CALIBRATION OF THE MASS–TEMPERATURE RELATION FOR CLUSTERS OF GALAXIES USING WEAK
GRAVITATIONAL LENSING

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ABSTRACT

The main uncertainty in current determinations of the power spectrum normalization, \( \sigma_8 \), from abundances of X-ray luminous galaxy clusters arises from the calibration of the mass–temperature relation. We use our weak lensing mass determinations of 30 clusters from the hitherto largest sample of clusters with lensing masses, combined with X-ray temperature data from the literature, to calibrate the normalization of this relation at a temperature of 8 keV, \( M_{\text{keV}} = (0.78 \pm 0.14) h^{-1} 10^{15} M_\odot \), at \( z \approx 0.23 \). This normalization is consistent with previous lensing-based results based on smaller cluster samples, and with some predictions from numerical simulations, but higher than most normalizations based on X-ray derived cluster masses. Assuming the theoretically expected slope \( \alpha = 3/2 \) of the mass–temperature relation, we derive \( \sigma_8 = 0.88 \pm 0.09 \) for a spatially-flat ΛCDM universe with \( \Omega_m = 0.3 \). There is significant intrinsic scatter in the mass–temperature relation indicating that this relation may not be very tight, at least at the high mass end. Furthermore, we find that for a given mass dynamically non-relaxed clusters are 75 ± 40% hotter than relaxed clusters.

Subject headings: Cosmology: observations — cosmological parameters — dark matter — gravitational lensing — Galaxies: clusters

1. INTRODUCTION

The abundance of massive clusters of galaxies provides sensitive constraints on the cosmological parameters that govern structure growth in the universe. However, these studies require reliable mass measurements for large samples of clusters with well-understood selection criteria. Cluster mass measurements used for such studies have traditionally come from virial analysis of the velocity dispersion measurements of cluster galaxies (e.g., Frenk et al. 1990; Carlberg et al. 1997; Borgani et al. 2009), or X-ray temperature measurements of the hot intra-cluster gas under the assumption that the gas is in hydrostatic equilibrium (for a review see Rosati, Borgani & Norman 2002). Satellite observatories such as ROSAT, ASCA, XMM-Newton and Chandra have made increasingly accurate X-ray temperature measurements of clusters, and have produced well-defined cluster samples of sufficient size to accurately measure the X-ray temperature and luminosity functions (e.g. Henry 2004; Böhringer et al. 2002). However, the relation between cluster mass and X-ray temperature and luminosity, respectively, must be determined to convert these into a reliable cluster mass function.

X-ray luminosities are available for large samples of clusters, but the X-ray luminosity is highly sensitive to the complex physics of cluster cores, making it challenging to relate to cluster mass. Measuring X-ray temperatures is observationally much more demanding, but the X-ray temperature is mainly determined by gravitational processes and is hence more directly related to cluster mass than X-ray luminosity. Both from simulations and observations the intrinsic scatter in mass around the mass–temperature relation is thus found to be much smaller (\( \Delta M/M \approx 0.15 \), Evrard, Metzler & Navarro 1996; Borgani et al. 2004; Sanderson et al. 2003; Vikhlinin et al. 2005) than the scatter in mass around the mass–luminosity relation (\( \Delta M/M \approx 0.4 \), Reiprich & Böhringer 2002).

Two different routes have been followed for determining the mass–temperature relation. Most studies have used a small sample (up to about a dozen) of supposedly well understood clusters for which the assumptions underlying the mass determination should be fulfilled to a high degree. The main concern for this approach is that the selected clusters may not be representative of the whole cluster population, and therefore the derived mass–temperature relation may only apply to a subset of clusters. Alternatively, the mass–temperature relation may be determined from a large sample of more objectively selected clusters. This is more fruitful when comparing such a locally determined mass–temperature relation to a sample of high-redshift clusters where the data quality does not allow a similar selection of the “most suitable” clusters. Also, mass–temperature relations derived from simulations are usually based on a large range of simulated clusters with no pre-selection. Hence it is most appropriate to compare observationally obtained mass–temperature relations determined from all available clusters to the relations from simulations. On the other hand, for some of the clusters in such a sample the hydrostatic assumption may be invalid, making X-ray based mass determinations unreliable for a subset of the clusters. A larger scatter (which may not be symmetric) around the mean mass–temperature relation may be expected, when such clusters are included.

