Robust weak-lensing mass calibration of Planck galaxy clusters

Anja von der Linden\textsuperscript{1,2,3} *, Adam Mantz\textsuperscript{4,5}, Steven W. Allen\textsuperscript{2,3,6}, Douglas E. Applegate\textsuperscript{7}, Patrick L. Kelly\textsuperscript{8}, R. Glenn Morris\textsuperscript{2,6}, Adam Wright\textsuperscript{2,3,6}, Mark T. Allen\textsuperscript{2,3}, Patricia R. Burchat\textsuperscript{2,3}, David L. Burke\textsuperscript{2,6}, David Donovan\textsuperscript{9}, Harald Ebeling\textsuperscript{9}

\textsuperscript{1}Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen Juliane Maries Vej 30, 2100 Copenhagen \textoplus, Denmark
\textsuperscript{2}Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, 452 Lomita Mall, Stanford, CA 94305-4085, USA
\textsuperscript{3}Department of Physics, Stanford University, 382 Via Pueblo Mall, Stanford, CA 94305-4060, USA
\textsuperscript{4}Kavli Institute for Cosmological Physics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637-1433, USA
\textsuperscript{5}Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637-1433, USA
\textsuperscript{6}SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA
\textsuperscript{7}Argelander-Institut für Astronomie, Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany
\textsuperscript{8}Department of Astronomy, University of California, B-20 Hearst Field Annex # 3411, Berkeley, CA 94720-3411, USA
\textsuperscript{9}Institute for Astronomy, 2680 Woodlawn Drive, Honolulu, HI 96822, USA

ABSTRACT

In light of the tension in cosmological constraints reported by the \textit{Planck} team between their SZ-selected cluster counts and Cosmic Microwave Background (CMB) temperature anisotropies, we compare the \textit{Planck} cluster mass estimates with robust, weak-lensing mass measurements from the \textit{Weighing the Giants} (WtG) project. For the 22 clusters in common between the \textit{Planck} cosmology sample and WtG, we find an overall mass ratio of $\langle M_{\text{Planck}}/M_{\text{WtG}} \rangle = 0.688 \pm 0.072$. Extending the sample to clusters not used in the \textit{Planck} cosmology analysis yields a consistent value of $\langle M_{\text{Planck}}/M_{\text{WtG}} \rangle = 0.698 \pm 0.062$ from 38 clusters in common. Identifying the weak-lensing masses as proxies for the true cluster mass (on average), these ratios are $\sim 1.6\sigma$ lower than the default mass bias of 0.8 assumed in the \textit{Planck} cluster analysis. Adopting the WtG weak-lensing-based mass calibration would substantially reduce the tension found between the \textit{Planck} cluster count cosmology results and those from CMB temperature anisotropies. We also find modest evidence (at $95\%$ confidence) for a mass dependence of the calibration ratio and discuss its potential origin in light of systematic uncertainties in the temperature calibration of the X-ray measurements used to calibrate the \textit{Planck} cluster masses. Our results exemplify the critical role that robust absolute mass calibration plays in cluster cosmology, and the invaluable role of accurate weak-lensing mass measurements in this regard.

Key words: galaxies: clusters: general; gravitational lensing: weak; cosmology: observations

1 INTRODUCTION

The \textit{Planck} satellite has recently provided new, precise cosmological constraints based on measurements of Cosmic Microwave Background (CMB) temperature anisotropies [\textit{Planck Collaboration} 2013a, hereafter P16], confirming that a spatially flat $\Lambda$CDM model provides an excellent description of the observable Universe. However, an uncomfortable result of the \textit{Planck} team’s analysis is that their cosmological constraints derived from the number density of galaxy clusters detected with \textit{Planck} through the Sunyaev-Zel’dovich (SZ) effect are in tension with the constraints from the CMB temperature power spectrum. This tension is particularly evident in the $\sigma_8-\Omega_m$ plane, where the $2\sigma$ confidence contours from \textit{Planck} cluster counts and the \textit{Planck} temperature fluctuations do not overlap [\textit{Planck Collaboration} 2013b, hereafter P20], with the cluster analysis preferring a lower value for the amplitude of matter fluctuations.

