Mon. Not. R. Astron. Soc. **000**, 1–6 (2015) Printed 9 November 2015 (MN LaTeX style file v2.2)

LoCuSS: Testing hydrostatic equilibrium in galaxy clusters

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9 November 2015

ABSTRACT

We test the assumption of hydrostatic equilibrium in an X-ray luminosity selected sample of 50 galaxy clusters at $0.15 < z < 0.3$ from the Local Cluster Substructure Survey (LoCuSS). Our weak-lensing measurements of M_{500} control systematic biases to sub-4 per cent, and our hydrostatic measurements of the same achieve excellent agreement between *XMM-Newton* and *Chandra*. The mean ratio of X-ray to lensing mass for these 50 clusters is $\beta_{\rm X}= 0.95 \pm 0.05$, and for the 44 clusters also detected by *Planck*, the mean ratio of *Planck* mass estimate to LoCuSS lensing mass is $\beta_{\rm P}= 0.95 \pm 0.04$. Based on a careful like-for-like analysis, we find that LoCuSS, the Canadian Cluster Comparison Project (CCCP), and Weighing the Giants (WtG) agree on $\beta_{\rm P} \simeq 0.9-0.95$ at $0.15 < z < 0.3$. This small level of hydrostatic bias disagrees at $\sim 5\sigma$ with the level required to reconcile *Planck* cosmology results from the cosmic microwave background and galaxy cluster counts.

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

1 INTRODUCTION

Accurate measurement of systematic biases in galaxy cluster masses is fundamental to cosmological exploitation of galaxy clusters, as has been highlighted recently by Planck Collaboration et al. (2015b). Much attention has focused on the systematic biases in the respective mass measurement techniques, principally via weak-lensing (e.g. Okabe et al. 2013; Applegate et al. 2014; Hoekstra et al. 2015; Okabe & Smith 2015) and X-ray (e.g. Rasia et al. 2006; Nagai, Vikhlinin & Kravtsov 2007; Meneghetti et al. 2010; Rasia et al. 2012; Martino et al. 2014) methods. Specifically, comparing lensing- and X-ray-based mass measurements tests the hydrostatic equilibrium assumption that underpins the X-ray-based mass measurements (e.g. Miralda-Escude & Babul 1995; Allen 1998;

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Smith et al. 2001, 2005; Mahdavi et al. 2008; Zhang et al. 2010; Richard et al. 2010; Mahdavi et al. 2013; Israel et al. 2014).

Our goal is to assess the implications of the new LoCuSS weak-lensing mass calibration (Okabe & Smith 2015; Ziparo et al. 2015) for hydrostatic bias and thus systematic uncertainties in cluster cosmology results. We combine Okabe & Smith's masses with hydrostatic masses from Martino et al. (2014). Both Okabe & Smith and Martino et al. control systematic biases in their respective mass measurements at sub-4 per cent. They are arguably the most accurate cluster mass measurements available to date. We also use mass estimates from Planck Collaboration et al. (2015a) that assume hydrostatic equilibrium, via an X-ray scaling relation and measurements of the integrated Compton Y parameter from *Planck* survey data. We describe our analysis and results in Section 2, discuss our results in Section 3, and conclude in Section 4. We assume $H_0 = 70\ \mathrm{km\,s^{-1}Mpc^{-1}}$, $\Omega_{\rm M}= 0.3$ and $\Omega_\Lambda= 0.7$ throughout.

