ARE CLUSTERS STANDARD CANDLES? GALAXY CLUSTER SCALING RELATIONS WITH THE SUNYAEV-ZELDOVICH EFFECT

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ABSTRACT

An extensive sample of galaxy clusters will be available in the coming years, detected through their Sunyaev-Zeldovich effect (SZE). We use a semianalytic model to study the scientific yield of combining SZE data with X-ray and optical follow-up observations. If clusters at a given redshift $z_0$ can be identified with virialized, spherical halos, they populate a well-defined “fundamental plane” (FP) in the parameter space of the three observables virial temperature ($T$), total Sunyaev-Zeldovich flux decrement ($\Delta S_\nu$), and angular size ($\theta$). The location and orientation of the FP, as well as its redshift evolution, are sensitive to both the internal evolution of clusters and to the underlying cosmological parameters. We show that if clusters are not standard candles (e.g., because of feedback or energy injection), then this can be inferred from the FP. Likewise, we study the dependence of the FP on the cosmological parameters $h$, $\sigma_8$, and $\Omega_m$, and quantify future constraints on these parameters. We also show that in the absence of any nongravitational effects, the scatter in the $(\Delta S_\nu, T)$-plane is significantly smaller than in either the $(\theta, T)$ or the $(\theta, \Delta S_\nu)$ planes. As a result, the $\Delta S_\nu-T$ relation can be an exceptionally sensitive probe of both cluster physics and cosmological parameters. A comparison of the amount of scatter in these three scaling relations will test the origin (cosmological vs. stochastic) of the scatter.

Subject headings: cosmological parameters — cosmology: theory — galaxies: clusters: general

1. INTRODUCTION

Galaxy clusters provide a uniquely useful probe of the fundamental cosmological parameters. The observed abundance of nearby clusters constrains the amplitude $\sigma_8$ and slope $n$ of the primordial power spectrum on cluster scales (Evrard 1989; Henry & Arnaud 1991; Bahcall & Cen 1992; White, Efstathiou, & Frenk 1993; Eke, Cole, & Frenk 1996; Pierpaoli, Scott, & White 2001), while the cluster mass function (Lilje 1992; Bahcall & Cen 1993; Viana & Liddle 1996) and redshift evolution (Oukbir & Blanchard 1992; Bahcall & Fan 1998; Blanchard & Bartlett 1998; Viana & Liddle 1999; Willick 2000) place useful constrains on the density parameters $\Omega_0$ and $\Omega_\Lambda$, as well as on the equation of state of the dark energy component (Wang & Steinhardt 1998; Haiman, Mohr, & Holder 2001).

The analyses above require an understanding of the internal physics of galaxy clusters and the extension of the physical properties of the local cluster sample toward higher redshifts. In other words, for cosmological studies one would ideally like to use clusters as “standard candles.” The central assumptions that make this possible are that clusters are virialized objects at characteristic background densities scaling with redshift as $\rho \propto (1 + z)^3$. Under these assumptions, the temperatures, masses, and redshifts of clusters are related by the virial theorem. As demonstrated recently by Haiman et al. (2001), the use of large future galaxy cluster surveys for cosmological studies is likely to be limited by the validity of these assumptions rather than by statistical uncertainties.

Galaxy clusters exhibit various useful scaling relations, such as those between mass and temperature ($M-T$; e.g., Mohr, Mathiesen, & Evrard 1999), luminosity and temperature ($L-T$; e.g., Eke, Navarro, & Frenk 1998), or size and temperature ($R-T$; e.g., Mohr & Evrard 1997). Analyses of these and other similar scaling laws have yielded insight into the physical nature of clusters. In addition, the scaling relations and their scatter also contain useful cosmological information (Verde et al. 2001b). The temperature of the hot intracluster medium (ICM) is a uniquely direct measure that can be accurately determined from X-ray spectra. On the other hand, the (X-ray) luminosity is sensitive to the density profiles near the cluster core, and the measurements of the masses (from gravitational lensing or from the velocity dispersion of member galaxies) and radii (e.g., from X-ray isophotes) typically suffer from systematic uncertainties and are thus less robust.