There are still poorly understood systematic uncertainties associated with establishing the mass–temperature relation. The normalization of the mass–temperature relation based on cluster masses determined from X-ray data (Finoguenov, Reiprich, & Böhringer 2001; Vikhlinin et al.)
tend to differ significantly between studies, and from the expectations based on numerical simulations (e.g., Evrard et al. 1996; Eke et al. 1998; Pen 1998; Borgani et al. 2004). The determination of this normalization, \( T_\text{s} \) (see eq. 3), is currently the dominating source of discrepancies between the reported values for the power spectrum normalization on the scale of galaxy clusters, \( \sigma_8 \), derived from the observed cluster temperature function (Huterer & White 2002; Seljak 2002; Pierpaoli et al. 2003; Henry 2004). Observations using X-ray based mass determinations have traditionally favored high values of \( T_\text{s} \) (and hence low values of \( \sigma_8 \)), while simulations have favored somewhat lower values of \( T_\text{s} \).

Gravitational lensing provides an opportunity to measure cluster masses without invoking the assumption of hydrostatic equilibrium in the hot intra-cluster gas implicit in the X-ray based mass determinations. Also, in this case the measurement of cluster mass is truly independent of the X-ray temperature measurement. Hjorth, Oukbir & van Kampen (1998) used weak gravitational mass measurements for eight clusters drawn from the literature to find a relation between mass over cluster-centric radius and temperature. They determined a normalization of this relation consistent with the values predicted by Evrard et al. (1996), but with a preference for somewhat higher cluster masses, if the redshift scaling of equation 3 is assumed. However, Smith et al. (2005; hereafter S05) determined a mass–temperature relation with a normalization significantly lower than indicated by the Hjorth et al. (1998) study. S05 based their results on a sample of 10 clusters with weak lensing masses and temperatures determined from Chandra data.

Here, we present a new weak gravitational lensing-based measurement of the normalization of the mass–temperature relation. The main improvements with respect to the work of Hjorth et al. (1998) and S05 is that we use a significantly larger cluster sample which represents a significant fraction of all the clusters in an even larger sample with well-defined objective selection criteria (Dahle et al. 2002; H. Dahle 2006, in preparation). An additional improvement over the work of Hjorth et al. (1998) is that the weak lensing analysis has been performed in a consistent way for all clusters, using the same shear estimator and making the same assumptions about e.g., the typical redshift of the lensed galaxy population and the degree of contamination by cluster galaxies. We note that the early data set of clusters with published weak lensing masses used by Hjorth et al. (1998) is biased at some level towards systems that were observed because of “extreme” properties, such as being the hottest or most X-ray luminous system known at the time, or having a large number of strongly gravitationally lensed arcs. Furthermore, we note that our gravitational lensing measurements are made at larger radii than probed by S05, requiring smaller extrapolations to estimate the mass within e.g., the virial radii of the clusters.

The data set used for the analysis is described in § 2. Our results for the mass–temperature relation and \( \sigma_8 \) are presented in § 3 and our results are compared to other work and the implications discussed in § 4.

Except when specifically noted otherwise (for easy comparison to previous results using different cosmologies), we assume a spatially–flat cosmology with a cosmological constant \((\Omega_m = 0.3, \Omega_{\Lambda} = 0.7)\), and the Hubble parameter is given by \( H_0 = 100h \text{ km s}^{-1} \text{Mpc}^{-1} \).
Calibration of mass–temperature relation

NFW-type mass density profile,

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

(Navarro, Frenk, & White 1997), to the observed reduced shear profile \(g_T(r)\) of each cluster. Here, \(\rho_c(z)\) is the critical density of the universe at the redshift of the cluster, and

$$\delta_c = \frac{200}{3} \left\ln \left(1 + c_{200} \right) - \frac{c_{200}^3}{1 + c_{200}} \right\right.$$  \hspace{1cm} (2)

We assumed a concentration parameter \(c_{200} = c_{vir}/1.194 = 4.9/(1 + z)\), corresponding to the median halo concentration predicted by Bullock et al. (2001) for a \(M_{vir} \sim 8 \times 10^{14} M_\odot\) cluster from simulations of dark matter halos in a \(\Lambda CDM\) universe. Here, \(c_{200} = r_{200} / r_s\), and \(c_{vir} = r_{vir} / r_s\), where \(r_{200}\) is defined as the radius within which the average mass density is 200 times the critical density \(\rho_c(z)\), and \(r_{vir}\) is the virial radius of the cluster.

