Closing up the cluster tension?

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ABSTRACT

The excellent measurements of the cosmic microwave background (CMB) fluctuations by \textit{Planck} allow us to tightly constrain the amplitude of matter fluctuations at redshift $z \sim 1100$ in the $\Lambda$-cold dark matter (LCDM) model. This amplitude can be extrapolated to the present epoch, yielding constraints on the value of the $\sigma_8$ parameter. On the other hand, the abundance of Sunyaev-Zeldovich (SZ) clusters detected by \textit{Planck}, with masses inferred using a hydrostatic equilibrium assumption, leads to a significantly lower value of the same parameter. This discrepancy is often dubbed the $\sigma_8$ tension in the literature and is sometimes regarded as a possible sign of new physics. Here, we examine a direct determination of $\sigma_8$ at the present epoch in $\Lambda$CDM, and thereby the cluster mass calibrations using cosmological data at low redshift, namely the measurements of $f\sigma_8$ from the analysis of the completed Sloan Digital Sky Survey. We combined redshift-space distortion measurements with \textit{Planck} CMB constraints, X-ray, and SZ cluster counts within the LCDM framework, but leaving the present-day amplitude of matter fluctuations as an independent parameter (i.e. no extrapolation is made from high-redshift CMB constraints). The calibration of X-ray and SZ masses are left as free parameters throughout the whole analysis. Our study yields tight constraints on the aforementioned calibrations, with values entirely consistent with results obtained from the full combination of CMB and cluster data only. Such an agreement suggests an absence of tension in the LCDM model between CMB-based estimates of $\sigma_8$ and constraints from low-redshift on $f\sigma_8$; however, it also indicates tension with the standard calibration of clusters masses.

Key words. cosmological parameters – galaxies: clusters: general

1. Introduction

The measurements of the fluctuations of the cosmic microwave background (CMB) by \textit{Planck} has provided a remarkable test of the $\Lambda$-cold dark matter (LCDM) picture. Nearly forty years after its foundation (Peebles 1982, 1984), the model is in tight agreement with CMB data, allowing us to estimate its main parameters to percent-level accuracy (\textit{Planck Collaboration VI} 2020). Data from the Wilkinson Microwave Anisotropy Probe combined with measurements from the Atacama Cosmology Telescope on small scales lead to essentially identical values with similar uncertainties (\textit{Aiola et al.} 2020), leaving little room for remaining systematics. However, estimates of several parameters obtained from low-redshift probes are strikingly different from \textit{Planck} best-fit values, with relatively high significance. The disagreement on the value of the local Hubble constant has attracted a lot of attention (\textit{Riess et al.} 2021) and is currently considered as a possible indication of tension between late and early Universe physics (\textit{Verde et al.} 2019).

Similarly, measurements of the amplitude of matter fluctuations at low redshift from lensing surveys yield values lower than those inferred from the CMB (\textit{Heymans et al.} 2021), although the issue remains a matter of debate. From the first year of the Dark Energy Survey (DES Y1), the $3 \times 2pt$ analysis (\textit{Abbott et al.} 2018) leads to a lower amplitude, although the collaboration concludes that the two data sets are consistent, while \textit{Lemos et al.} (2021) derived a $2.3\sigma$ tension. However, the recent DES Y3 analysis from the $3 \times 2pt$ data (\textit{DES Collaboration} 2021) concludes that their data are consistent with the predictions of the model favoured by the \textit{Planck} 2018 data.

The abundance of galaxy clusters and its evolution with redshift are known to provide interesting cosmological constraints widely discussed in the literature (\textit{Oukbir & Blanchard} 1992; \textit{White et al.} 1993; \textit{Bahcall & Cen} 1993; \textit{Bartlett & Silk} 1993; \textit{Hattori & Matsuzawa} 1995; \textit{Henry} 1997), with a strong sensitivity to the growth rate of cosmic structures (\textit{Blanchard & Bartlett} 1998). Recent analyses of those abundances provide an additional source of tension on the amplitude of matter fluctuations. Indeed, Sunyaev-Zeldovich (SZ) clusters number counts as measured by \textit{Planck} have been found to be much lower than expected from the CMB-only best-fit LCDM model when using a fiducial mass-SZ signal calibration, derived from X-ray observations coupled to hydrostatic mass estimations (\textit{Planck Collaboration XX} 2014; \textit{Planck Collaboration XXIV} 2016). Those results indicate a value of the amplitude of matter fluctuations more in line with the weak lensing results previously mentioned.