A direct probe of the hot gas in galaxy clusters is provided by the so-called Sunyaev-Zeldovich effect (SZE; Sunyaev & Zeldovich 1980). Cosmic microwave background (CMB) photons interact with the hot ionized intracluster gas along

1 Hubble Fellow.
their path, distorting the CMB spectrum. In the Rayleigh-Jeans regime, the distortion results in a “decrement” (SZD) of the CMB temperature that depends only on the optical depth to Compton scattering and the cluster temperature and not on the redshift of the cluster. While the SZE has currently been measured only in a handful of clusters, future SZE surveys can detect rich clusters up to arbitrary redshifts; for example, a recently initiated interferometric survey (Holder et al. 2000) covering 12 deg$^2$ will detect hundreds of clusters below redshift $z = 3$, and the proposed Atacama Cosmology Telescope (ACT; L. Page et al. 2002, in preparation) would allow all galaxy clusters of masses above $4 \times 10^{14} M_\odot$ in a survey area of 100 deg$^2$ to be detected.

The SZE can be characterized in two ways: by its “surface brightness” (i.e., the value of the SZD per unit solid angle) near the central region of the cluster or by its total flux decrement (i.e., the SZD integrated over the whole solid angle of the cluster). While SZE studies have so far mainly utilized the central SZD, here we propose to use the total SZ flux decrement. This quantity should be a more robust indicator of global cluster properties and has a different dependence on cosmological parameters than the central SZD. However, the total decrement has been difficult to measure to date. Single-dish experiments can in principle measure the total decrement, but in practice the need to subtract large backgrounds has resulted in limited signal-to-noise ratios (Mason, Myers, & Readhead 2001; Myers et al. 1997). The most precise SZE observations have so far been obtained with interferometers. Interferometric surveys (Joy et al. 2001; Kneissl et al. 2001; Grego et al. 2001; Reese et al. 2000; Carlstrom et al. 2002; Jones et al. 2001; Birkinshaw 1998 and references therein) observations offer several advantages over observations made with single dishes, in terms of better control over systematics and contamination effects. However, at present the angular size that can be imaged is small, relative to the angular size of the massive clusters that can be studied at the current sensitivities. Hence, these observations typically do not cover the whole cluster and instead still measure only the central decrement.

The prospects for measuring the total SZD will dramatically improve in the next few years. Forthcoming SZE (e.g., DASI, CBI) and cosmic microwave background (CMB) experiments will not only measure the total SZD of an extended cluster sample but, in many cases, will also resolve the temperature fluctuation over the angular size of the whole cluster. For example, MAP (Bennett et al. 1995)$^2$ will detect tens of clusters and resolve a few of them, and Planck (Bersanelli et al. 1996; Mandolesi et al. 1998)$^3$ will detect $\sim 10^4$ clusters and resolve and measure the total SZD of 1% of them (Kay, Liddle, & Thomas 2001). An experiment such as ACT could map the CMB anisotropy over 100 deg$^2$ with a resolution of 1.7'. This would allow all galaxy clusters of masses above $4 \times 10^{14} M_\odot$ in the CMB map region to be detected through the SZE. The experiment would also determine spectroscopic redshifts of more than 300 clusters and implement optical and X-ray follow-up to determine their X-ray temperatures.

In this paper, we investigate the scientific potential of measuring the cluster total SZD in the context of a well-studied cluster sample for which X-ray and optical follow-up are available. As illustrated in § 3, the total SZD ($\Delta S_T$) is an integrated quantity over the whole cluster, not just along the central line of sight, and should thus be more sensitive to global cluster properties. In particular, $\Delta S_T$ probes a unique combination of the physical parameters of the hot intracluster gas, different from those inferred from X-ray observations and from other data. This allows the construction of new scaling relations. In this paper, we examine these scaling relations in detail. We are motivated by the forthcoming sample of clusters with measured SZDs, as well as by the strong need for observational tests of the assumption that clusters can be used as standard candles. Our goals are (1) to predict scaling relations that involve the SZD, together with their scatter, and (2) to study how these scaling relations depend on assumptions about the cluster structure (i.e., that clusters are standard candles), as well as on the underlying cosmological parameters. In particular, we quantify these dependencies in the context of cluster samples, such as those expected to be available in the near future, for which it will be possible to combine SZE and X-ray observations.