The \textit{Planck} team suggest two possible explanations for this tension. One is that the calibration of their cluster mass estimates, which are based on hydrostatic mass measurements derived from \textit{XMM-Newton} X-ray observations, is biased low. Expecting some level of non-thermal pressure support to be present in even relatively relaxed clusters, their default cluster-cosmology analysis
assumes \( (M_{\text{Planck}}/M_{\text{ Wig}}) = (1 - b) \equiv 0.8 \)\(^1\). Reconciling the observed tension between Planck SZ cluster counts and the CMB power spectrum would, however, require a lower ratio. Alternatively, keeping the Planck mass calibration fixed at \( (1 - b) = 0.8 \), the Planck team argue that their CMB and SZ-cluster data could be explained by a species-summed neutrino mass of \( \Sigma m = (0.58 \pm 0.20) \) eV, a result that is in tension with the 95 per cent confidence upper limit of 0.23 eV derived from the Planck CMB analysis with additional datasets (P16), and earlier studies using WMAP CMB data plus independent X-ray and optical cluster measurements (Mantz et al. 2010; Reid et al. 2010).

In this letter, we investigate the reliability of the Planck cluster mass measurements by comparing them with robust, independently derived weak-lensing mass measurements from the Weighing the Giants (WtG) project (von der Linden et al. 2014; Kelly et al. 2014; Applegate et al. 2014). As has been discussed in the literature, systematic uncertainty in the absolute calibration of cluster masses is currently the most significant challenge facing cluster cosmology (WIG; see also Vikhlinin et al. 2009; Mantz et al. 2010\(^a\); Rozo et al. 2010; Sehgal et al. 2011; Benson et al. 2013; Allen et al. 2011; LSST Dark Energy Science Collaboration 2012). Weak lensing provides our most promising method to calibrate the absolute masses of clusters since it measures the total mass directly, without relying on baryonic tracers, and is expected, from simulations, to be accurate (i.e. exhibit minimal bias in the mean). However, since the masses recovered by weak-lensing measurements are inherently noisy (the scatter in mass from typical ground-based studies is estimated to be \( \sim 30 \) per cent; Becker & Kravtsov 2011), relatively large samples of clusters are required to determine the mass calibration to high precision. With current samples of 30–50 clusters (Okabe et al. 2010; Hoekstra et al. 2012; WIG), the statistical precision achievable is already, in principle, better than 10 per cent, requiring a detailed understanding of the systematic uncertainties involved.

The WIG project targeted a subset of clusters in catalogs based on the ROSAT All-Sky Survey (RASS; Truemper 1993). The overlap between those X-ray detected clusters and the Planck cluster catalog is substantial (see Planck Collaboration 2013c, hereafter P29). For the WIG project, we acquired high-quality, multi-color optical imaging for 51 clusters at \( 0.15 < z < 0.7 \) (von der Linden et al. 2014). In Applegate et al. (2014), we examined the sources of systematic uncertainty involved in estimating weak-lensing masses from the WIG data, and provided methods to quantify and mitigate them. We showed that, with measurements for 51 clusters, the overall cluster mass calibration can be determined to an accuracy of 8 per cent, roughly a factor of two improvement on previous work. An important additional aspect was that the development of weak-lensing masses provides an excellent external, independent dataset to assess the calibration of the Planck cluster masses.

The masses and mass ratios quoted in this paper assume a flat ΛCDM cosmological model with \( \Omega_m = 0.3 \) and \( H_0 = 100 h \text{km/s/Mpc} \), where \( h = 0.7 \).

\( \beta_{\text{low}} = \left( \frac{M_{\text{Planck}}}{M_{\text{WIG}}} \right) = 0.68_{-0.050}^{+0.056} \) (stat) \( \pm 0.049 \) (syst) \().

\( \beta_{\text{low}} \) was verified that this procedure returns unbiased estimators of the mean and standard deviation of a log-normal distribution, even in the presence of intrinsic scatter and if the measurement uncertainties correlate with the measured values (as can be seen in Fig. 1) less massive clusters have larger error bars and higher \( M_{\text{Planck}}/M_{\text{WIG}} \).

\( 1 \) The Planck team also present cosmology results obtained by marginalizing over the range \( 0.7 < (1 - b) < 1.0 \).
The systematic uncertainty quoted here expresses the systematic uncertainty on the weak-lensing masses, i.e. it includes all entries in Table 4 of [Applegate et al. 2014] with the exception of the scatter due to triaxiality, which is accounted for here in the statistical uncertainty. Extending the sample to all 38 clusters yields a consistent result:

\[ \beta_{\text{all}} = 0.698^{+0.039}_{-0.037} \text{ (stat)} \pm 0.049 \text{ (syst)} \]

The weak-lensing masses are expected to yield the true cluster mass on average, and thereby enable a robust calibration of other mass proxies (see discussion in von der Linden et al. 2014, Applegate et al. 2014). Therefore, by identifying \( \beta = (1 - b) \), these results suggest that the mass calibration adopted by the Planck team, \((1 - b) = 0.8\), underestimates the true cluster masses by between 5 and 25 per cent on average.

