WEAK LENSING CALIBRATED $M$–$T$ SCALING RELATION OF GALAXY GROUPS IN THE COSMOS FIELD

K. Kettula$^1$, A. Finoguenov$^1$, R. Massey$^2$, J. Rhodes$^{3,4}$, H. Hoekstra$^5$, J. E. Taylor$^6$, P. F. Spinelli$^{7,8}$, M. Tanaka$^9$, O. Ilbert$^{10}$, P. Capak$^{11}$, H. J. McCracken$^{12}$, and A. Koekemoer$^{13}$

$^1$ Department of Physics, University of Helsinki, Gustaf Hällström katu 2a, FI-00014 Helsinki, Finland; kimmo.kettula@iki.fi
$^2$ Institute for Computational Cosmology, Durham University, South Road, Durham DH1 3LE, UK
$^3$ California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125, USA
$^4$ Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
$^5$ Leiden Observatory, Leiden University, Niels Bohrweg 2, NL-2333-CA Leiden, The Netherlands
$^6$ Department of Physics and Astronomy, University of Waterloo, 200 University Avenue West, Waterloo, ON N2L 3G1, Canada
$^7$ Instituto de Astronomía, Geofísica e Ciências Atmosféricas (IAG), Rua do Matão, 1226 Ciadida Universitária 05508-090, São Paulo, SP, Brazil
$^8$ Museu de Astronomia e Ciências Afins (MAST), Rua General Bruce, 586 Bairro Imperial de São Cristóvão 20921-030, Rio de Janeiro, RJ, Brazil
$^9$ National Astronomical Observatory of Japan, Osawa 2-21-1, Mitaka, Tokyo 181-8588, Japan
$^{10}$ LAM, CNRS-UNiv Aix-Marseille, 38 rue F. Joliot-Curis, F-13013 Marseille, France
$^{11}$ Spitzer Science Center, 314-6 Caltech, 1201 East California Boulevard Pasadena, CA 91125, USA
$^{12}$ Institut d’Astrophysique de Paris, UMR 7095, 98 bis Boulevard Arago, F-75014 Paris, France
$^{13}$ Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

Received 2013 June 20; accepted 2013 September 25; published 2013 November 6

ABSTRACT

The scaling between X-ray observables and mass for galaxy clusters and groups is instrumental for cluster-based cosmology and an important probe for the thermodynamics of the intracluster gas. We calibrate a scaling relation between the weak lensing mass and X-ray spectroscopic temperature for 10 galaxy groups in the COSMOS field, combined with 55 higher-mass clusters from the literature. The COSMOS data includes Hubble Space Telescope imaging and redshift measurements of 46 source galaxies per arcminute$^2$, enabling us to perform unique weak lensing measurements of low-mass systems. Our sample extends the mass range of the lensing calibrated $M$–$T$ relation an order of magnitude lower than any previous study, resulting in a power-law slope of $48^{+0.13}_{-0.09}$. The slope is consistent with the self-similar model, predictions from simulations, and observations of clusters. However, X-ray observations relying on mass measurements derived under the assumption of hydrostatic equilibrium have indicated that masses at group scales are lower than expected. Both simulations and observations suggest that hydrostatic mass measurements can be biased low. Our external weak lensing masses provide the first observational support for hydrostatic mass bias at group level, showing an increasing bias with decreasing temperature and reaching a level of $30\%$–$50\%$ at 1 keV.

Key words: cosmology: observations – galaxies: groups: general – gravitational lensing: weak

Online-only material: color figures

1. INTRODUCTION

As the largest gravitationally bound objects in the universe, galaxy clusters and groups have proven to be important cosmological probes. They reside in the high-mass end of the cosmic mass function and have a formation history that is strongly dependent on cosmology. Therefore, the mass function of galaxy clusters and groups functions as an independent tool for constraining cosmological parameters.

Clusters and groups are now readily detected up to redshifts of unity and above through X-ray emission of hot intracluster gas, optical surveys of galaxies and the Sunyaev–Zel’dovich effect in the millimeter range. The masses of these systems have typically been inferred through thermal X-ray emission or the velocity dispersion of galaxies. Both of these methods rely on the assumption of hydrostatic or gravitational equilibrium in the cluster or group, which is not always valid. Clusters and groups are found in a myriad of dynamical states and there is increasing evidence for non-thermal pressure support in the intracluster gas, skewing the mass estimates derived under the assumptions of a hydrostatic equilibrium (HSE; e.g., Nagai et al. 2007; Mahdavi et al. 2008, 2013; Shaw et al. 2010; Rasia et al. 2012).

Fortunately, gravitational lensing has proven to be a direct way of measuring cluster and group masses regardless of the dynamical state or non-thermal pressure support in the system.

$^{14}$ With intracluster gas, we refer to the intergalactic gas in both galaxy groups and clusters. We follow the convention of referring to those systems with mass lower than $\sim 10^{14} M_\odot$ as groups and higher as clusters.
In gravitational lensing, the presence of a large foreground mass such as a galaxy cluster or group will bend the light radiating from a background source galaxy. In weak gravitational lensing, the ellipticity of a source galaxy is modified, whereas strong lensing also produces multiple images of a single source. The weak lensing-induced change in ellipticity is commonly referred to as shear. However, source galaxies typically have a randomly oriented intrinsic ellipticity that is significantly larger than the lensing-induced shear. Therefore, the shear has to be averaged over a large sample of source galaxies in order to measure a weak lensing signal used to infer the mass of the lensing system.