This paper is organized as follows. In § 2, we describe our cluster model and its input model parameters. In § 3, we summarize the main observables that the model predicts: redshift ($z$), virial temperature ($T$), Sunyaev-Zeldovich decrement ($\Delta S_T$), and angular size ($\theta$). In § 4 we show that in this model at a fixed $z$ in $(T, \Delta S_T, \theta)$-space, clusters are expected to be distributed on a “fundamental plane” with nearly negligible scatter in the $(\Delta S_T, T)$-projection and that the plane’s orientation depends on redshift and on the background cosmology. In § 5, we parameterize deviations from our cluster model caused by additional energy input, or by a lack of full virialization, and quantify their effects on the scaling relations. Similarly, in § 6, we quantify the effects on the scaling relations caused by varying several cosmological parameters. In § 8, we discuss our main results and the implications of this work, and in § 9, we summarize our conclusions.

2. MODEL INGREDIENTS

In this section we describe our model for cluster physics. In this model clusters are assumed to be virialized and to have formed through the collapse of a spherical top-hat perturbation to a truncated isothermal sphere. This model is of course an idealization but is a first step toward the predictions of cluster scaling relations that involve the SZD. We then parameterize deviations from this simple model in an attempt to mimic the effect of physical processes other than gravity. Detailed comparison of the model and the parameterization of deviations from it with numerical cluster simulations will be presented in a forthcoming paper.

2.1. Spherical Collapse

If clusters form by the collapse of a spherical top-hat perturbation (e.g., Peebles 1980), the average density $\rho_{vir}$ enclosed within the radius $R_{vir}$ of a cluster of total (dark matter + baryon) mass $M_{vir}$ that forms at redshift $z_f$ is given

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2 See also http://MAP.gsfc.nasa.gov.
3 See also http://astro.estec.esa.nl/SA-general/Projects/Planck.
by (e.g., Kitayama & Suto 1996, hereafter KS96)

$$\frac{\rho_{\text{vir}}}{\rho(z_f)} = 18\pi^2 \varphi(z_f),$$  \hspace{1cm} (1)

where the factor $\varphi(z_f)$ describes departures from a standard Einstein–de Sitter universe and is given by

$$\varphi(z_f) \approx 1 + 0.4093 W_f^{0.9052},$$  \hspace{1cm} (2)

where

$$W_f = 1/\Omega_f - 1,$$  \hspace{1cm} (3)

and

$$\Omega_f = \frac{\Omega_0 (1 + z_f)^3}{\Omega_0 (1 + z_f)^3 + (1 - \Omega_0 - \Omega_\Lambda) (1 + z_f)^2 + \Omega_\Lambda}.$$  \hspace{1cm} (4)

In the above equations, $\rho_{\text{vir}}(z_f) = \Omega_0 \rho_{\text{crit},0} (1 + z_f)^3$ is the mean matter density at redshift $z_f$, where $\Omega_0$ and $\Omega_\Lambda$ are the present-day densities of matter and cosmological constant, in units of the critical density $\rho_{\text{crit},0}$.

We assume that the cluster is isothermal and that the gas acquires the virial temperature of the halo. In this case, the temperature is related to the mass and virial radius by the virial theorem,

$$T_{\text{vir}} \ = \ \frac{R_{\text{vir}}}{1 \text{kEV} \text{1 Mpc}} \ = \ 0.88 \ \frac{M_{\text{vir}}}{10^{14} M_\odot},$$  \hspace{1cm} (5)

where we have assumed that the gas has a mean molecular weight of $\mu = 0.59$, appropriate for a fully ionized mixture of H and He with a number density ratio of $n_{\text{He}}/n_{\text{H}} = 0.08$. Combining equations (1)–(5), the temperature of a cluster is given in terms of its mass and formation redshift:

$$\frac{T_{\text{vir}}}{\text{kEV}} = 0.62 (1 + z_f) \left( \frac{\Omega_0 h^2}{0.17} \right)^{1/3} \times \left( \frac{M_{\text{vir}}}{10^{14} M_\odot} \right)^{2/3}.$$  \hspace{1cm} (6)

Here $h \equiv H_0/100$ km s$^{-1}$ Mpc$^{-1}$ is the Hubble constant. This equation quantifies the intuition that clusters virializing at an earlier epoch are hotter than clusters of the same mass that virialize at later times. Real clusters do not form at a single moment but rather accrete matter over a period of time. Equation (6) is equivalent to the $M$-$T$ relation of, e.g., Bryan & Norman (1998), if $z_f = z_0$. This “recent formation” approximation is valid if the cluster accretion/merger rate remains sufficiently high as in the case of an $\Omega_0 = 1$ universe. If instead $\Omega_0 < 1$, the recent formation approximation might not be valid.