### 3.2 Evidence for a mass-dependent calibration problem

By eye, Fig. 1 suggests that the ratio between the WtG weak-lensing and Planck mass estimates depends on the cluster mass: at masses \( \lesssim 6 \times 10^{14} M_\odot \), the mass estimates roughly agree, whereas the discrepancy appears significant for more massive clusters. To quantify the evidence for such a mass-dependent bias, we use the Bayesian linear regression method developed by Kelly (2007) to fit \( \log(M_{\text{WtG}}) \) as function of \( \log(M_{\text{Planck}}) \) (fitting the masses directly avoids the correlated errors in the mass ratios one would have to account for if fitting the data as shown in Fig. 1). While we show \( \log M_{\text{Planck}} \) as function of \( M_{\text{WtG}} \) in Fig. 2 to reflect that the weak-lensing masses are our proxy for true cluster masses, we assign the Planck mass estimates to be the independent variable to reduce the effects of Malmquist bias: \( M_{\text{Planck}} \) scales with the survey observable, and by choosing it as the independent variable, we provide a mass estimate for each data point which is to first order independent of other selection effects (as X-ray selection to first order does not correlate with SZ selection biases, and the lensing data are a subsample of an X-ray selected catalog). The Kelly (2007) method accounts for measurement errors in both variables, as well as for intrinsic scatter in the dependent variable. Rephrasing the results as a power-law, the best-fit relation for the 22 clusters in the cosmology sample is:

\[
\left( \frac{M_{\text{Planck}}}{10^{15} M_\odot} \right) = \left( \frac{M_{\text{WtG}}}{10^{15} M_\odot} \right)^{0.68 \pm 0.11},
\]

where the systematic uncertainty on the weak-lensing mass calibration is accounted for in the uncertainty on the coefficient. In 24 per cent of the Monte Carlo samples, the slope (of \( \log(M_{\text{Planck}}) \) vs. \( \log(M_{\text{WtG}}) \)) is unity or larger; i.e. the evidence for a mass-dependent bias is at the \( \sim 1 \sigma \) level for these 22 clusters.

To further test for a mass-dependent bias, it is instructive to include the additional 16 clusters in common between Planck and WtG that are not used in the Planck cluster cosmology analysis, as these slightly extend the mass range probed. For all 38 clusters, we find a consistent and more precise result:

\[
\left( \frac{M_{\text{Planck}}}{10^{15} M_\odot} \right) = \left( \frac{M_{\text{WtG}}}{10^{15} M_\odot} \right)^{0.68 \pm 0.11},
\]

In 4.9 per cent of the Monte Carlo samples, the slope is unity or larger; i.e. the confidence level for a slope less than unity is 95 per cent.

5 We note that when using bootstrap realizations of an unweighted simple linear regression as a more agnostic fit statistic, we recover the same slope,
4 DISCUSSION

4.1 Implications for cosmological constraints

Comparing Planck cluster mass estimates (calibrated with hydrostatic mass estimates from XMM-Newton data) with weak-lensing-based mass measurements from the Weighing the Giants project, we have measured the bias of the Planck masses to be \( \beta_{\text{bias}} = (M_{\text{Planck}}/M_{\text{weak}}) = (1 - b) = 0.688 \pm 0.072 \) for 22 clusters in the Planck cosmology sample \( \beta_{\text{bias}} = 0.698 \pm 0.062 \) for all 38 clusters in common between the two studies. This result assumes that the WtG mass measurements are unbiased to the level of accuracy discussed in Applegate et al. [2014]. Our result suggests that the default mass calibration adopted by the Planck team, \( (1 - b) = 0.8 \), underestimates the true masses of Planck clusters by 5–25 per cent on average. More than half of the probability distribution we find for \( b = (1 - b) \) is outside of the range of 0.7–1.0 that the Planck team marginalize over in their most conservative analysis.

A significantly lower value for the mass bias would reduce the tension between their SZ cluster count and CMB analyses (P20, also see [Rozo et al. 2014]). Adopting the WtG mass calibration, which includes a sizable range of lower values for the mass bias would therefore reduce the tension and bring the constraints into significantly better agreement.

4.2 On the origin of the mass bias

The mass estimates used by the Planck team are based on hydrostatic modeling of XMM-Newton X-ray data for 20 relatively relaxed clusters (Arnaud et al. [2010]). The mass bias term, \( 1 - b \), is primarily intended to account for departures from hydrostatic equilibrium (the ‘hydrostatic bias’). In practice, the bias term must account for any systematic offset between mass estimates and true masses. These include not just the hydrostatic bias, but also the effects of, e.g., instrument calibration, substructure and non-thermal pressure.

