.817 ± 0.024	0.811 ± 0.015	0.825 ± 0.018

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