The temperature of a real cluster depends on the formation epoch because an earlier formation epoch (suitably defined) makes the (dark) halo more concentrated (e.g., Lacey & Cole 1994; Navarro, Frenk, & White 1997; Gigna et al. 1998; Eke, Navarro, & Steinmetz 2001; Bullock et al. 2001; Wechsler et al. 2002). It is still an open issue if the formation epoch plays an important role in the observed cluster properties. A theoretical study using hydrodynamic simulations (Mathisen 2001) finds no evidence for a relationship between cluster temperature and formation redshift, but KS96 and Voit & Donahue (1998) argue that, since the formation epoch affects the shape of the dark matter halo in the semi-analytic prediction of the $M$-$T$ relation, the cluster formation redshift plays an important role.

On the observational side, Finoguenov, Reiprich, & Böhringer (2001) and Bahcall & Comerford (2002) find evidence that the cluster formation epoch is important in reproducing the observed slope and scatter of the $M$-$T$ relation and the behavior of the $M/L$ ratio, respectively (see their §3 and 5, respectively).

We thus include this effect following KS96: we define a formation epoch for the dark halo (and thus for the cluster) as in Lacey & Cole (1994), and we allow the cluster to grow in mass after virialization. We note that clusters of a given mass $M$ observed at a redshift $z_0$ form over a range of earlier redshifts $z_f \geq z_0$. Equations (5)–(6) then give the temperature and mass of a cluster when it first forms and virializes. In principle, both the mass and the temperature can change between $z_f$ and $z_0$. As argued in KS96, numerical simulations (e.g., Evrard 1990; Navarro, Frenk, & White 1995) indicate that the temperature does not significantly evolve after virialization. We therefore make the assumption here that the final temperature of the cluster at redshift $z_0$ is equal to $T_{\text{vir}}$. However, since this is an important assumption, below we also consider models that describe departures from this assumption (see §2.3).

However, clusters do grow in mass after virialization. To account for this growth, we assume that the ratio between the final mass $M$ and the virial mass $M_{\text{vir}}$ is a ”universal” constant $M_{\text{vir}} = f_M M$ for all clusters (see Lacey & Cole 1993; we relax this assumption below). Following Viana & Liddle (1996), we set $f_M = 0.75$, which was calibrated using $N$-body simulations.

### 2.2. Mass Function and Age Distribution

The mass and formation redshift of a cluster are not directly measurable quantities. Nevertheless, it is possible to compute the cluster mass function, $dN/dM(M, z_0)$ (e.g., Press & Schechter 1974; Sheth, Mo, & Tormen 1999; Jenkins et al. 2001), and also the statistical distribution of the formation redshifts $z_f$ of clusters of a given mass $M$ observed at redshift $z_0$, $dN/dz_f(M, z_0)$ (e.g., Lacey & Cole 1993; Sasaki 1994). In what follows, we use the standard Press & Schechter (1974) mass function, with fitting formualae for the cosmological transfer function (Sugiyama 1995) and for the critical overdensity $\delta_c(z)$ for collapse (KS96):

$$\delta_c(z) = \delta_0 (1 + z) g(0)/g(z),$$

$$\delta_0 \approx \frac{3(12\pi)^{1/2}}{20} (1 + 0.0123 \log_{10} \Omega_f).$$  \hspace{1cm} (7)

Here $(1 + z)/g(z)$ is the usual linear theory growth factor (Peebles 1980). To obtain the formation redshift distribution for clusters of mass $M$ at redshift $z_0$, we follow equation (2.26) in Lacey & Cole (1993) and define ”formation redshift” as the redshift at which clusters first acquire a fixed fraction $f_M = 0.75$ of their final mass. This choice of $f_M$ has been calibrated using $N$-body simulations.