2 ANALYSIS AND RESULTS

2.1 Sample and mass measurements

The sample comprises 50 clusters from the *ROSAT* All-sky Survey catalogues (Ebeling et al. 1998, 2000; Böhringer et al. 2004) that satisfy: $-25^\circ < \delta < +65^\circ$, $n_H \leqslant 7\times10^{20}\mathrm{cm}^2$, $0.15 \leqslant z \leqslant 0.3$, $L_X[0.1-2.4\,\mathrm{keV}]/E(z) \geqslant 4.1\times10^{44}\ \mathrm{erg\,s^{-1}}$, where $E(z) = \sqrt{\Omega_{\rm M}\ (1+z)^3 + \Omega_\Lambda}$. The clusters are therefore selected purely on L_X, ignoring other physical parameters. We focus on measurements of M_{500}, defined as the mass enclosed within r_{500}, i.e. the radius within which the mean density of the cluster is 500 times the critical density of the universe ($\rho_{\rm crit}$). M_{500} for a cluster at a redshift of z is therefore: $M_{500} = 500\rho_{\rm crit}(z)\,4\pi {r_{500}}^3/3$.

We use weak-lensing masses from (Okabe & Smith 2015, see also Ziparo et al. 2015). The two largest systematic biases in these weak-lensing masses are shear calibration (3 per cent) and contamination of background galaxy catalogues (1 per cent). The former calibration is derived from extensive image simulations, including shears up to $g \simeq 0.3$; the latter is based on selecting galaxies redder than the red sequence of cluster members using a radially-dependent colour-cut. Okabe & Smith also used full cosmological hydrodynamical numerical simulations (McCarthy et al. 2014; Le Brun et al. 2014) to calibrate systematic biases in mass modeling to sub-1 per cent. In this article we use weak-lensing mass measurements calculated after correcting for the shape measurements and contamination biases – see Okabe & Smith's Table A.1.

We use hydrostatic masses from Martino et al. (2014), who modelled X-ray observations of the clusters assuming that the X-ray emitting cluster gas is in hydrostatic equilibrium with the cluster potential. Forty three had been observed by *Chandra* and 39 with *XMM-Newton*. For the 21 clusters observed by both, the average ratio of *Chandra* to *XMM-Newton* hydrostatic mass was 1.02 ± 0.05 with an intrinsic scatter of ~ 8 per cent. We use hydrostatic M_{500} from Table 2 of Martino et al., adopting masses from *Chandra* where available, and otherwise from *XMM-Newton* data. We add 8 per cent systematic uncertainty in quadrature to the statistical error on hydrostatic mass to account for the intrinsic scatter noted above. Note that Martino et al. use data from ACIS-I and ACIS-S on *Chandra* and EPIC (including both PN and MOS) on *XMM-Newton*.

We obtain estimates of M_{500} from Planck Collaboration et al. (2015a) for 44 clusters. These masses are based on measurements of the spherical Compton Y measurement from the millimetre wave data, and a relationship between Y_X and M_{500} derived from X-ray observations of a sample of 20 clusters at $z < 0.2$ selected to have "relaxed" X-ray morphology, where Y_X is the iteratively defined pseudo-pressure of the X-ray emitting gas, $Y_X \equiv M_{\rm gas}.T_X$ (Arnaud, Pointecouteau & Pratt 2007; Arnaud et al. 2010). As such, the *Planck* mass estimates assume the clusters are in hydrostatic equilibrium.

2.2 Method of calculation

We define β as the geometric mean ratio of the hydrostatic mass, $M_{\rm HSE}$, to the weak-lensing mass, $M_{\rm WL}$, for a sample of n clusters:

$$\beta = \exp\left[\frac{\sum_{i=1}^{n} w_i \,\ln\!\left(\frac{M_{\rm HSE,i}}{M_{\rm WL,i}}\right)}{\sum_{i=1}^{n} w_i}\right], \quad (1)$$

where w_i is the weight attached to each cluster. We calculate the uncertainty on β as the standard deviation of the geometric means of 1000 bootstrap samples each numbering n clusters. Measurements of β based on direct measurement of $M_{\rm HSE}$ from X-ray data are denoted as $\beta_{\rm X}$, and measurements based on *Planck* mass estimates are denoted as $\beta_{\rm P}$.