The direct mass measurement methods described above are observationally expensive and not always applicable to low-mass or high-redshift systems. This has spurred the study of mass proxies. As X-ray observations have proven to be the most observationally expensive and not always applicable to low-mass or high-redshift systems. This has spurred the study of mass proxies. As X-ray observations have proven to be the most efficient way for constructing cluster and group catalogs, typically X-ray observables such as luminosity, \( L_X \), spectroscopic temperature, \( T_X \), and thermal energy of the intracluster gas, \( Y_X = T_X \times M_{\text{gas}} \), are used as mass proxies. Consequently, defining and calibrating these X-ray mass proxies is instrumental for strongly lensing and calibrating these X-ray mass proxies is instrumental for

The direct mass measurement methods described above are observationally expensive and not always applicable to low-mass or high-redshift systems. This has spurred the study of mass proxies. As X-ray observations have proven to be the most efficient way for constructing cluster and group catalogs, typically X-ray observables such as luminosity, \( L_X \), spectroscopic temperature, \( T_X \), and thermal energy of the intracluster gas, \( Y_X = T_X \times M_{\text{gas}} \), are used as mass proxies. Consequently, defining and calibrating these X-ray mass proxies is instrumental for

The scaling between cluster or group temperature and mass is very fundamental. The simple self-similar model for cluster evolution developed by Kaiser (1986), which assumes pure gravitational heating of intracluster gas, predicts that cluster temperature is a direct measure of the total gravitational potential and thus mass of the system. The predicted scaling of mass to temperature is a power law with a slope of \( 3/2 \). Deviations from the self-similar prediction can consequently be used to study non-gravitational physics affecting the gas.

Unfortunately, cluster and group masses are typically derived from X-ray observations under the assumption of HSE regardless of dynamical state. Also, temperatures are usually derived from the same observation as hydrostatic masses, introducing possible covariance between the observed quantities. The hydrostatic \( M-T \) relations typically give power-law slopes in the range of 1.5–1.7 (see Böhringer et al. 2012; Giohodini et al. 2013, for summaries of recent literature). Notably, samples that only include higher-mass systems with temperatures above 3 keV tend to predict \( M-T \) relations that have a slope close to the self-similar prediction of 1.5, whereas samples including lower-mass systems tend to predict a slightly steeper proportionality.

The accuracy of the calibration of mass–temperature scaling can be significantly improved by using independent weak lensing cluster mass measurements. However, this type of study has only been performed in the cluster mass regime by Smith et al. (2005), Hoekstra (2007), Okabe et al. (2010), Jee et al. (2011), Hoekstra et al. (2012), and Mahdavi et al. (2013). The aim of this work is to calibrate the scaling between weak lensing masses and X-ray temperatures of the hot intracluster gas for a sample of galaxy groups in the COSMOS survey field. This work is an extension to Leauthaud et al. (2010), who investigated the scaling between weak lensing mass and X-ray luminosity in the same field.

This paper is organized as follows. We present the data and galaxy group sample used for our analysis in Sections 2 and 3, and give details on the X-ray and weak lensing analysis in Sections 4 and 5. We present the resulting \( M-T \) relation in Section 6, discuss our findings in Section 7, and conclude and summarize our findings in Section 8. Throughout this paper, we assume WMAP nine year cosmology (Hinshaw et al. 2012), with \( H_0 = 70 \, h_{70} \, \text{km s}^{-1} \, \text{Mpc}^{-1} \), \( \Omega_M = 0.28 \), and \( \Omega_L = 0.72 \). All uncertainties are reported at a 68% significance, unless stated otherwise.

2. COSMOS DATA

In this section, we briefly present the observations of the COSMOS survey field used for our analysis. The COSMOS survey consists of observations of a contiguous area of 2 deg\(^2\) with imaging at wavelengths from radio to X-ray and deep spectroscopic follow-up (see, e.g., overview by Scoville et al. 2007b).

2.1. Lensing Catalog

The shear measurements of source galaxies are based on Hubble Space Telescope (HST) imaging of the COSMOS field using the Advanced Camera for Surveys (ACS) Wide Field Channel (WFC; Scoville et al. 2007a; Koekemoer et al. 2007). As the COSMOS field was imaged during 640 orbits during HST cycles 12 and 13, the ACS/WFC imaging of the COSMOS field is the HST survey with the largest contiguous area to date. The derivation of shear measurement is described in detail by Leauthaud et al. (2007, 2010, 2012). The shear measurement has been calibrated on simulated ACS images containing a known shear (Leauthaud et al. 2007), and we have updated that with each subsequent improvement of the catalog.

The final weak lensing catalog contains accurate shape measurements of 272,538 galaxies, corresponding to approximately 46 galaxies per arcminute\(^2\), and a median redshift of \( z = 1.06 \). Of the source galaxies, 25,563 have spectroscopic redshift measurements from the zCOSMOS program (Lilly et al. 2007), the remaining source galaxies have photometric redshifts measured using more than 30 bands (Ilbert et al. 2009).

2.2. X-Ray Group Catalog

The X-ray group catalog we used has been presented in George et al. (2011) and is available online. In brief, we used all XMM-Newton (described in Hasinger et al. 2007; Cappelluti et al. 2009) and Chandra observations (Elvis et al. 2009) performed prior to 2010 in catalog construction. Point source removal has been produced separately for Chandra and XMM before combining the data, as described in Finoguenov et al. (2009), producing a list of 200+ extended sources. We run a red-sequence finder to identify the galaxy groups following the procedure outlined in Finoguenov et al. (2010). Extensive spectroscopy available for the COSMOS field allowed a 90% spectroscopic identification of the \( z < 1 \) group sample. George et al. (2012) explored the effect of centering by taking an X-ray center or the most massive group galaxy (MMGG).

Previously, the X-ray group catalog had been used in Leauthaud et al. (2010) to calibrate the \( M-L \) relation. It has been shown there that there is a correlation between the level of X-ray emission and the significance of the weak lensing signal. In the current work, we take advantage of the fact that the significance required to measure the mean X-ray temperature allows us to perform individual mass measurements, and although the sample size is much smaller when compared to the \( M-L \) relation, we do not need to stack several groups in order to produce the results. The high significance of the selected groups also has a much better defined X-ray centering.
3. SAMPLE SELECTION

We selected sources from the COSMOS X-ray group catalog (Section 2.2) with a detection significance of 10σ and above. As we chose to exclude cluster cores from temperature determination (see Section 4) and consequently only use regions with low scatter in pressure (Arnaud et al. 2010), our sample should not be affected by selection bias.

Our initial sample contained 13 sources. However, we excluded the group with id number 6 because X-ray coverage was not sufficient to constrain the spectroscopic temperature. We further excluded the sources with id numbers 246 and 285, as they are located at the edge of the COSMOS field and thus fall outside the coverage of the HST observations (Section 2.1).