The aforementioned discrepancies, which arise when comparing results from low-redshift probes and CMB data, have opened the door to new physics, although no simple solution to these tensions has emerged yet (\textit{Jedamzik et al.} 2021). Cluster data from DES Y1 yielded a surprisingly low amplitude for matter fluctuations and the density parameter $\Omega_m$ (\textit{Abbott et al.} 2020) and is regarded as a clear sign of the presence of systematics. It is therefore of high interest to find probes of the amplitude of matter fluctuations that are independent of lensing data. The purpose of the present work is to examine the amplitude of matter fluctuations from the eBOSS redshift-space distortion (RSD) measurements in the LCDM model and its implications for cluster mass calibration.
In Sect. 2, we summarise the calibration-related issues that appear when using cluster samples as cosmological probes. We recall the tension between the amplitude of the calibration required to fit the Planck SZ cluster counts compared to the fiducial calibration adopted in the Planck analysis of the same sample (Planck Collaboration XX 2014). This tension between cluster counts and CMB observations is a long-standing problem (Blanchard & Douspis 2005), the significance of which was raised above 4σ by the Planck results. In Sect. 3, we present the self-calibration approach we followed in order to derive constraints on 

\[ \Omega_m \Delta(z) \] 



\[ \frac{1}{1+z}, \]

\[ T = A_{TM}(h M_\odot)^{2/3} \left( \frac{\Omega_m \Delta(z)}{178} \right)^{1/3} \]



\[ \Delta(z) \] 



\[ \left( 1 + b \right) \]

\[ M_{500} \]

\[ \frac{1}{178} \]

\[ A_{TM} \]

\[ h M_\odot \]

\[ \left( 1 + b \right) M_{500} \]

\[ 0.7 \]

\[ 2 \]

\[ 10^{-4} \text{Mpc}^2 \]

\[ \left( 6 \times 10^{14} M_\odot \right)^{2/3} \]

\[ \frac{Y_s}{\left( 6 \times 10^{14} M_\odot \right)^{1/2}} \]

\[ Y_s \]

\[ 0.19 \]

\[ 0.66 \]

\[ 0.127 \pm 0.023 \]

\[ \sigma_{TM} \]

\[ \left( 0.6 \times 10^{14} M_\odot \right)^{2/3} \]

\[ \left( 0.6 \times 10^{14} M_\odot \right)^{1/2} \]

\[ 1 \]

\[ 0.8 \]

\[ 0.6 \pm 0.28 \]

\[ 0.6 \]

\[ 0.6 \pm 0.28 \]

\[ 0.6 \pm 0.6 \]

\[ (1+b) \]

\[ 0.8 \]

\[ 0.6 \pm 0.28 \]

\[ 0.6 \pm 0.6 \]

\[ 0.127 \pm 0.023 \]

\[ \Omega \]

\[ 0.02 \]

\[ 0.1 \]

\[ 0.1 \]

\[ 0.02 \]

\[ 0.1 \]

\[ 0.02 \]
4. Results: Matter fluctuation amplitude and clusters calibration

The above self-calibration approach amounts to inferring the late $\sigma_8$ from the eBOSS data using priors from Planck on all other cosmological parameters (and thus only on the shape of the power spectrum of matter fluctuations but not its amplitude). Our final constraints on $\sigma_8$ therefore essentially results from the local RSD measurements with priors on other cosmological parameters obtained from Planck. This allows us to obtain joint constraints on the late amplitude of matter fluctuations and the calibration of cluster scaling relations. Our final constraints are fully summarised in Fig. 1, where confidence (68% and 95%) contours and 1D marginalised posteriors are shown for our parameters of interest, namely the cluster calibration parameters, as well as the standard $S_8$ parameter:

$$S_8 \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5},$$  

(4)

To quantify the amplitude of matter fluctuations, To obtain those constraints, we performed a Markov chain Monte Carlo analysis using the ECLAIR (Ilč et al. 2021) and CosmoMC (Lewis & Bridle 2002; Lewis 2013) suites of codes, varying the full range of standard cosmological and nuisance parameters associated with the data sets used.