We aim to maximize sensitivity of the weights, w_i, to data quality, and minimize sensitivity to physical properties and/or geometry of the clusters. When calculating $\beta_{\rm X}$ we adopt the reciprocal of the sum of the squares of the fractional error on X-ray-based $M_{\rm HSE}$ (denoted here explicitly as $M_{\rm X}$) and the absolute error on $M_{\rm WL}$:

$$w_i = \left[\left(\frac{\delta M_{\rm X,i}/M_{\rm X,i}}{\langle \delta M_{\rm X}/M_{\rm X}\rangle}\right)^2 + \left(\frac{\delta M_{\rm WL,i}}{\langle \delta M_{\rm WL}\rangle}\right)^2\right]^{-1} \quad (2)$$

The weighting with respect to the hydrostatic masses reflects the fact the absolute error on $M_{\rm X}$ is tightly correlated with $M_{\rm X}$ itself. This is because the X-ray spectra of more massive (hotter) clusters contain less emission features than spectra of cooler clusters, thus making hydrostatic mass measurements intrinsically less precise for hotter clusters despite them being brighter. In contrast the fractional error on $M_{\rm X}$ is not a strong function of $M_{\rm X}$, and so the mass dependence of the weighting scheme is significantly reduced. The weighting with respect to the weak-lensing masses reflects the fact that the absolute error on $M_{\rm WL}$ traces the weak-lensing data quality more faithfully than the fractional error on $M_{\rm WL}$. Indeed, given the uniformity of our weak-lensing data (Okabe & Smith 2015), the fractional error would up-weight clusters with large values of $M_{\rm WL}$, thus biasing our results to clusters with large masses and/or that are observed at small angles with respect to their major axis (Meneghetti et al. 2010). The latter effect would introduce a geometric bias into our results. When calculating $\beta_{\rm P}$ we adopt the reciprocal of the sum of the squares of the absolute errors on $M_{\rm Planck}$ and $M_{\rm WL}$:

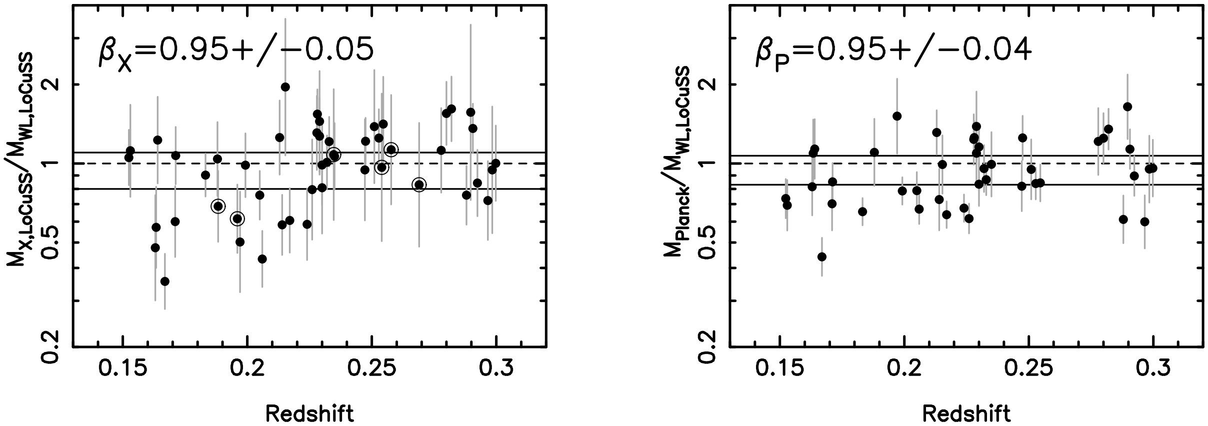

Figure 1. Left – Ratio of X-ray-based hydrostatic mass to weak-lensing mass versus redshift for the 50 clusters in the LoCuSS sample, adding an open circle around clusters not detected by *Planck*. Right – Ratio of *Planck* mass estimate to weak-lensing mass versus redshift for 44 clusters in the LoCuSS sample. Both – The Pearson correlation coefficient for mass ratio versus redshift confirms that the *possible* trend of mass ratio with redshift seen by eye in these panels is statistically insignificant. The horizontal dashed lines mark $\beta = 1$, and the solid lines show the $\pm 3\sigma$ confidence interval on $\beta_{\rm X}$ (left; §2.3) and $\beta_{\rm P}$ (right; §2.4).