The remaining 10 sources in our sample all have a clear X-ray peak with a single optical counterpart and are free of projections (Finoguenov et al. 2007, XFLAG = 1). As our data allows us to extend our lensing analysis out to large radii, possible substructure in the central parts visible in X-rays is not relevant for our mass estimates. Instead, infalling subgroups at cluster outskirts are more important. Based on our X-ray group catalog, we can rule out this kind of substructure at >20%–30% level in mass.

We adopt the coordinates of the X-ray peaks as the locations of the group centers, but we also tested the effect of using the MMGG as a center in performing the lensing analysis (Section 5.3). The properties of the clusters in our sample are presented in Table 1. The deep X-ray coverage and high density of background galaxies with determined shear in the COSMOS field allows us to treat each system individually in our analysis.

4. X-RAY REDUCTION AND ANALYSIS

For the X-ray analysis, we used EPIC-pn data from the XMM-Newton wide field survey of the COSMOS field (Hasinger et al. 2007) with the latest calibration information available in 2012 October and XMM Scientific Analysis System release xmmssas_20120621_1321-12.0.1. We produced event files with the epchain tool and merged the event files of pointings that were within 10′ of the adopted group center for each system. The merged event files were filtered, excluding bad pixels and CCD gaps and periods contaminated by flares, and including only events with patterns 0–4. We generated out-of-time event files, which we subsequently used to subtract events registered during pn readout.

We extracted spectra from an annulus corresponding to 0.1–0.5 R500 (see Table 2). As differences of a few 10% in the inner and outer radii of the X-ray extraction region will be smeared out by the point-spread function (PSF), we determined R500 from the virial radius in the X-ray group catalog (Section 2.2, based on the M–L relation of Leauthaud et al. 2010), assuming a halo concentration of five. The groups were visually inspected for point sources, which we masked using a circular mask with a 0.5′ radius. We grouped the spectra to a minimum of 25 counts bin−1.

As the groups in the COSMOS field do not fill the field of view, we used the merged event files to extract local background spectra. We selected background regions using the criteria that they are located at a minimum distance of R500 (~2′–6′), determined from the X-ray group catalog Section 2.2) and a maximum distance of 10′ from the adopted group center, and that they do not contain any detectable sources. The background spectra where used as Xspec background files in subsequent spectral fits and thus subtracted from the data.

For X-ray spectroscopy, we used an Xspec model consisting of an absorbed thermal APEC component in a 0.5–7.0 keV energy band, with solar abundance tables of Grevesse & Sauval (1998) and absorption cross-sections of Balucinska-Church & McCammon (1992). We fixed the metal abundance to 0.3 of the solar value, and used redshift and Galactic absorption column density values listed in Table 1. In order to account for spatial variation in the Galactic foreground, we included an additional thermal component with a temperature of 0.26 keV and solar abundance and found that the contribution from this component was negligible.

As the inner radii of the extraction regions is smaller than the EPIC-pn PSF, some flux from the excluded central 0.1 R500 region might scatter to the extraction region. We accounted for this scatter by extracting spectra from the excluded central regions and fitting them with a similar model as described above. We estimated the scatter to the 0.1–0.5 R500 extraction regions using the best-fit model and added the contribution due to the scatter to our analysis. The core regions of groups with id numbers 29 and 220 did not possess a sufficient number.

### Table 1

| Id | N_H^a | z | R.A. (J2000)^b | Decl. (J2000)^b |
|----|--------|---|---------------|----------------|
| 11 | 1.80   | 0.220 | 150.18980    | 1.65725       |
| 17 | 1.78   | 0.372 | 149.96413    | 1.68033       |
| 25 | 1.75   | 0.124 | 149.85146    | 1.77319       |
| 29 | 1.74   | 0.344 | 150.17996    | 1.76887       |
| 120 | 1.80  | 0.834 | 150.50502    | 2.22506       |
| 149 | 1.77  | 0.124 | 150.41566    | 2.43020       |
| 193 | 1.69  | 0.220 | 150.09093    | 2.39116       |
| 220 | 1.71  | 0.729 | 149.92343    | 2.52499       |
| 237 | 1.70  | 0.349 | 150.11774    | 2.68425       |
| 262 | 1.84  | 0.343 | 149.60007    | 2.82118       |

Notes.

^a Id number in the COSMOS X-ray group catalog (Section 2.2).

^b The Leiden/Argentine/Bonn Survey weighted average galactic absorption column density (Kalberla et al. 2005).

^c R.A. and decl. of the X-ray peak.

### Table 2

| Id | 0.1 R500^a (arcmin) | 0.5 R500^a (arcmin) | T_X^c (keV) | f scan^d (%) | Sign.^e (σ) | χ^2 f Degrees of Freedom |
|----|----------------------|----------------------|-------------|-------------|-------------|-------------------------|
| 11 | 0.35                 | 1.77                 | 2.2 ± 0.2   | 5           | 24.5        | 273.42                  | 263                      |
| 17 | 0.19                 | 0.96                 | 2.1 ± 0.2   | 21          | 18.2        | 96.36                   | 91                       |
| 25 | 0.37                 | 1.87                 | 1.3 ± 0.2   | 3           | 11.8        | 139.40                  | 121                      |
| 29 | 0.18                 | 0.89                 | 2.3 ± 0.5   | 3           | 3.2         | 24.75                   | 26                       |
| 120 | 0.13                | 0.67                 | 3.9 ± 0.6   | 10          | 16.6        | 66.49                   | 69                       |
| 149 | 0.42                | 2.08                 | 1.4 ± 0.5   | 4           | 19.1        | 123.95                  | 132                      |
| 193 | 0.20                | 1.02                 | 1.2 ± 0.7   | 14          | 3.9         | 27.54                   | 23                       |
| 220 | 0.16                | 0.79                 | 4.6 ± 0.9   | ...         | 15.8        | 43.49                   | 32                       |
| 237 | 0.20                | 0.99                 | 2.2 ± 0.5   | 12          | 5.3         | 24.99                   | 26                       |
| 262 | 0.21                | 1.03                 | 3.3 ± 0.8   | 5           | 5.7         | 40.14                   | 33                       |

Notes.

^a Inner radii of the extraction region.

^b Outer radii of the extraction region.