To practically implement the approach explained earlier, we considered a ΛCDM model where the overall amplitude of matter fluctuations $\sigma_8$ is freed in the range of late-redshifts ($z \sim [0, 1]$). This approach was previously adopted by the Planck CMB data via the self-calibration approach. A direct combination of the two (with cluster samples) leads to tight constraints on the calibration due to the stringency of Planck data. The effect of adding eBOSS RSD data leads to constraints that are indistinguishable from Planck-only ones, as illustrated by the dashed lines and contours in Fig. 1. Those results are therefore essentially identical to the Planck-only ΛCDM results of Ilč et al. (2019) mentioned in Sect. 2 (apart from the update to 2018 data). However, we remind the reader that the tightness of those CMB-based constraints on the cluster calibration may be misleading. It is only through the extrapolation of the tight early-Universe constraints on matter fluctuations that the CMB is able to break the known degeneracy between the $\Lambda$ and (an extrapolated) $\sigma_8$.

In order to obtain constraints on the current value of $\sigma_8$ – and thus on the cluster calibration – that stem primarily from the eBOSS data, we slightly tweaked the ΛCDM model by introducing an additional degree of freedom. More specifically, the growth factor of structures is multiplied by a constant – left as a free parameter – over the redshift range corresponding to our cluster samples (roughly $z \sim [0, 1]$). In practice, this allows us to decouple from early times and directly control the present value of $\sigma_8$ in the model. Once we introduce data, the behaviour of the background (at all times) and the perturbation sector (up to $z \sim 1$) remain similarly constrained by the CMB. Meanwhile, $\sigma_8$ is almost entirely constrained by low-redshift probes since the CMB is mostly insensitive to late-Universe physics.

Such a method of rescaling matter fluctuations is acceptable since in ΛCDM models (and other minimally coupled dark energy models) the late-time growth is scale independent. This property was used, for instance, in Euclid Collaboration (2020) (when exploring a simple modification of gravity) or for the DES Y1 analysis presented in Muir et al. (2021).

As stated earlier, our objective is to infer the galaxy cluster mass calibration with the addition of eBOSS RSD data to

on the growth of structures. More specifically, RSD provides a way of measuring $f(z)\sigma_8(z)$, where $f(z)$ is the so-called growth rate of matter:

$$f(z) \equiv \frac{\text{d} \ln \sigma_8}{\text{d} \ln a},$$  

(3)

while $\sigma_8(z)$ is a measure of the amplitude of matter fluctuations at redshift $z$. These measurements rely only on data from the clustering of galaxies in redshift space. Inferring the amplitude of $\sigma_8$ from the eBOSS RSD data alone does not lead to stringent limits (see Fig. 9 in Alam et al. 2021). Priors on cosmological parameters help to reduce these uncertainties (see Fig. 11 in the same reference). Here, we want to use the eBOSS RSD data in combination with Planck CMB data in order to provide a self-calibration for clusters within the ΛCDM model, without the addition of any external prior on the mass calibration. We note that RSD and CMB data are essentially independent and can be combined easily without accounting for their covariance. In the following, we use as data sets: (i) the aforementioned RSD measurements from eBOSS, specifically the RSD-only line in Table 3 of Alam et al. (2021); (ii) the latest CMB data from Planck, including the full fiducial likelihoods for the low- and high-multipole temperature and E-mode polarisation, released in 2018; (iii) the local sample of X-ray clusters from Ilč et al. (2015); (iv) the sample of SZ clusters from Planck Collaboration XXIV (2016).

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As anticipated, it does not lead to stringent constraints on cluster calibrations when combined only with CMB data (cf. blue solid lines and filled contours in Fig. 1). The SZ cluster sample is indeed too small to allow a stringent self-calibration, even if the background parameters are restricted by the Planck 2018 CMB constraints. We therefore repeated the same self-calibration approach, but added the eBOSS RSD data to the CMB and cluster counts. This new approach allows a combination of local cosmological data with Planck CMB constraints on cosmological parameters but without adding any prior on the amplitude of fluctuations, and thereby not on the calibration either, which can be now estimated from the combined set of data. We obtained tight constraints (68% confidence limits thereafter, unless stated otherwise) on the corresponding parameters:

\[(1 - b) = 0.608^{+0.063}_{-0.068} \text{ and } A_{\text{TM}} = 7.48^{+0.55}_{-0.68}.\] (5)

as illustrated by the solid red lines and filled contours in Fig. 1. These low-redshift-based constraints on the calibration constitute the main conclusion of our analysis: in the context of the ΛCDM model, our calibration derived from the low-redshift eBOSS data is 3σ away from its (1 – b) ~ 0.8 value. We also produced tight constraints on the $S_8$ parameter:

\[S_8 \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5} = 0.841 \pm 0.038.\] (6)