The lensing properties of the NFW model have been calculated by Bartelmann (1996) and Wright & Brainerd (2000). From our fit, we calculated \(M_{500}\), the mass enclosed by the radius \(r_{500}\). The mass estimates are listed in Table 1. The shear measurements used for the fit were made at clustercentric radii 50'' < \(r < 180''\) for the clusters that were observed with 2048^2 CCD cameras and 150'' < \(r < 550''\) for the clusters that were observed with the UH8K camera. By comparison, we find \(r_{500}\) values typically in the range 300'' < \(r_{500} < 600''\) for the clusters we study here. Since we extrapolate an NFW profile, assuming the median concentration parameter given above, any intrinsic scatter in \(c_{vir}\) will introduce an extra uncertainty in the cluster mass estimates. However, we find that the level of scatter predicted by Bullock et al. (2001) (a 1σ \(\Delta (\log c_{vir}) \sim 0.18\) gives a negligible contribution to the overall error budget for the cluster masses.

The measured gravitational lensing signal is sensitive to the two-dimensional surface mass distribution, including mass associated with the cluster outside \(r_{500}\), and random structures seen in projection along the line of sight (Metzler, White & Loken 2001; Hoekstra 2001; Clowe, De Lucia & King 2004; de Putter & White 2005). This will introduce additional uncertainty (and potentially a net bias) to any lensing-based estimates of the cluster mass contained within a 3D volume. Studies based on simulated clusters (e.g., Clowe et al. 2004) indicate that the net bias is no more than a few percent when 3D cluster masses are estimated by fitting observations of \(g_T(r)\) to predictions from theoretical models of the mass distribution, such as the NFW model. However, the scatter in the mass estimates from projection effects amount to a weak lensing mass dispersion of \(\sim 15 - 25\%\) for massive galaxy clusters, which should be added to the observational uncertainties of the lensing mass estimates. In this paper, we have assumed a lensing mass dispersion of 0.26 resulting from projection effects, corresponding to the value estimated by Metzler, White & Loken (2001) from their N-body simulations. Although these authors considered a somewhat different mass estimator, more recent estimates indicate a similar mass dispersion for the NFW profile fitting method that we have used.

The absence of reliable information about the individual redshifts of the faint galaxies used for the weak lensing measurement will inevitably result in some degree of confusion between lensed background galaxies and unlensed cluster galaxies. The magnitude of this effect will depend on the projected number density of cluster galaxies, and should thus have a strong dependency on cluster radius. Hence, a radially dependent correction factor was applied to the shear measurements to correct for contamination from cluster galaxies in the faint galaxy catalogs that were used to measure the gravitational shear (these catalogs included all galaxies in the cluster fields that were detected at a signal-to-noise ratio \(6 < S/N < 100\), with no additional selection based on e.g., galaxy color). The magnitude of this correction was estimated from the radial dependence of the average faint galaxy density in two “stacks” of clusters observed with the UH8K camera, one at \(z \sim 0.3\) and the other at \(z \sim 0.2\), assuming that the contamination is negligible at the edge of the UH8K fields, \(> 1.5 h^{-1}\) Mpc from the cluster center. The estimated degree of contamination is shown in Figure 1.

Eight of the clusters in our sample were also included in the combined strong and weak gravitational lensing study of S05, based on observations of a sample of 10 X-ray luminous galaxy clusters at \(z \sim 0.2\) using the Hubble Space Telescope. These authors estimated the projected cluster mass within a clustercentric radius of 250\(h^{-1}\) kpc, assuming an Einstein-de Sitter (\(\Omega_m = 1, \Omega_{\Lambda} = 0\)) cosmology. Figure 2 shows a comparison of the mass values listed by S05 with our cluster mass estimates, using the best-fit NFW model to derive projected cluster masses, assuming the same cosmology as S05. These authors assumed a spatially constant contamination of 20% cluster galaxies in their background galaxy catalogs at radii < 2', while we find an average contamination of 30% for our data at these radii. Hence, for the plot in Figure 2 we have adjusted our radially dependent contamination correction such that the average contamination at small radii is consistent with that assumed by S05. We find that our cluster mass estimates are generally consistent with those of S05, although with a tendency for slightly higher masses.