^c X-ray temperature of the group.

^d Fraction of the flux in the 0.1–0.5 R500 Region scattered from the central region.

^e Statistical significance of the thermal X-ray component.

^f χ² of the best-fit model.
of photons to fit a spectrum and we estimate that the scatter from the central region is negligible for these systems. For the remaining systems, the fraction of flux in the extraction region scattered from the central region varies between 3\% and 21\% (see Table 2).

We detected the thermal emission component in the 0.1–0.5 R_{500} region with a statistical significance of 3.2\sigma – 24.5\sigma and best-fit temperatures in the range of 1.2–4.6 keV (see Figure 1 and Table 2). Thus our sample extends the measurements of weak lensing based M – T relations to a lower temperature range than previous studies by a factor of four (Hoekstra 2007; Okabe et al. 2010; Jee et al. 2011; Mahdavi et al. 2013).

5. WEAK LENSING ANALYSIS

For our weak lensing analysis, we used the COSMOS shear catalog.

5.1. Lensing Signal

In our analysis, we measured the lensing signal independently for each system in our sample in terms of azimuthally averaged surface mass density contrast \( \Delta \Sigma (r) \). A spherically symmetric mass distribution is expected to induce a shear, which is oriented tangentially to the radial vector. This signal is also known as the \( E \) mode. The cross-component shear, or \( B \)-mode signal, is angled at 45° from the tangential shear and the azimuthally averaged value is expected to be consistent with zero for a perfect lensing signal.

The azimuthally averaged surface mass density contrast is related to the projected tangential shear of source galaxies \( \gamma_t \) by

\[
\Delta \Sigma (r) = \bar{\Sigma} (r) - \Sigma (r) = \Sigma_{\text{crit}} \times \gamma_t (r),
\]

where \( \bar{\Sigma} (r) \) is the mean surface mass density within the radius \( r \), \( \Sigma (r) \) is the azimuthally averaged surface mass density at radius \( r \), and \( \Sigma_{\text{crit}} \) is the critical surface mass density. The critical surface mass density depends on the geometry of the lens–source system as

\[
\Sigma_{\text{crit}} = \frac{c^2}{4\pi G D_{\text{OS}} D_{\text{LS}}}.
\]

Here \( c \) is the speed of light; \( G \) is Newton’s gravitational constant; and \( D_{\text{OS}} \), \( D_{\text{OL}} \), and \( D_{\text{LS}} \) are the angular diameter distances between observer and source, observer and lens, and lens and source, respectively.

For each lensing system, we selected the source galaxies from the COSMOS shear catalog with a projected distance of 0.1–4 Mpc in the lens plane and a lower limit for the 68\% confidence interval for the photometric redshift higher than the redshift of the lensing system. Approximately 23\% of the source galaxies in the lensing catalog have secondary photometric redshift peaks. In order to avoid biasing mass estimates due to catastrophic outliers, we exclude these galaxies from our analysis.

The lensing signal might be diluted, if a significant number of group galaxies are scattered into the source sample. For instance, Hoekstra (2007) showed in Figure 3 that the effect is modest for high-mass clusters using ground based data (~20\% at \( R_{2500} \)). As our space based data is deeper, giving a larger number of sources, and we analyze low-mass systems with a smaller number of member galaxies, the effect on our sample is significantly smaller. The effect is mainly limited to the central parts of the groups, which we cut out from our analysis. Furthermore, as our photometric redshifts are based on 30+ bands and we exclude source galaxies with secondary redshift peaks, our lensing masses are unaffected by contamination by group members.

We calculated the surface mass density contrast \( \Delta \Sigma_{i,j} \) for each lens–source pair using Equations (1) and (2). For the computation of \( \Delta \Sigma_{i,j} \), spectroscopic redshift was used instead of photometric redshift for those source galaxies where it was available. As we compute \( \Delta \Sigma \) at radii greater than 0.1 Mpc, our lensing signals are largely unaffected by non-weak shear or contributions from the central galaxy (Leauthaud et al. 2010). As an illustration, we show the combined and binned tangential and cross-component lensing signals for all sources in the sample in Figure 2.

The uncertainty of the observed tangential shear \( \sigma_{\gamma_T} \) is affected by the measurement error of the shape \( \sigma_{\text{meas}} \) and the uncertainty due to the intrinsic ellipticity of source galaxies \( \sigma_{\text{int}} \), known as intrinsic shape noise. Leauthaud et al. (2007, 2010) estimated the intrinsic shape noise of source galaxies in the COSMOS shear catalog to \( \sigma_{\text{int}} = 0.27 \).

Nearby large-scale structure (LSS) can also contribute to the uncertainty of lensing mass estimates (Hoekstra 2001, 2003). For the COSMOS field, Spinelli et al. (2012) found that the LSS affects the shear measurements as an external source of noise, where the average contribution to the uncertainty of the
tangential shear is $\sigma_{\text{LSS}} = 0.006$. We ignore the correlation of the $\sigma_{\text{LSS}}$ contribution between different source galaxies. Thus, the total uncertainty of the tangential shear measurements for each source galaxy can be approximated by

$$\sigma_{\gamma}^2 \approx \sigma_{\text{meas}}^2 + \sigma_{\text{int}}^2 + \sigma_{\text{LSS}}^2,$$

where the correlation between $\sigma_{\text{meas}}$ and $\sigma_{\text{LSS}}$ is small, the correlation between $\sigma_{\text{int}}$ and the other two terms vanishes.

For this work, we use $\sigma_{\text{meas},i}$ from the updated Leauthaud et al. (2010) catalog, $\sigma_{\text{int}} = 0.27$ and $\sigma_{\text{LSS}} = 0.006$.