$$w_i = \left[\left(\frac{\delta M_{\rm Planck,i}}{\langle \delta M_{\rm Planck} \rangle} \right)^2 + \left(\frac{\delta M_{\rm WL,i}}{\langle \delta M_{\rm WL} \rangle} \right)^2 \right]^{-1} \quad (3)$$

The weighting with respect to the Planck mass estimates follows a similar motivation to that described above for the weak-lensing masses.

2.3 Comparing LoCuSS weak-lensing and X-ray masses

We compare weak-lensing masses with X-ray masses, with each computed within their independently derived r_{500} (Figure 1, left panel), obtaining $\beta_{\rm X}= 0.95 \pm 0.05$. Arguably a more accurate calculation uses hydrostatic and weak-lensing masses measured within the same radius. We therefore recalculate $\beta_{\rm X}$ based on X-ray and lensing masses both computed within the weak-lensing-based r_{500} (hereafter $r_{\rm WL,500}$), obtaining $\beta_{\rm X}= 0.87{\pm}0.04$, 1.2σ lower than the former measurement, however note that adopting $r_{\rm WL,500}$ as the radius for both masses introduces a covariance that we have neglected in our calculation.

2.4 Comparing LoCuSS weak-lensing masses and Planck mass estimates

We compare weak-lensing mass measurements with the *Planck* mass estimates to compute $\beta_{\rm P}$ (Figure 1, right panel), obtaining $\beta_{\rm P}= 0.95 \pm 0.04$, in excellent agreement with $\beta_{\rm X}$ (§2.3). Note that the apertures within which our weak-lensing masses are computed are independent of the apertures used by Planck Collaboration et al. (2015a) when calculating the *Planck* mass estimates. We double check the consistency between $\beta_{\rm X}$ and $\beta_{\rm P}$ by repeating the X-ray/lensing comparison (§2.3) for the 44 clusters detected by *Planck* and considered in this section, obtaining $\beta_{\rm X}= 0.97 \pm 0.06$. The agreement between $\beta_{\rm X}$ and $\beta_{\rm P}$ is therefore not sensitive to the six clusters that have not been detected by *Planck*.

3 DISCUSSION

We now compare our results with previous observational studies, noting in passing that our measurements of hydrostatic bias are in line with numerous cosmological numerical hydrodynamical simulations (e.g. Nagai, Vikhlinin & Kravtsov 2007; Meneghetti et al. 2010; Rasia et al. 2012; Le Brun et al. 2014).

3.1 Comparison with pointed X-ray surveys

Martino et al. (2014) compared their hydrostatic masses (used in this letter) with LoCuSS weak-lensing masses (Okabe et al. 2010, 2013), obtaining $\beta_{\rm X}\simeq 0.93$. This result is fully consistent with our $\beta_{\rm X}= 0.95 \pm 0.05$, that uses the new LoCuSS weak-lensing masses from Okabe & Smith (2015).