2.2. X-ray data

For clusters in the weak lensing data set, we compiled a list of corresponding X-ray temperatures from the literature. For many of these clusters, their global temperature, or even a temperature map, has been determined using data from Chandra and/or XMM-Newton. However, these temperatures constitute a rather heterogeneous sample, for which the systematics are not well established. Consequently, X-ray temperatures were primarily drawn from the samples of Ota & Mitsuda (2004), Allen (2000) and White (2000), each
providing a homogeneous measure of the global cluster temperature (i.e., temperature measured within a cluster-centric radius close to \( r_{500c} \)) for a major fraction of the clusters in the weak lensing sample. All these authors derived temperatures based on analysis of ASCA spectra. For two clusters not in either of the samples mentioned above we extracted published temperatures from other sources.

Specifically, from the works of Ota & Mitsuda (2004) and Allen (2000) we extracted temperatures estimated by these authors by fitting an isothermal plasma model with the Galactic absorbing column density as a free parameter to ASCA spectra. The temperatures taken from White (2000) were derived by fitting an isothermal plasma model with the nominal Galactic absorbing column density fixed, but since only energies above 1 keV are used in the White (2000) spectral fitting the fixed column density should not introduce systematic effects relative to the temperatures from the Ota & Mitsuda (2004) and the Allen (2000) samples. For the remaining two clusters we extracted published temperatures obtained in a similar way (see Table 1).

For the clusters in two or more samples, their derived temperatures agree within the uncertainties, and for any cluster the derived temperatures differ by less than 20% between samples. Also, the mean of temperature differences between any two of the samples by Ota & Mitsuda (2004), Allen (2000), and White (2000) is less than 3%, indicating the low level of systematic temperature variance between different analyses.

Although the isothermal plasma model has proven too simplistic for nearby clusters, the global cluster temperature is straightforward to derive from observations as well as simulations, enabling a rather direct comparison between observations and theory. Furthermore, for the majority of distant \((z \gtrsim 0.5)\) clusters only global isothermal temperatures can be obtained in the foreseeable future. Hence, we refrain from going into the detailed spatial and spectral modeling of the intracluster gas. The effects of cluster dynamics, “cooling cores”, non-sphericity etc. generally affect the global temperatures only at the 10%-20% level (e.g., Evrard, Metzler, & Navarro 1996; White 2000; Smith et al. 2005).

3. RESULTS

The mass–temperature relation expected from simple theoretical arguments for a self-similar cluster population with sub-dominant non-gravitational forces is

\[
\frac{M_{\text{vir}}(T, z)}{10^{15}h^{-1}M_\odot} = \left( \frac{T}{T_\ast} \right)^{3/2} \left( \frac{\Delta_c E^2}{\Omega_\Lambda(z)} \right)^{-1/2} \left[ 1 - 2 \frac{\Omega_\Lambda(z)}{\Delta_c} \right]^{-3/2},
\]

where \(\Delta_c\) is the mean overdensity inside the virial radius in units of the critical density at the relevant redshift and \(E^2 = \Omega_m(1 + z)^3 + \Omega_\Lambda + \Omega_d(1 + z)^2\). Using the fitting formula of Pierpaoli et al. (2001), we find that the value of \(\Delta_c\) ranges from 113 (at the low-redshift end of our sample) to 124 for the clusters listed in Table 1. The redshift-dependent quantities contained in eq. 3 must be calculated individually for each cluster, as they would otherwise produce an artificial 10% variation in \(T_\ast\) over the redshift range spanned by our cluster sample.

We obtained mass–temperature relations by fitting the data in Table 1 using the BCES\((X_2|X_1)\) estimator of Akritas & Bershady (1996) to the following parameterization of the mass–temperature relation,

\[
\log \left( \frac{M_{\text{vir}}}{A \times 10^{15}h^{-1}M_\odot} \right) = \alpha \log \left( \frac{kT}{8\text{keV}} \right) + \log M_0,\]

where \(A\) equals the product of the last two terms in eq. 3 and the slope is left as a free parameter, rather than being fixed at the theoretically expected value \(\alpha = 3/2\). The procedure of Akritas & Bershady (1996) takes uncertainties in temperatures as well as in weak lensing masses into account, and makes no assumptions about the intrinsic scatter of both quantities. Results from fitting sub-samples as well as the full sample are presented in Table 2 and Figure 3.