Our main motivation for the above choices is ”technical”: the convenient semi-analytical derivation of $dN/dz_f$ is applicable only to the mass function in the standard Press-Schechter theory; at present, no analogous derivation exists for the improved mass functions, such as that of Jenkins et al. (2001). We also note that our conclusions below do not crucially depend on the shape of the distributions $dN/dz_f$ and $dN/dM$ (rather, they depend on how the mass function scales with cosmological parameters). Nevertheless, it is
important to emphasize that improvements over the Press-Schechter mass function have already been made, and simulations have possibly uncovered differences in the abundance of massive clusters (e.g., Seth et al. 1999; Jenkins et al. 2001). Our analysis can be straightforwardly generalized to different choices for the mass function and formation redshift distribution, as the latter becomes available.

2.3. Deviations from Simple Spherical Collapse

The simple model described above assumes that clusters are fully virialized objects whose abundance and structure are dictated by gravitational physics alone. Lack of full virialization, ongoing mergers, or feedback from galaxy formation can modify these predictions. For example, the above simple scaling relations, together with the assumption that the X-ray luminosity $L_X$ is dominated by bremsstrahlung emission, predicts $L_X \propto T^2$, while observations indicate a steeper relation $L_X \propto T^3$ (see, e.g., Kaiser 1991; Evrard & Henry 1991; Bryan & Norman 1998). Although different explanations are still possible (Bryan 2000), this steep slope suggests additional heat input to the gas prior to virialization, which preferentially lowers the central density, and therefore the X-ray emissivity, in smaller clusters (see, e.g., Kaiser 1991; Bialek, Evrard, & Mohr 2001 and references therein for recent work on this subject).

Regardless of the underlying physical cause, we here model deviations from our simplified model by introducing two additional parameters, $\xi$ and $\alpha$, and thus generalizing equation (6) as follows:

$$T_{vir} \propto (1 + z_f)^{\alpha} M_{vir}^{\xi}$$

(for an alternative modeling see Benson, Reichardt, & Kamionkowski 2002). The choice of $\xi = 1.5$ and $\alpha = 1$ corresponds to the original equation (6), while different values of $\xi$ and $\alpha$ describe deviations from the simplest model. By design, both of these parameters capture departures from purely gravitational virial equilibrium (see eq. [5]). The first parameter, $\xi$, mimics the effect of heat input. Preferential heating of small clusters corresponds to flattening the $T-M$ relation, i.e., to values of $\xi \geq 1$. This type of flattening has already been observed, e.g., $\xi \sim 1.6$ (Mohr & Evrard 1997), $\xi = 1.72$ (Muanwong et al. 2001, from analysis of cluster simulations), $\xi \approx 1.81$ (Xu, Jin, & Wu 2001), and $\xi = 1.98 \pm 0.18$ (Mohr et al. 1999); 7%, 10%, 20%, and 25% variations, respectively. Within the context of the spherical top-hat model, this discrepancy is partly alleviated by the fact that smaller clusters form over a broader range of redshifts and are on average hotter than one would expect if they had all formed in the same redshift range as the more massive ones (which, on average, form closer to $z = z_0$). We find that the effective slope $\xi_{eff}$, under the assumption of $f_M = 0.75$, would be $\xi_{eff} \sim 1.6$. Nevertheless, it is important to model possibly still larger deviations from the $\xi = 1.5$ scaling behavior.

The second parameter, $\alpha$, quantifies deviations from the assumption that clusters at all redshifts are fully virialized. It is reasonable to consider, for example, the possibility that clusters at higher redshifts are more likely to be detected in the process of their initial collapse/assembly and are less likely to be fully virialized than their lower redshift counterparts. This effect is mimicked by a choice of $\alpha \leq 1$, implying that clusters are “colder” at higher redshifts. Interestingly, there are examples of clusters hotter than one would expect if they were virialized (and can be taken as evidence for ongoing mergers or some other form of energy injection; e.g., Tucker et al. 1998; Roettiger, Loken, & Burns 1997; Evrard, Metzler, & Navarro 1996); this case is mimicked by a choice of $\alpha \geq 1$.

We emphasize once again that the parameterizations that we chose above are somewhat arbitrary. However, they allow us to investigate quantitatively the level of deviations from our fiducial model that will be detectable in forthcoming surveys.