The Canadian Cluster Comparison Project (CCCP) obtained $\beta_{\rm X}= 0.88 \pm 0.05$ with both hydrostatic and weak-lensing masses measured within $r_{\rm WL,500}$ (Mahdavi et al. 2013). Hoekstra et al. (2015) updated the CCCP weak-lensing masses, reporting masses ($M_{\rm WL}$ ($< r_{500}$)) on average 19 per cent higher than Hoekstra et al. (2012) and Mahdavi et al. (2013). Applying a factor 1.19 "correction" to the denominator of the CCCP $\beta_{\rm X}$ implies $\beta_{\rm X}\simeq 0.74$. However we note that Martino et al. (2014) found that Mahdavi et al.'s hydrostatic masses are on average ~ 14 per cent lower than LoCuSS hydrostatic masses for 21 clusters in common (see Martino et al. for details). Applying a further factor 1.14 correction to the numerator brings CCCP up to $\beta_{\rm X}\simeq 0.84$, in agreement with our $\beta_{\rm X}= 0.87 \pm 0.04$ (§2.3).

Israel et al. (2014) considered eight clusters at $z \simeq 0.5$ from the 400d survey, obtaining $\beta_{\rm X}= 0.92^{+0.09}_{-0.08}$, in good agreement with our measurements. Note that this is based on the first line of their Table 2, which gives the most like-for-like comparison with our methods.

After we submitted this letter Applegate et al. (2015) posted a preprint that compares weak-lensing and hydrostatic mass measurements within X-ray-based r_{2500} for a sample of 12 "relaxed" clusters. Detailed comparison of their results with ours is hindered by the absence of individual cluster masses in Applegate et al., and their small sample. Their main result is a ratio of weak-lensing mass to hydrostatic mass within r_{2500} of 0.96 ± 0.13. They also comment that they obtain a ratio of 1.06 ± 0.13 at r_{500}. We repeat our calculation of $\beta_{\rm X}$ described at the end of §2.3 within matched apertures with weak-lensing mass as the numerator and hydrostatic mass as the denominator, obtaining a weak-lensing to hydrostatic mass of 1.15 ± 0.04 at r_{500}.

3.2 Comparison with Sunyaev-Zeldovich effect surveys

Weighing the Giants (WtG) and CCCP have reported $\beta_{\rm P}= 0.70 \pm 0.06$ and $\beta_{\rm P}= 0.76 \pm 0.08$ respectively (von der Linden et al. 2014; Hoekstra et al. 2015), both based on the Planck Collaboration et al. (2014) masses. These measurements are lower than our $\beta_{\rm P}= 0.95 \pm 0.04$ at 3.5σ and 2.1σ respectively.

We apply our methods, including absolute mass errors weighting (§2.2), to the clusters and masses used by von der Linden et al. (2014), obtaining $\beta_{\rm P}= 0.80 \pm 0.07$. von der Linden et al. do not state explicitly their method of calculation, however if we weight uniformly then we obtain $\beta_{\rm P}= 0.69 \pm 0.07$, in agreement with them. Next, we update the WtG results to the Planck Collaboration et al. (2015a) measurements of $M_{\rm Planck}$, obtaining slightly higher values: $\beta_{\rm P}= 0.72 \pm 0.07$ and $\beta_{\rm P}= 0.83 \pm 0.07$ for uniform and absolute mass error weighting respectively. Splitting the clusters into two redshift bins, with the lower redshift bin matching LoCuSS, and again using absolute mass error weighting, we obtain $\beta_{\rm P}$ $(z < 0.3) = 0.90 \pm 0.09$ and $\beta_{\rm P}$ $(z > 0.3) = 0.71 \pm 0.07$. This is consistent with our results at $z < 0.3$, and suggests $\beta_{\rm P}$ might be a function of redshift.

We also apply our methods to the clusters and masses considered by Hoekstra et al. (2015), obtaining $\beta_{\rm P}= 0.83 \pm 0.07$. We reproduce the published CCCP result if we weight the clusters uniformly, in which case we obtain $\beta_{\rm P}= 0.77\pm0.07$. Updating to the Planck Collaboration et al. (2015a) masses, gives a slightly higher value of $\beta_{\rm P}= 0.85 \pm 0.08$ (using absolute mass error weights). So far we have followed Hoekstra et al. in using their deprojected aperture mass measurements. However, both LoCuSS and WtG obtain masses by fitting an NFW model to the shear profile. To obtain a like-for-like comparison we therefore use Hoekstra et al.'s NFW-based masses, the Planck Collaboration et al. (2015a) masses, and absolute mass error weights, obtaining $\beta_{\rm P}= 0.92 \pm 0.08$. Finally, we split the CCCP sample into two redshift bins, as above, and find $\beta_{\rm P}$ $(z < 0.3) = 0.96 \pm 0.09$ and $\beta_{\rm P}$ $(z > 0.3) = 0.61 \pm 0.09$. This is consistent with our results at $z < 0.3$, again suggesting $\beta_{\rm P}$ depends on redshift.