For the full data set (for those clusters with temperature from more than one sample the temperature was taken in prioritized order from Ota & Mitsuda (2004), Allen (2000), and White (2000)) we find the following normalization of the mass–temperature relation at 8 keV, at the mean redshift of
our cluster sample:

\[ M_{500c} = M_{\text{skel}}(z) \times 10^{15} h^{-1} M_\odot \left( \frac{kT}{8 \text{ keV}} \right)^\alpha, \]  
(5)

with \( \alpha = 0.49 \pm 0.80 \) and \( M_{\text{skel}}(z = 0.23) = M_0 A(z = 0.23) = 0.78 \pm 0.14 \). It is evident that the slope of the mass–temperature relation is not well-determined since our data only span a modest range at the high mass/high temperature end of the cluster distribution. In fact, it is not obvious that there is a tight mass–temperature relation at the high temperature end probed here.

### 3.1. Normalization of the mass–temperature relation and \( \sigma_8 \)

The concentration of clusters around \( \sim 8 \) keV enables a robust measurement of the normalization of the mass–temperature relation at the high–mass end. Even though the slope of the mass–temperature relation varies substantially between the three sub-samples the normalizations agree within their statistical uncertainty. We note that for all fits, the four different regressions of \( \text{Akritas & Bershady} \ 1996 \) all result in normalizations within 20%.

In order to obtain the strongest constraints on the mass–temperature relation normalization we take advantage of previous studies of massive clusters \( \text{Finoguenov, Reiprich, & Böhringer} \ 2001 \), \( \text{Allen, Schmidt, & Fabian} \ 2001 \), \( \text{Arnaud, Pointecouteau, & Pratt} \ 2005 \), showing that the mass–temperature relation slope is close to \( \alpha = 3/2 \) as expected from simple gravitational collapse models \( \text{Kaiser} \ 1986 \).

If we assume \( \alpha = 3/2 \) with a representative uncertainty of 10% (e.g. \( \text{Finoguenov, Reiprich, & Böhringer} \ 2001 \)), and take \( M_{\text{crit}} = 1.65 M_{500c} \) (which is the appropriate relation at the average cluster redshift for our chosen NFW model), we find \( T_* = 1.28 \pm 0.20 \) for the full sample. Results for similar calculations of \( T_* \) based on various subsamples are listed in Table 1. From the \( \sigma_8 - T_* \) relation plotted by \( \text{Pierpaoli, Borgani, Scott, & White} \ 2003 \) in their Figure 2, we find \( \sigma_8 = 0.88 \pm 0.09 \), based on our full sample. We note that this relation is valid only for an intrinsic scatter in temperature of \( \lesssim 10\% \) around the mean mass–temperature relation. A larger intrinsic scatter will imply a lower value of \( \sigma_8 \). We provide our constraints on the intrinsic scatter below.

### 3.2. Scatter in the mass–temperature relation

The squared scatter in lensing mass, \( M_{500c} \), around the best fit is the sum of the squared measurement error and the squared intrinsic scatter \( (\sigma_M^{\text{err}})^2 = (\sigma_M^{\text{err}})^2 + (\sigma_M)^2 \), and we find
$\sigma^\text{tot}_M = 0.94$. This is larger than the mean lensing mass error, $\sigma^\text{err}_M = 0.52$, indicating either a sizable intrinsic scatter in mass or that the measurement errors are under-estimated.

Accounting for errors in both mass and temperature, we find an intrinsic scatter in $T_\star$ of $0.3^{+0.20}_{-0.30}$. There is a 77% probability that the scatter in temperature is larger than 10%, favoring somewhat lower values of $\sigma_8$ than quoted above. However, most of the scatter is caused by the low mass clusters.

3.3. Relaxed vs. non-relaxed clusters

We looked into whether relaxed clusters and non-relaxed clusters have the same normalization of the mass–temperature relation. Our “relaxed” cluster sample consists of A586, A963, A1835, A1995, A2204, A2261, RXJ1720, and RXJ1532. These are clusters with “spherical” optical and X-ray morphology, and no known cluster-scale dynamic disturbances. For the relaxed clusters we find a normalization of the mass–temperature relation of $M_\text{8keV,relax} = 1.56 \pm 0.32$ while the normalization for the non-relaxed clusters is $M_\text{8keV,nonrelax} = 0.68 \pm 0.12$ (see Figure 4). The higher normalization of relaxed clusters is supported by the fact that the mean mass of relaxed clusters is a factor 1.5 larger than the mean mass of “non-relaxed” clusters, although the relaxed and the non-relaxed clusters span roughly the same temperature range.