These values are entirely consistent with those obtained in the standard analysis of the ΛCDM model (i.e. where $\sigma_8$ is a derived parameter), for which (1 – b) = 0.620 ± 0.029 and $S_8$ = 0.834 ± 0.016 when using the combination of clusters and the full Planck CMB data (dashed blue). The addition of RSD data from eBOSS does not lead to any appreciable improvement (dashed red). This calibration is also consistent with weak lensing mass estimates from von der Linden et al. (2014), but lies at the extremes of various observational direct determinations. Some statistical analyses based on clusters also lead to results consistent with our conclusions (Zu et al. 2014). Finally, similarly to Ilić et al. (2019), we examined the constraints obtained when extending the ΛCDM with a modification of gravity via the y parametrisation. The use of the Planck 2018 CMB data leads to

\[(1 - b) = 0.652^{+0.054}_{-0.062}.\] (7)

This value is 1σ higher than when Planck 2015 is used (Ilić et al. 2019) and is not significantly improved by the addition of the eBOSS RSD data.

The SZ signal from clusters also contributes to the average fluctuations in the CMB (Cole & Kaiser 1988) and also induces a global y Compton distortion (Barbosa et al. 1996). Planck mapped the tSZ component over the sky accurately, and the power spectrum of this component can be used as a useful source of constraints on cosmological parameters (Komatsu & Seljak 2002; Salvatì et al. 2018). Several recent works have applied this approach in combination with weak lensing surveys or galaxy surveys to obtain constraints on the calibration (Koukoufilippas et al. 2020; Chiang et al. 2020). A direct comparison with our approach is, however, difficult as the ingredients are different. Our analysis for ΛCDM models, which leads to a calibration tightly constrained resulting from the addition of the eBOSS low-redshift data, sheds new light on the calibration issue.

5. Conclusion

In the present work, we addressed the issue of the calibration used in cluster mass–observable relations in a self-consistent way in the context of the ΛCDM model. For this purpose, we derived posterior distributions on calibration parameters, using the latest Planck CMB data, SZ, and X-ray clusters counts, as well as SDSS RSD data. We left the amplitude of matter fluctuations at late times as a free parameter; that is, independent of the early-Universe constraints of CMB data.

As such, we obtained calibrations relying essentially on the low-redshift data from eBOSS to constrain the late amplitude of matter fluctuations, with priors on other cosmological parameters obtained from Planck. This provides the first stringent constraints from the self-calibration approach obtained via low-redshift data. The resulting constraints on the calibrations $(1 - b)$ and $A_{\text{TM}}$ for ΛCDM are entirely consistent with the values obtained in the standard analysis in which the amplitude is derived directly from the Planck CMB data. The preferred value of the SZ mass calibration parameter, $(1 - b)$ remains on the order of 0.6 and 3σ away from the fiducial value adopted in Planck Collaboration XX (2014). These calibrations stem from the amplitude of matter fluctuations $\sigma_8$ or equivalently the $S_8$ parameter – entirely consistent with those derived in the standard analysis of the ΛCDM case from the full Planck data. It is worth noting that the recent DES Y3 results also report an amplitude $\sigma_8$ for ΛCDM models consistent with Planck 2018, while their cosmic-shear-only analysis may suffer from theoretical uncertainties in their modelling (Amon et al. 2021). After the first version of this paper was submitted, the DES Collaboration presented their analysis of the cross-correlation signal between their lensing map and the thermal SZ effect from Planck and ACT, allowing a determination of the calibration $(1 - b) = 0.56 \pm 0.02$ (Pandey et al. 2021). Those results seem to lean towards conclusions similar to ours.

Fixing the cluster mass calibrations is a critical ingredient for cluster cosmology and for the understanding of gas physics in clusters: the role of non-gravitational heating processes is known to be decisive in determining their final observational properties. Clearly, if a value of the $(1 - b)$ calibration close to 0.6 can be consolidated, it would point towards consistency between the present day amplitude of matter fluctuations as measured by late-Universe probes and the one inferred from CMB data in the ΛCDM model. This would consequently call for a revision of the current models of non-gravitational physics in clusters shaping their baryonic component. Additionally, we expect a significant improvement of the determination of clusters masses in the coming decade, thanks to the advent of the next generation of large-scale surveys such as Euclid\(^1\), the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST)\(^2\), or the Nancy Grace Roman Space Telescope\(^3\). Not only will such surveys greatly increase the overall statistics of detected clusters, but unprecedented weak lensing measurements should shed additional light on those objects and provide robust and independent estimates of cluster masses.

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