Hydrostatic biases at the 10–20 per cent level at \( r_{500} \) (in the sense that X-ray measurements underestimate the true mass) are expected to exist even in relatively relaxed, massive clusters (e.g. Nagai et al. [2007]). This expectation is reflected in the choice of \( (1 - b) = 0.8 \) by the Planck team. On the calibration side, cluster temperature (and therefore mass, \( M \propto T^{1/2} \)) estimates from XMM-Newton are typically lower than Chandra-based values for massive clusters: whereas XMM-Newton and Chandra cluster temperature measurements agree well for relatively low-mass systems (with temperatures \( kT < 2 \text{ keV} \)), for massive clusters \( (kT \gtrsim 5 \text{ keV}) \) typical of systems found in the Planck SZ survey, XMM-based temperature estimates tend to be about 20 per cent lower than Chandra values (Schellenberger et al. [2012], Grant et al. [2013], Mahdavi et al. [2013]). This implies that an XMM-based \( M_{500} \) mass estimate for a \( \gtrsim 6 \text{ keV} \) cluster will be \( \sim 30 \) per cent lower than the corresponding Chandra value. The temperature-dependent discrepancy between the two cautions that mass proxies which incorporate X-ray temperature measurements require careful mass-temperature-dependent calibration efforts. In this context, the trend in the ratio of Planck and WtG masses, implying larger bias at higher masses, is interesting. In combination, the effects of hydrostatic masses biases and temperature-dependent systematic offsets can easily reach 30 per cent, and provide a natural explanation for both the value of \( \beta = (1 - b) = M_{\text{Planck}}/M_{\text{weak}} \) we observe, and the mass-dependent slope in the logarithmic ratio.

We deem it unlikely that the WtG weak-lensing measurements have a significant mass-dependent bias. Simulations indicate that weak-lensing mass estimates derived by fitting an NFW profile over the radial range used in the WtG study (which does not exceed the cluster virial radii nor extend too close to the cluster centers) should be nearly unbiased for systems in the mass range probed here (Oguri & Hamana [2011], Becker & Kravtsov [2011], Babé et al. [2012]). Any remaining biases affecting the WtG masses should be at most of the order of a few per cent. We note also that by comparing Planck \( M_{500} \) estimates with their own weak-lensing mass estimates for five clusters, Gruen et al. [2013] report a mass dependence of the mass ratio in the same sense as we find.

Our results highlight the need for robust weak-lensing measurements to complement X-ray and SZ data in determining mass estimates for galaxy clusters. Whereas X-ray measurements can provide precise, low-scatter mass proxies for clusters, exhibiting minimal (\(<10–15\text{ per cent}) intrinsic scatter with respect to true mass (e.g. Allen et al. [2004, 2008], Kravtsov et al. [2006]), weak-lensing data can provide an accurate absolute mass calibration of these proxies. In this way, through the combination of multi-wavelength data, the dominant systematic uncertainty currently affecting cluster cosmology can be largely circumvented.

5 SUMMARY AND CONCLUSION

In light of the reported tension between the cosmological constraints inferred from Planck SZ cluster counts and Planck CMB temperature anisotropies, we have compared the Planck team’s cluster mass estimates with weak-lensing-based mass measurements determined by the Weighing the Giants project. For the 22 clusters in common between the Planck cluster sample and WtG that are used in the Planck cluster cosmology analysis, we find the average mass ratio to be \( M_{\text{Planck}}/M_{\text{weak}} = (1 - b) = 0.688 \pm 0.072 \) for all 38 clusters in common between the two studies, we find \( M_{\text{Planck}}/M_{\text{weak}} = 0.698 \pm 0.062 \). These values are \( \sim 1.6\sigma \) below the default bias adopted by P20, \( (1 - b) = 0.8 \). Half of the likelihood we determine is not included in the range over which the Planck study marginalizes (0.7–1.0) for part of their analysis. Adopting the WtG mass calibration would raise the value of \( \sigma_{\text{b}} \) inferred from the Planck SZ cluster counts and alleviate the tension with the Planck CMB results.

We find modest (95 per cent) evidence for a mass-dependence of the mass calibration, with a best-fit power-law of \( M_{\text{Planck}} \propto M_{\text{weak}}^{-0.68^{+0.15}_{-0.11}} \). As a possible origin for such a mass dependence we identify the temperature-dependent calibration uncertainty of the X-ray hydrostatic measurements used to calibrate the Planck cluster mass estimates.

Weak-lensing measurements provide an excellent complement to X-ray and SZ data in enabling the robust calibration of cluster masses. In forthcoming work (Mantz et al., in prep.), we will present cosmological constraints utilizing the full WtG sample in conjunction with X-ray selected cluster catalogs and extensive Chandra follow-up data.
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