The scatter in mass for the relaxed sample ($\sigma^\text{tot}_M = 0.77$) is similar to the scatter for the non-relaxed sample ($\sigma^\text{err}_M = 0.88$). The mean error for both samples is $\sigma^\text{err}_M = 0.57$. Either relaxed clusters spread as much around their mass–temperature relation as clusters in general, or we have used a poor definition of “relaxed” clusters. However, the fact that the normalization of the mass–temperature relation for relaxed clusters is significantly higher than for non-relaxed clusters indicates that there is a physical difference between the two sub-samples. From the present study, it thus seems that relaxed clusters do not form a tighter mass–temperature relation than clusters in general.

For a given mass, non-relaxed clusters are found to be $\sim 75 \pm 40\%$ hotter than relaxed clusters. Since we consider global, isothermal temperatures, the presence of “cooling cores” in relaxed clusters will result in a lower global temperature than the virial temperature. However, this effect is at the 10%-20% level (e.g., Smith et al. 2003a) so this cannot alone explain the temperature difference between relaxed and non-relaxed clusters. Based on the mass–temperature relation from 10 clusters (3 of which are considered relaxed), S05 also find that non-relaxed clusters are hotter than relaxed clusters. An objective classification of the degree of relaxation for a sizeable cluster sample is required for further quantifying the size of this effect.

4. DISCUSSION

Based on the hitherto largest sample of X-ray luminous clusters with derived lensing masses, we present a normalization of the mass–temperature relation at the high mass end, $M_\text{8keV} = (0.78 \pm 0.14) h^{-1} 10^{15} M_\odot$. This value is higher than the lensing based mass–temperature normalization of S05, based on a smaller cluster sample, but is consistent with this within 1$\sigma$ errors; see Table 2. Mass–temperature relations with masses determined from X-ray data tend to have a lower normalization than lensing based relations, and they are only marginally consistent with our normalization. This is also the case for the two recent studies of Vikhlinin et al. (2005) and Arnaud, Pointecouteau, & Pratt (2005) based on smaller samples of lower mass (and hence cooler) clusters. Vikhlinin et al. (2005) measured cluster masses inside $r_{500}$ from X-ray observations of a sample of 13 low redshift clusters with a median temperature of 5.0 keV while Arnaud, Pointecouteau, & Pratt (2005) determined the normalization from X-ray derived masses of 10 nearby clusters with a mean temperature of 4.8 keV. The two studies agree on the same normalization, higher than previous X-ray mass.
based studies, but there still seems to be a ≈ 20% discrepancy between X-ray and lensing derived mass–temperature relations.

We note, however, that the lensing based and X-ray based normalizations are made at different redshifts, and that this discrepancy would vanish if the redshift-dependence predicted by the self-similar collapse model in equation 5 were neglected. Given the heterogeneous nature of these data sets, any claim of significant departures from self-similarity would be premature, but this clearly provides an interesting avenue for future research, involving even larger cluster samples spanning a wider interval in redshift.

We confirm the result of Smith et al. (2005) that non-relaxed clusters are on average significantly hotter than relaxed clusters. This is qualitatively consistent with N-body/hydrodynamical cluster simulations which show that major mergers can temporarily boost the X-ray luminosities and temperatures well above their equilibrium values (e.g. [Randall et al. 2002]).

In contrast to several previous (mainly X-ray mass based) published mass–temperature relations, the normalization derived in this study is in good agreement with the normalization derived from numerical simulations. However, the accuracy of the normalization is not good enough to discriminate between simulations including different physical processes.