2.4. Modeling the Scatter

The model described above is “deterministic”: the only source of scatter that it predicts in the observables is that caused by the fact that clusters have a distribution of different formation redshifts. This scatter is a direct consequence of cosmological initial conditions (which translates into a “scatter” by subsequent gravitational collapse) and probes the high-$\sigma$ tail of the primordial overdensity distribution function (Verde et al. 2001b). For example, in the mass-temperature or size-temperature relations, this causes a scatter whose magnitude monotonically increases with decreasing temperature.

It appears that this scatter alone is sufficient to account for the scatter in the observed $M-T$ relation (Viana & Liddle 1996; Horner, Mushotzky, & Scharf 1999; Finoguenov et al. 2001; Xu et al. 2001) and, for a suitable choice of $\sigma_8$, for the observed scatter in the size-temperature relation (Verde et al. 2001b; Mohr & Evrard 1997; Mohr et al. 2000). Nevertheless, it is interesting to contrast the predictions of this “cosmological” scatter with scatter that can be caused by different physics. For example, in a recent analysis of hydrodynamic cluster simulations (Mathiesen 2001), the X-ray temperatures do not appear to depend on the formation redshift (although see Evrard 1990 and Navarro et al. 1995, who find that cluster temperatures do not change after the cluster forms). These simulations are not yet conclusive since the expected correlation between formation redshift and cluster temperature could be smaller than the scatter because of small-number statistics in the simulations. On the other hand, the observational scatter might even be due mostly to uncertainties in the mass and temperature (or size) determinations. We here nevertheless consider alternative origins for the scatter as a possibility.

We will distinguish two extreme cases as a deterministic scenario, in which the cluster temperature depends on the formation redshift with no additional source of scatter, and a stochastic scenario, in which the temperature scales directly with the observed redshift and there is some additional source of scatter. In the latter case, the additional scatter may simply be observational, or it may be caused by processes that influence cluster temperatures, such as feedback from galaxy formation, other forms of heating or cooling, or simply that $f_M$ is not constant from cluster to cluster. Regardless of the source of this stochasticity, we assume that, on average, the X-ray temperature of a cluster depends on its mass, redshift of observation, and cosmology through equation (6), with the substitution $z_f \rightarrow z_0$, but that there is, in addition, an intrinsic scatter around this mean $T(z_0)$ relation. We model this scatter as random deviations in the temperature from cluster to cluster, where the deviations $\Delta T$ are Gaussian distributed with a fractional rms width $x \equiv \Delta T/T$. 
In reality, the scatter seen in cluster scaling relations is likely due to a combination of a deterministic effect (such as in our deterministic scenario) and a random variation from cluster to cluster (such as in the stochastic scenario). For example, as we discuss in § 5.1 below, approximately the same scatter in the \((M, T)\)-distribution could be obtained within the deterministic scenario (with \(f_M = 0.75, x = 0\)) or from a different scenario in which the formation redshift distribution was narrower (i.e., \(f_M > 0.75\)) but the cluster temperature had some additional random variation (i.e., \(x > 0\)). The parameter \(x\), together with \(f_M\), quantifies how much of the observed scatter is due to cosmological initial conditions versus other sources. The deterministic scenario corresponds to \(f_M = 0.75, x = 0\); the stochastic scenario corresponds to \(f_M = 1, x > 0\); and in-between cases are described by \(f_M < 1, x > 0\).

### 2.5. Summary of Model Parameters

In principle, one would like to set all parameters of our model to be free and investigate what joint constraint can be imposed from observations. However, the number of parameters makes this approach impractical, and we are forced to impose constraints using other observations. We assume the background cosmology to be a flat Λ cold dark matter (CDM) model (as supported by recent CMB data; Mauzskopf et al. 2000; de Bernardis et al. 2000; Jaffe et al. 2001), described by the parameters \(\Omega_0\) and \(h\). Unless otherwise stated, we will assume that the combination \(\Omega_0 h^2\) is a constant (justified by the fact that forthcoming CMB experiments will constrain this combination to better than 5%). We also assume a baryon fraction \(\Omega_0 h^2 = 0.02\), consistent with recent D/H measurements (e.g., Burles & Tytler 1998). This leaves \(h\) as the only free cosmological parameter, and we will further impose \(0.2 < h < 0.9\). The primordial power spectrum is specified by the normalization \(\sigma_8\) and slope \(n\); however, we here assume \(n = 1\) (supported by recent CMB data), and, unless otherwise stated, we also adopt \(\sigma_8 = 0.495\Omega_0^{-0.6}\) (inferred from local cluster abundance; Viana & Liddle 1999; Pierpaoli et al. 2001).