### 5.2. Lensing Mass Estimates

Numerical simulations indicate that the density profile of galaxy clusters or groups typically follow the Navarro–Frenk–White (NFW) profile (Navarro et al. 1997), given by

$$\rho(r) = \frac{\delta_c \rho_c}{(r/r_s)(1 + r/r_s)^2}.$$  

In this work, we define total group mass as the mass inside which the mean NFW mass density $\langle \rho \rangle = 200 \rho_c r_s$. We denote this mass by $M_{200}$ and define it as $M_{200} = M(r_{200}) = 200 \rho_c 4\pi r_{200}^3$. The NFW concentration parameter $c_{200} = r_{200}/r_s$ gives the relation between $r_{200}$ and the characteristic scale radius $r_s$. Finally, the density contrast in the NFW profile (Equation 4) is defined as

$$\delta_{200} = \frac{200}{3} \left[ \frac{3}{c_{200}^3} \ln(1 + c_{200}) - \frac{c_{200}}{1 + c_{200}} \right].$$

The analytic solution for the surface mass density contrast signal corresponding to a NFW profile $\Delta\Sigma_{\text{NFW}}$ is given by

$$\Sigma_{\text{NFW}}(x) = \begin{cases} 
\frac{2r_s \delta_c \rho_c}{x(1-x)} \left[ 1 - \frac{2}{\sqrt{1-x^2}} \text{arctanh}\left(\frac{1}{\sqrt{1-x^2}}\right) \right], & x < 1, \\
\frac{2r_s \delta_c \rho_c}{x^2 - 1} \left[ 1 - \frac{2}{\sqrt{x^2 - 1}} \text{arctan}\left(\frac{\sqrt{x^2 - 1}}{1}\right) \right], & x > 1, 
\end{cases}$$

where $x = R/r_s$ (e.g., Bartelmann 1996; Wright & Brainerd 2000; Kneib & Natarajan 2011). The solution depends on the mass, concentration parameter, and redshift of the lensing system. For this work, we assume that $M_{200}$ and $c_{200}$ are related by

$$c_{200} = \frac{5.71}{(1 + z_d)^{0.47}} \left( \frac{M_{200}}{2.0 \times 10^2 h^{-1} M_\odot} \right)^{-0.084}$$

given by Duffy et al. (2008). We experimented with letting concentration vary freely, however, the shear data did not allow for this extra degree of freedom. Thus as the redshifts of the systems in our sample are known, the only unknown in the solution of $\Delta\Sigma_{\text{NFW}}$ is mass $M_{200}$.

We estimated the masses by fitting $\Delta\Sigma_{\text{NFW}}$ to the measured $\Delta\Sigma$ (Section 5.1), in a radial range of 0.1–4 Mpc. The data were not binned for the fit. We used the Metropolis–Hastings Markov Chain Monte Carlo algorithm for $\chi^2$ minimization (see Figures 3 and 4) and found best-fit $M_{200}$ in the range of...
The Astrophysical Journal, 778:74 (11pp), 2013 November 20

Kettula et al.

Figure 4. Azimuthally averaged mass surface density contrast $\Delta \Sigma$ profiles of the individual systems used for the weak lensing analysis. The profile is measured in a radial range of 0.1–4 Mpc. Data show the measured $\Delta \Sigma$, the solid lines show the $\Delta \Sigma$ of the best-fit NFW density profiles while the dotted lines indicate the statistical uncertainty of the fitted profiles. The profile fits are performed to un-binned data, here the data are binned to 20 equally spaced radial bins for plot clarity.

Figure 5. Plot showing weak lensing mass $M_{200}$ versus redshift $z$ of the COSMOS systems analyzed in this work.

$\sim 0.3–6 \times 10^{14} \, h^{-1} M_\odot$ (see Figure 5 and Table 3). This mass range is consistent with the low X-ray temperatures described above.

5.3. Centering Comparison

George et al. (2012; see also Hoekstra et al. 2011) showed that miscentering the dark matter halo can bias the lensing mass of the halo low. Therefore we investigated the effects of the uncertainty of the centering of the dark matter halo on our lensing mass estimates by performing the weak lensing analysis described above with centering on the locations of the X-ray peaks and MMGGs (from George et al. 2011) and comparing the resulting halo masses.

The offset between the MMGGs and X-ray peaks is typically less than the uncertainty of the position of the X-ray centroid, which is given by $32''$ divided by the signal-to-noise ratio.

Table 3

| Id | $M_{500}$ | $M_{200}^a$ | $M_{200}^b$ | $c_{200}$ | $\chi^2$ | Degrees of Freedom | MMGG/X-Ray Centering Ratio |
|----|----------|------------|------------|-----------|----------|-------------------|---------------------------|
| 11 | 1.28+0.14 | 1.79+0.20  | 1.79+0.20  | 4.74      | 25762.57 | 22571            | 1.03+0.39                 |
| 17 | 0.92+0.52 | 1.31+0.73  | 1.31+0.73  | 4.38      | 2749.11  | 19060            | 1.00+0.56                 |
| 25 | 0.26+0.19 | 0.27+0.26  | 0.27+0.26  | 6.42      | 7375.62  | 64811            | 1.00+0.94                 |
| 29 | 0.93+0.44 | 1.31+0.62  | 1.31+0.62  | 4.48      | 19686.50 | 16968            | 0.99+0.47                 |
| 120 | 0.66+1.00 | 0.92+1.51  | 0.92+1.51  | 3.22      | 5122.80  | 4296             | 1.00+0.65                 |
| 149 | 0.97+0.34 | 1.32+0.47  | 1.32+0.47  | 5.38      | 103367.55 | 91433            | 0.99+0.363                |
| 193 | 0.25+0.25 | 0.34+0.33  | 0.34+0.33  | 5.75      | 47237.02 | 41059            | 1.01+0.98                 |
| 220 | 3.76+1.29 | 5.88+2.01  | 5.88+2.01  | 2.85      | 7443.86  | 6108             | 0.80+0.33                 |
| 237 | 0.63+0.36 | 0.86+0.50  | 0.86+0.50  | 4.70      | 21859.89 | 19021            | 1.06+0.47                 |
| 262 | 0.82+0.47 | 1.15+0.66  | 1.15+0.66  | 4.54      | 10039.91 | 8546             | 1.01+0.57                 |

Notes.

a Centered on the X-ray peak.

b Halo concentration of the best-fit NFW profile given by the mass–concentration relation in Equation (7).

c $\chi^2$ of the best-fit model.

d The number of source galaxies in the weak lensing analysis for each system is given by the degrees of freedom +1.

e The ratio of $M_{200}$ centered on the MMGG to $M_{200}$ centered on the X-ray peak; see Section 5.3.
Guzzo et al. (2007) performed a weak lensing analysis of the massive galaxy group at redshift \( z = 0.73 \) in the COSMOS field with id number 220 in the X-ray group catalog. They reported a very high weak lensing mass of \( 6.3 \times 10^{15} M_{\odot} \) for the dark matter halo, which is in apparent tension with the X-ray mass of \( M_{\text{500}} \approx 1.6 \times 10^{14} M_{\odot} \) derived from their X-ray spectroscopic temperature \( T_X = 3.5 \pm 0.6 \) keV using \( M-T \) relations from the literature.