Our results show that X-ray based measurements of the cluster abundances, after reducing the major systematic uncertainties associated with the mass–temperature normalization, give an amplitude of mass fluctuations on cluster scales that is consistent with other methods. This lends additional support to the “concordance model” cosmology, and lends credence to the basic assumptions of Gaussian density fluctuations. Our determination of \( \sigma_8 = 0.88 \pm 0.09 \) is higher than most of the recent \( \sigma_8 \) determinations from cluster data (for a compilation of these, see e.g., [Henry 2004]). However, our finding is consistent with the value derived from weak gravitational lensing in the combined Deep and Wide CFHT Legacy Survey (\( \sigma_8 = 0.86 \pm 0.05 \); Semboloni et al. 2005) based on the halo model of density fluctuations (Smith et al. 2003b). It is also consistent with the CMB+2dFGRS+Ly_α forest result (\( \sigma_8 = 0.84 \pm 0.04 \)) of Spergel et al. (2003), with the joint CMB + weak lensing analysis of Contaldi, Hoekstra, & Lewis (2003), which gave \( \sigma_8 = 0.89 \pm 0.05 \), and with recent CMB analyses ([Bond et al. 2005]) yielding \( \sigma_8 = 0.9 \). Hence, there is now good agreement between a wide variety of methods to determine \( \sigma_8 \). We caution, however, that our quoted value of \( \sigma_8 \) is based on the assumption that the intrinsic scatter about the mass–temperature relation is \( \lesssim 10\% \), and that our \( \sigma_8 \) estimate will be biased high if the true scatter significantly exceeds this value ([Pierpaoli, Borgani, Scott, & White 2003]).

The limiting factor of our measurement of the normalization of the mass–temperature relation is the magnitude of the measurement errors. In order for the mass–temperature relation to be a competitive route for constraining cosmological parameters and to discriminate between simulations with different input physics, the normalization must be measured to better than \( \sim 10\% \) accuracy. However, there are good prospects for improving on these results in the near future. Firstly, the superior spectro-imaging capabilities of Chandra and XMM-Newton will allow the construction of large, homogenous cluster temperature samples. A comparison to tailored simulations with realistic physics, analyzed in the same way as observations, will advance our understanding of systematics and the link between the mass–temperature relation and structure formation (C.B. Hededal et al. 2006, in preparation). Secondly, more accurate weak lensing-based mass measurements of a larger sample of clusters are feasible as large mosaic CCD cameras that can probe intermediate-redshift clusters beyond their virial radii are now common, and the cluster sample could easily be doubled from a similar survey in the Southern celestial hemisphere.

Finally, we note that a more direct measurement of \( \sigma_8 \) from weak lensing by clusters is feasible, provided that weak lensing mass estimates are available for a large, well-defined, volume-limited cluster sample. This makes it feasible to calculate the cluster mass function directly from the lensing masses, rather than indirectly via the X-ray temperature function (Dahle 2006). Since mass estimates based on baryonic tracers of the total cluster mass only enters indirectly as a selection criterion (e.g., clusters selected based on X-ray luminosity above a certain threshold), the method will be less susceptible to systematic and random errors, as it does not require an accurate characterization of the scatter around the mean mass–temperature relation.

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TABLE 4

<table>
<thead>
<tr>
<th>Method</th>
<th>$\langle z \rangle$</th>
<th>$M_{8keV}(z = 0.23)$</th>
<th>Slope</th>
<th>Reference</th>
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<tr>
<td>X-rays</td>
<td>0.09</td>
<td>0.54 ± 0.04</td>
<td>Fitted</td>
<td>Arnaud, Pointecouteau, &amp; Pratt (2005)</td>
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<td></td>
<td>0.09</td>
<td>0.56 ± 0.04</td>
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<tr>
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<td>Fixed</td>
<td>S05</td>
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<td></td>
<td>0.23</td>
<td>0.78 ± 0.14</td>
<td>Fitted</td>
<td>This study</td>
</tr>
<tr>
<td>Simulations</td>
<td>0.04</td>
<td>0.68 ± 0.10</td>
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<td>Evrard, Metzler, &amp; Navarro (1996)</td>
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<td></td>
<td>0.00</td>
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</tbody>
</table>

Note. — Included here are some recent studies with a quoted normalization of the $M_{500} - T$–relation, scaled to $M_{8keV}$, i.e., the mass contained within $r_{500}$ of a cluster with $kT = 8keV$, with errors propagated, and assuming $h = 1$. The listed normalization has been scaled to a common redshift of $z = 0.23$, assuming the redshift dependence expected for a self-similar collapse model, as given by eq. 3. The normalization of S05, which was determined within a fixed physical radius of $250h^{-1}$ kpc in an Einstein-de Sitter universe, has been scaled to $M_{500}$ for our adopted cosmology, making the same assumptions about an NFW-type mass profile as we have made for our own data. For each study, we indicate whether the slope of the relation was calculated from a fit to the data, or whether the slope was fixed at the theoretically expected value.