In summary, our model is fully specified by the following seven parameters:

1–3. The cosmological parameters \(\Omega_0\), \(h\), and \(\sigma_8\), two of which can be eliminated by other constraints.

4–5. The parameters \(f_M\) and \(x\) that describe scatter in the scaling relations attributable to cosmological initial conditions and to other sources, respectively.

6–7. The parameters \(\xi\) and \(\alpha\) that describe departures from the fully virialized simple top-hat collapse models.

For illustrative purposes we define a “fiducial model” by the following choice of parameters: \(h = 0.65\), \(\Omega_0 h^2 = 0.17\), \(\Omega_0 = 0.4\), \(\Omega_0 = 0.6\), \(\sigma_8 = 0.86\), \(f_M = 0.75\), \(x = 0\), \(\xi = 1.5\), and \(\alpha = 1\) for the deterministic model; for the stochastic model we chose \(x = 0.13\) and \(f_M = 1\), with all other parameters unchanged. In addition to these parameters, to predict the Sunyaev-Zeldovich decrement (see § 3 below), we need to know the mass fraction of baryons that constitute the hot gas in the ICM. This fraction \(f_{\text{ICM}}\) can be inferred from a comparison of the cluster’s X-ray flux and X-ray temperature; here we assume \(f_{\text{ICM}} \sim 0.2\) with a weak temperature dependence: \(f_{\text{ICM}} = 0.2 T^{0.26}(z/0.5)^{-3/2}\) (Mohr et al. 1999). We note here that the value of \(f_{\text{ICM}}\) should be a lower limit to the ratio \(\Omega_b/\Omega_0\); the temperature dependence reflects the fact that low-mass clusters are more likely to loose their gas from energy-injection or preheating mechanisms, while the dependence on \(h\) depends on the method employed to measure it. The method of Mohr et al. (1999) is a determination for the whole clusters, while the method of, e.g., Grego et al. (2000) yields a different \(h\)-dependence but is based on the central SZD. We have checked that the results we present here do not depend qualitatively on the specific choice of the dependence of \(f_{\text{ICM}}\) on \(h\).

### 3. Observables

The observables of a cluster that we utilize in this paper are the redshift \((z_0)\), temperature \((T)\), total Sunyaev-Zeldovich flux decrement \((\Delta S_{\text{SZ}})\), and angular size \((\theta)\). Within our model, the redshift and temperature are independent parameters and have already been specified. Cluster redshifts can be obtained observationally, e.g., from their member galaxies out to \(z_0 \sim 1\) through deep optical and near-infrared observations, and cluster temperatures can be obtained from X-ray spectra out to similar redshifts. Here we define the Sunyaev-Zeldovich decrement and the angular size.

The SZD along a line of sight to a cluster in the Rayleigh-Jeans regime of the CMB is given by (e.g., Holder et al. 2000)

\[
\frac{\Delta T_{\text{CMB}}}{T_{\text{CMB}}} = \frac{g k_B \sigma_T}{m_e c^2} \int dl n_e(l) T_e(l),
\]

where \(g = -2\), \(m_e\) is the electron rest mass, \(c\) is the speed of light, \(\sigma_T\) is the Thomson cross section, \(T_{\text{CMB}}\) is the CMB temperature, \(T_e\) is the electron temperature, \(n_e\) is the electron number density, and the integral is along the line of sight. Expressed in terms of a decrease in the observed flux, \(\Delta S_{\text{e}} = 2k_B\Delta T_{\text{CMB}}^2 / c^2 d\Omega\) (where \(d\Omega\) is the smaller of the solid angle of the observations and the solid angle subtended by the cluster), equation (9) implies that the total observed SZD \((\Delta S_{\text{e}})\) for a cluster can be related to its total mass via