Our X-ray spectroscopic temperature of \( 4.6^{+1.0}_{-0.7} \) keV is consistent with the X-ray analysis of Guzzo et al. (2007). However, we found a weak lensing \( M_{\text{500}} \) of \( 4.1^{+1.41}_{-1.23} \times 10^{14} M_{\odot} \) (scaled to \( h = 1.0 \) as used by Guzzo et al. 2007). This is more than an order of magnitude lower than the lensing mass of Guzzo et al. (2007), but consistent within errors with the mass predictions from X-ray analyses. This implies that the previously reported high lensing mass is the total mass of the whole superstructure, whereas the lower mass implied by both X-rays and our lensing analysis is the mass of the galaxy group. This argument is further supported by the clustering analysis of groups in the COSMOS field (see Section 5.4 and Allevato et al. 2012). We further note that the exclusion of this source from our sample would not affect our results.

6. M–T SCALING RELATION

We used our center-excised X-ray temperatures and weak lensing group masses in the COSMOS field (Tables 2 and 3) to calibrate the scaling relation between these two quantities. As the systems in our sample have both low mass and temperature, we are probing a largely unexplored region of the mass–temperature plane.

In the self-similar model cluster, group mass and temperature are related by a power law

\[
M \times E(z) = N \times T_X^\alpha,
\]

with slope \( \alpha = 3/2 \) (Kaiser 1986). Here \( E(z) \), defined as

\[
E(z) = \frac{H(z)}{H_0} = \sqrt{\Omega_M(1+z)^3 + \Omega_k},
\]

for flat cosmologies, describes the scaling of overdensity with redshift.

Scaling relations at galaxy group masses are typically derived for \( M_{\text{500}} \) (e.g., Finoguenov et al. 2001; Sun et al. 2009; Eckmiller et al. 2011), i.e., the mass inside the radius where the average density is 500 times the critical density of the universe. We rescaled the lensing masses derived above to this value using the best-fit NFW profiles to enable direct comparison. We assumed the power-law relation given by Equation (8) and linearized it by taking a logarithm

\[
\log_{10} \frac{M_{\text{500}}E(z)}{10^{14}h^{-1}_{70}} = \log_{10} N + \alpha \times \log_{10} \frac{T_X}{3 \text{keV}}.
\]

We evaluated the logarithm of the normalization and the slope of the \( M-T \) relation using the FITEXY linear regression method with bootstrap resampling to compute statistical uncertainties of the fit parameters.

For the COSMOS systems, we obtained the best-fit parameters \( \alpha = 1.71^{+0.57}_{-0.40} \) and \( \log_{10} N = 0.39^{+0.04}_{-0.10} \) with \( \chi^2 = 5.07 \) for 8 degrees of freedom (see Table 4, Figures 7 and 8). However, as

5.5. Massive Galaxy Group at \( z = 0.73 \)

Guzzo et al. (2007) performed a weak lensing analysis of the massive galaxy group at redshift \( z = 0.73 \) in the COSMOS field with id number 220 in the X-ray group catalog. They reported a very high weak lensing mass of \( 6.3 \times 10^{15} M_{\odot} \) for the dark matter halo, which is in apparent tension with the X-ray mass of \( M_{\text{500}} \approx 1.6 \times 10^{14} M_{\odot} \) derived from their X-ray spectroscopic temperature \( T_X = 3.5^{+0.6}_{-0.4} \) keV using \( M-T \) relations from the literature.

Our X-ray spectroscopic temperature of \( 4.6^{+1.0}_{-0.7} \) keV is consistent with the X-ray analysis of Guzzo et al. (2007). However, we found a weak lensing \( M_{\text{500}} \) of \( 4.1^{+1.41}_{-1.23} \times 10^{14} M_{\odot} \) (scaled to \( h = 1.0 \) as used by Guzzo et al. 2007). This is more than an order of magnitude lower than the lensing mass of Guzzo et al. (2007), but consistent within errors with the mass predictions from X-ray analyses. This implies that the previously reported high lensing mass is the total mass of the whole superstructure, whereas the lower mass implied by both X-rays and our lensing analysis is the mass of the galaxy group. This argument is further supported by the clustering analysis of groups in the COSMOS field (see Section 5.4 and Allevato et al. 2012). We further note that the exclusion of this source from our sample would not affect our results.

6. M–T SCALING RELATION

We used our center-excised X-ray temperatures and weak lensing group masses in the COSMOS field (Tables 2 and 3) to calibrate the scaling relation between these two quantities. As the systems in our sample have both low mass and temperature, we are probing a largely unexplored region of the mass–temperature plane.

In the self-similar model cluster, group mass and temperature are related by a power law

\[
M \times E(z) = N \times T_X^\alpha,
\]

with slope \( \alpha = 3/2 \) (Kaiser 1986). Here \( E(z) \), defined as

\[
E(z) = \frac{H(z)}{H_0} = \sqrt{\Omega_M(1+z)^3 + \Omega_k},
\]

for flat cosmologies, describes the scaling of overdensity with redshift.

Scaling relations at galaxy group masses are typically derived for \( M_{\text{500}} \) (e.g., Finoguenov et al. 2001; Sun et al. 2009; Eckmiller et al. 2011), i.e., the mass inside the radius where the average density is 500 times the critical density of the universe. We rescaled the lensing masses derived above to this value using the best-fit NFW profiles to enable direct comparison. We assumed the power-law relation given by Equation (8) and linearized it by taking a logarithm

\[
\log_{10} \frac{M_{\text{500}}E(z)}{10^{14}h^{-1}_{70}} = \log_{10} N + \alpha \times \log_{10} \frac{T_X}{3 \text{keV}}.
\]

We evaluated the logarithm of the normalization and the slope of the \( M-T \) relation using the FITEXY linear regression method with bootstrap resampling to compute statistical uncertainties of the fit parameters.