After we submitted this letter Battaglia et al. (2015) reported weak-lensing follow up of the Atacama Cosmology Telescope (ACT) thermal Sunyaev-Zeldovich (SZ) cluster sample. They commented that WtG and CCCP measurements of $\beta_{\rm P}\simeq 0.7 - 0.8$ may be biased *high* because clusters that are not detected by *Planck* are excluded from their calculations. They estimated the possible bias by assigning to the non-detections a mass equal to the *Planck* 5σ detection threshold and thus including these clusters in the calculations of $\beta_{\rm P}$. They found that this reduces the CCCP and WtG $\beta_{\rm P}$ values by ~ 0.06 and ~ 0.16 respectively. We expect any bias of this nature to be small in our analysis because only six clusters from our sample of fifty are not detected by *Planck*. Nevertheless, we perform the calculations outlined by Battaglia et al. and successfully reproduce their values for WtG and CCCP. We then estimated the possible bias in our results, and find that including the 6 non-detections reduces our measurement of $\beta_{\rm P}$ by just ~ 0.04. We also estimate the bias for WtG and CCCP using just their clusters at $z < 0.3$, and obtain ~ 0.04. Biases caused by excluding *Planck* non-detections appear to dominate neither our results nor comparison with WtG and CCCP at $z < 0.3$.

4 CONCLUSIONS AND PERSPECTIVE ON "PLANCK COSMOLOGY"

We have used three sets of independent mass measurements to develop a consistent picture of the departures from hydrostatic equilibrium in the Local Cluster Substructure Survey (LoCuSS) sample of 50 clusters at $0.15 \leqslant z \leqslant 0.3$. These clusters were selected purely on their X-ray luminosity, declination, and line of sight hydrogen column density. The mass measurements comprise weak-lensing masses (Okabe & Smith 2015; Ziparo et al. 2015), direct measurements of hydrostatic masses using X-ray observations (Martino et al. 2014), and estimated hydrostatic masses from Planck Collaboration et al. (2015a). The main strength of our results is the careful analysis of systematic biases in the weak-lensing and hydrostatic mass measurements referred to above, and summarized in §2.1.

We obtain excellent agreement between our X-ray-based and *Planck*-based tests of hydrostatic equilibrium, with $\beta_{\rm X}= 0.95 \pm 0.05$ (§2.3) and $\beta_{\rm P}= 0.95 \pm 0.04$ (§2.4). The masses used for these calculations are measured within independently derived estimates of r_{500}. We also remeasured $\beta_{\rm X}$ using X-ray masses measured within the weak-lensing-based r_{500}, obtaining $\beta_{\rm X}= 0.87\pm0.04$ (§2.3), suggesting that the actual level of hydrostatic bias, of astrophysical interest, might be slightly larger than inferred from the calculations based on independent measurement apertures.