For the COSMOS systems, we obtained the best-fit parameters \( \alpha = 1.71^{+0.57}_{-0.40} \) and \( \log_{10} N = 0.39^{+0.04}_{-0.10} \) with \( \chi^2 = 5.07 \) for 8 degrees of freedom (see Table 4, Figures 7 and 8). However, as
all our systems have low masses and large errors, the constraint on the scaling relation suffers from rather large uncertainties.

We therefore extended our sample with additional measurements at higher temperatures/masses. Hoekstra et al. (2011) determined weak lensing masses for a sample of 25 moderate X-ray luminosity clusters drawn from the 160 square degree survey (160SD; Vikhlinin et al. 1998; Mullis et al. 2003) using HST ACS observations. Unfortunately, X-ray temperatures are available for only five systems, which we use here. To extend the mass range further, we also include measurements for 50 massive clusters that were studied as part of the Canadian Cluster Comparison Project (CCCP). The lensing masses, based on deep CFHT imaging data, are presented in Hoekstra et al. (2012), whereas the X-ray temperatures are taken from Mahdavi et al. (2013). The X-ray temperatures in Mahdavi et al. (2013) are obtained with both Chandra and XMM-Newton, but the Chandra temperatures are adjusted to match the XMM-Newton calibration.

This gives us a total sample of 65 systems with masses and temperatures spanning the range of a few times $10^{13}$ to a few times $10^{15} M_{\odot}$ and 1–12 keV. Fitting the $M_{500}$–$T_X$ relation to the whole extended sample, we obtained the best-fit parameters $\alpha = 1.48^{+0.13}_{-0.09}$ and $\log_{10} N = 0.34^{+0.02}_{-0.04}$ with $\chi^2 = 112.57$ for 63 degrees of freedom (see Table 4, Figures 7 and 8).

We evaluated the intrinsic scatter of the relation by making a distribution of the ratio of data to the best-fit model for each point and computing the dispersion. The resulting scatter in mass at fixed $T$ for the relation fitted to COSMOS data points and to the full sample are consistent, 28% ±13% and 28% ±

### Table 4

| Sample | Slope ($\alpha$) | Normalization ($\log_{10} N$) | Intrinsic Scatter (%) | $\chi^2$ | Degrees of Freedom |
|--------|------------------|-------------------------------|-----------------------|---------|-------------------|
| COSMOS | $1.70^{+0.57}_{-0.40}$ | $0.39^{+0.04}_{-0.10}$ | 28 ± 13 | 5.07 | 8 |
| COSMOS+CCCP+160SD | $1.48^{+0.13}_{-0.09}$ | $0.34^{+0.02}_{-0.04}$ | 28 ± 7 | 112.57 | 63 |
| COSMOS+CCCP+160SD, modified $T_X$ | $1.40^{+0.12}_{-0.10}$ | $0.32^{+0.02}_{-0.03}$ | 35 ± 9 | 117.99 | 63 |

7% respectively, indicating that the samples are consistent with each other.

### 7. DISCUSSION

The slope of our best-fit relation of the full sample $1.48^{+0.13}_{-0.09}$ is consistent with the self-similar prediction of $3/2$ (Kaiser 1986). Unfortunately, direct comparison of our best-fit relation to most other weak lensing calibrated $M$$-$$T$ relations is not possible. Okabe et al. (2010) calibrated deprojected center-excised temperatures (whereas our temperatures are projected) to $M_{500}$ for the LoCuSS cluster sample, consisting of only cluster mass systems, and attained a slope of $1.49 \pm 0.58$. Hoekstra et al. (2007) and Jee et al. (2011) calibrated X-ray temperatures to weak lensing $M_{2500}$ for cluster mass systems and attained slopes of $1.34^{+0.30}_{-0.28}$ and $1.54 \pm 0.23$, respectively. As their mass definition differs from ours and masses are thus derived from a smaller region, their relations are not directly comparable to our analysis. In the case of Jee et al. (2011), the clusters are also at a significantly higher redshift than our sample, representing a cluster population at an earlier evolutionary stage.

However, Mahdavi et al. (2013) used the 50 CCCP clusters, which are also included in our sample, to fit scaling relations between X-ray observables and lensing masses. For $M_{500}$–$T_X$ scaling, they obtained a slope of $1.97 \pm 0.89$ and $1.42 \pm 0.19$ with a scatter in mass of 46% ± 23% and 17 ± 8 using $R_{500}$ derived from weak lensing and X-ray analysis, respectively. Both of these are consistent within the error bars with our findings.

The fact that the published lensing-calibrated $M$$-$$T$ relations at cluster masses and our group mass predict consistent slopes indicates that both clusters and groups follow the same mass-to-temperature scaling. This is in apparent tension with relations...
relying on HSE mass estimates, which generally predict steeper slopes and lower normalization when group mass systems are included (see Figure 9). For example, Finoguenov et al. (2001) used ASCA observations of the extended HIFLUGCS sample consisting of 88 systems spanning a similar mass and temperature range as our full sample and obtained a slope of 1.636 ± 0.044 for the $M_{500}$–$T_X$ relation, Sun et al. (2009) calibrated a similar relation to archival Chandra observations of 43 groups and 14 clusters and obtained a slope of 1.65 ± 0.04, and Eckmiller et al. (2011) obtained a slope of 1.75 ± 0.06 for a sample consisting of 112 groups and HIFLUGCS clusters. However, Vikhlinin et al. (2009) used a sample of clusters with $T_X \gtrsim 2.5$ keV to calibrate a $M_{500}$–$T_X$ relation under the assumption of HSE and obtained a slope of 1.53 ± 0.08, consistent with our weak lensing relations.

The difference in slope between hydrostatic and our weak lensing calibrated $M$–$T$ relation is significant at $\sim 1\sigma$–$2\sigma$ level (see Figure 10). The steeper slope and lower normalization of HSE relations amounts to a temperature-dependent bias between the scaling relations at an up to $\sim 2\sigma$ significance (see Figure 9, lower panel).