Our measurement of $\beta_{\rm P}$ is larger (implying smaller hydrostatic bias) than recent results from the WtG and CCCP surveys (von der Linden et al. 2014; Hoekstra et al. 2015) at 3.5σ and 2.1σ respectively (§3.2). However if we restrict the WtG and CCCP sample to the same redshift range as LoCuSS ($0.15 < z < 0.3$), use a consistent method to calculate $\beta_{\rm P}$ (§2.2), and incorporate up to date *Planck* mass estimates (Planck Collaboration et al. 2015a) into the WtG and CCCP calculations, we obtain $\beta_{\rm P}$ $(z < 0.3) = 0.90\pm0.09$ and $\beta_{\rm P}$ $(z < 0.3) = 0.96 \pm 0.09$ respectively. This highlights that the previously reported low values of $\beta_{\rm P}$ appear to be dominated by clusters at $z > 0.3$, with $\beta_{\rm P}$ $(z > 0.3) \sim 0.6 - 0.7$. We also note that estimates of bias in $\beta_{\rm P}$ caused by excluding clusters not detected by *Planck* (Battaglia et al. 2015) are ~ 0.04 for clusters at $z < 0.3$, and $\gtrsim 0.1$ at $z > 0.3$, in the sense that these biases reduce $\beta_{\rm P}$. In short, any bias appears to be sub-dominant to statistical uncertainties at $z < 0.3$, that is the main focus of this letter.

We are therefore lead to a view that $\beta_{\rm P}\simeq 0.9 - 0.95$ at $z < 0.3$ and $\beta_{\rm P}\lesssim 0.6$ at $z > 0.3$. The very low value at $z > 0.3$ could be caused by systematic biases in mass measurements that relate to observational or measurement effects, and not to the validity of hydrostatic equilibrium. It is plausibe that systematic biases in weak-lensing mass measurements are better controlled at $z < 0.3$ than at $z > 0.3$, because for observations to fixed photometric depth, the sensitivity of the weak-lensing mass measurements to the accuracy of the redshift distribution of the background galaxies increases with cluster redshift. It would also be interesting to consider the possibility of redshift-dependent biases in the *Planck* mass estimates.

Our results imply a hydrostatic bias parameter, $(1-b)$, at the upper end of the range of values considered as a prior by Planck Collaboration et al. (2015b) for their cluster cosmology analysis. Intriguingly, our measurements are compatible with the CMB lensing constraints of $(1-b) = 1.01^{+0.24}_{-0.16}$ (Melin & Bartlett 2015), although the uncertainties on this pioneering measurement were admittedly large. On the other hand, our measurements disagree at $\sim 5\sigma$ with the value of $(1-b) = 0.58 \pm 0.04$ computed by Planck Collaboration et al. (2015b) as being required to reconcile the *Planck* primary CMB and SZ cluster counts. Moreover, the *Planck* CMB cosmology results are in tension with numerous independent large-scale structure probes of cosmology in addition to cluster number counts (e.g. Heymans et al. 2013; Mandelbaum et al. 2013; McCarthy et al. 2014; Beutler et al. 2014; Samushia et al. 2014; Battaglia, Hill & Murray 2015; Planck Collaboration et al. 2015c; Hojjati et al. 2015), adding further indirect support to our results. It has been suggested that the *Planck* CMB/clusters tension might point to exciting new physics, including possible constraints on neutrinos (e.g. Planck Collaboration et al. 2015b). However, it is clear that significant further work is first required on systematic uncertainties in cluster mass measurement, especially for clusters at $z > 0.3$.

ACKNOWLEDGMENTS

We acknowledge helpful discussions with Doug Applegate, Nick Battaglia, Stefano Ettori, Henk Hoekstra, Anja von der Linden, Adam Mantz, Jean-Baptiste Melin, and Mauro Sereno. GPS acknowledges support from the Royal Society. GPS, FZ, CPH, SLM, ML, PEM acknowledge support from the Science and Technology Facilities Council (STFC). This work was supported by “World Premier International Research Center Initiative (WPI Initiative)” and the Funds for the Development of Human Resources in Science and Technology under MEXT, Japan, and Core Research for Energetic Universe in Hiroshima University (the MEXT program for promoting the enhancement of research universities, Japan). CPH was funded by CONICYT Anillo project ACT-1122. MJ acknowledges the STFC [grant number ST/F001166/1].

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