Simulations indicate that HSE masses may be biased low due to non-thermal pressure support and kinetic pressure from gas motion (e.g., Nagai et al. 2007; Shaw et al. 2010; Rasia et al. 2012). Furthermore, the deviation from self-similarity in the $M$–$T$ relation implied by HSE mass estimates is hard to reproduce in simulations (Borgani et al. 2004). Thus the preferred interpretation is a deviation between hydrostatic and lensing masses, amounting to $\sim 30$%–50% at 1 keV. Our study provides the first observational support for this scenario at group scales. This effect has previously been observed at cluster masses by Mahdavi et al. (2008, 2013).

The effect of deviation between hydrostatic and lensing masses on scaling relations has previously been studied by Nagai et al. (2007). They simulated a sample of groups and clusters in a mass range approximately consistent with our extended sample, including effects of cooling and star formation. The simulated clusters were used for mock Chandra observations to calibrate $M_{500}$–$T_X$ relation using both true masses and masses derived under the HSE condition. Their best-fit relation using true masses is consistent with our lensing relation, whereas their hydrostatic relation very accurately follows the observed hydrostatic relation of Sun et al. (2009); see Figures 9 and 10. This provides further evidence that a bias in hydrostatic masses can affect the shape of scaling relations.

7.1. X-Ray Cross-calibration

Cross-calibration issues in the energy dependence of the effective area of X-ray detectors affects cluster spectroscopic temperatures obtained with different instruments (e.g., Snowden et al. 2008; Nevalainen et al. 2010; Kettula et al. 2013; Mahdavi et al. 2013). Recent observations indicate cluster temperatures measured with Chandra are typically $\sim 15$% higher than those measured with XMM-Newton (Nevalainen et al. 2010; Mahdavi et al. 2013). As we compare our lensing-calibrated $M$–$T$ relation relying on XMM-Newton temperature measurements (or Chandra temperatures modified to match XMM-Newton) to Chandra-based relations in literature, we investigate here if the detected discrepancies can be attributed to X-ray cross-calibration uncertainties.

Whereas cluster temperatures $\gtrsim 4$ keV are typically inferred from the shape of the bremsstrahlung continuum, which depends strongly on the energy dependence of the effective area, lower group temperatures are mainly determined from emission lines and are thus independent of energy-dependent cross-calibration. This effect is seen in comparisons of group and cluster temperatures obtained with XMM-Newton and Chandra (Snowden et al. 2008). As the measured energy of a photon at the detector also depends on the redshift of the source, we use the temperature- and redshift-dependent modification given by

$$T_X^{\text{modified}} = T_X^{\text{XMM}} \times \left(1 + \frac{0.15 T_X^{\text{XMM}}}{10 \text{keV}} \left(\frac{1}{1+z}\right)\right)$$

(11)

to modify our XMM-Newton-based temperatures to match the Chandra calibration (see Figure 11).
and XMM-Newton have slopes consistent with self-similarity for both Chandra calibration uncertainties and that lensing-calibrated relations

\( M \) systems spanning a wide mass and temperature range of 50 clusters from the CCCP survey. This gave a sample of groups in the COSMOS field, 5 clusters from the 160SD survey, lensing. We conclude that the differences between HSE and find that HSE still predicts lower masses at group scales than

Comparing this result with HSE relations from the literature, we extend the statistical analysis of this work.

We calibrated a scaling relation between weak lensing masses and spectroscopic X-ray temperatures for a sample of 10 galaxy groups in the COSMOS field, 5 clusters from the 160SD survey, and 50 clusters from the CCCP survey. This gave a sample of 65 systems spanning a wide mass and temperature range of \( M_{500} \sim 10^{13}–10^{15} \, M_\odot \) and \( T_X \sim 1–12 \, \text{keV} \) extending weak lensing calibrated \( M–T \) relations to an unexplored region of the mass–temperature plane.

We found that the best-fit slope of the relation is consistent with the prediction for self-similar cluster evolution of Kaiser (1986). This is in apparent tension with HSE relations at group scales in literature, which use X-ray masses derived under HSE. These relations typically predict steeper slopes and lower normalizations.

The deviations from self-similarity implied by HSE relations are likely due to HSE masses being biased low in comparison to unbiased lensing masses. We find that the bias increases with decreasing temperature, amounting to \( \sim 30\%–50\% \) at 1 keV. This effect has been detected in simulations and our study provides the first observational evidence for it at group scales. We also show that this effect is not a product of cross-calibration issues between X-ray detectors.

We conclude that this work demonstrates the importance of unbiased weak lensing calibrated scaling relations for precision cosmology with galaxy clusters and groups. Although costly, more weak lensing surveys of galaxy groups are needed to extend the statistical analysis of this work.

8. SUMMARY AND CONCLUSIONS

We calibrated a scaling relation between weak lensing masses and XMM-Newton-based temperatures for a sample of 10 galaxy groups in the COSMOS field, 5 clusters from the 160SD survey, and 50 clusters from the CCCP survey. This gave a sample of 65 systems spanning a wide mass and temperature range of \( M_{500} \sim 10^{13}–10^{15} \, M_\odot \) and \( T_X \sim 1–12 \, \text{keV} \) extending weak lensing calibrated \( M–T \) relations to an unexplored region of the mass–temperature plane.

We found that the best-fit slope of the relation is consistent with the prediction for self-similar cluster evolution of Kaiser (1986). This is in apparent tension with HSE relations at group scales in literature, which use X-ray masses derived under HSE. These relations typically predict steeper slopes and lower normalizations.

The deviations from self-similarity implied by HSE relations are likely due to HSE masses being biased low in comparison to unbiased lensing masses. We find that the bias increases with decreasing temperature, amounting to \( \sim 30\%–50\% \) at 1 keV. This effect has been detected in simulations and our study provides the first observational evidence for it at group scales. We also show that this effect is not a product of cross-calibration issues between X-ray detectors.

We conclude that this work demonstrates the importance of unbiased weak lensing calibrated scaling relations for precision cosmology with galaxy clusters and groups. Although costly, more weak lensing surveys of galaxy groups are needed to extend the statistical analysis of this work.