\[
\Delta S_{\text{e}} = \frac{2\nu k_B^2 \nu^2 \sigma_T T_{\text{CMB}} f_{\text{ICM}} T_e M}{\mu_m m_p c^4 d_4(z)^2}, \tag{10}
\]

where \(\nu\) is the frequency, \(\mu_m = 1.15\) is the mean molecular weight per electron, \(m_p\) the proton rest mass, \(d_4\) is the angular diameter distance, \(z\) is the cluster redshift, \(f_{\text{ICM}}\) is the ICM mass fraction, and \(M\) denotes the mass enclosed within the virial radius of the halo. Equation (10) also assumes that the electron density–weighted mean temperature \(T_e\) can be identified with the virial temperature as given in equation (5) (this is satisfied by definition in our assumed isothermal clusters; we implicitly assume that \(T_e\) also equals the actual observed X-ray temperature \(T_X\)). Finally, equation (10) assumes that the solid angle of the observations is larger than or equal to the solid angle subtended by the cluster. Equation (10) can be rewritten in convenient units in terms

\[\text{4 The reason behind this choice will be explained in § 5.1.}\]
of the observables $z$ and $T_X$ as

$$\frac{\Delta S_{\nu}}{\mu Jy} = 0.26 \left(\frac{\nu}{\text{GHz}}\right)^2$$
\[\times f_{\text{ICM}} \frac{M}{10^{14} M_\odot} \frac{T_X}{\text{keV}} \frac{h^2}{F(z_0)^2},\]  \hspace{1cm} (11)

where $F(z_0)$ is the dimensionless angular diameter distance,

$$F(z_0) = \frac{1}{1+z_0} - \frac{1}{1+z_0} \frac{\int_0^\infty dz' \frac{1}{\sqrt{(1+z')^2(1+\Omega_0 z') - z'(2+z')\Omega_0}}}{1+z_0} \left[u(1, \Omega_0) - u\left(\frac{1}{1+z_0}, \Omega_0\right)\right],$$  \hspace{1cm} (12)

where the expression for $u$ can be found in equation (1) of Pen (1999) and $z_0$ is the cluster redshift. The observable quantities here are $z_0$, $T_X$, and $\Delta S_{\nu}$.

In our model, the angular size of a cluster simply corresponds to the virial radius, $\theta = R_{\text{vir}}/d_A$. The spherically averaged profiles (of, e.g., temperature) found in numerical simulations do indicate the presence of virialization shocks, as expected from the top-hat collapse model. However, rather than a single strong shock, there tends to be several weaker shocks, extending to larger radii (see, e.g., Bryan & Norman 1998). Nevertheless, we here assume that the angular size is given by the virial radius, as obtained from the top-hat collapse model (see further discussion below):

$$\theta = \frac{(\Delta S_{\nu}/\mu Jy)/f_{\text{ICM}} F(z_0)}{15.6 f_{\text{ICM}} (\nu/\text{GHz})^2 (T_X/\text{keV})^2 h}. \hspace{1cm} (13)$$

Consistent with our earlier assumption, we have assumed that the cluster grows in mass by a factor of $1/f_{\text{ICM}} = 1.3$ between $z_f$ and $z_0$. In practice, this angular size can be measured accurately only if a cluster is resolved, and therefore an estimate of $\theta$ will be available only for a fraction of the clusters in a data set. For example, the Planck Surveyor satellite will resolve only about $\sim 1\%$ of all SZE clusters (Kay et al. 2001), but the ACT, with a 1'/7 resolution, will resolve most detected clusters at $z \lesssim 1$ (L. Page et al. 2002, in preparation). Angular sizes can, in principle, also be obtained from clusters resolved in X-ray observations. In practice, this involves measuring the profile and fitting to a model; this fit will be constrained essentially by the core radius rather than the virial radius (although the latter can be inferred by extrapolation once the radial profile is fitted to the model).

It is likely that in a given sample not all observables will be known for each cluster, and the model prediction for some observables (e.g., for the angular size) are less robust than for others. Below, we briefly consider the ideal case, in which all four observables ($z$, $T$, $\Delta S_{\nu}$, and $\theta$) are reliably measured for a cluster sample. We then concentrate on cases where only the subsets ($z$, $T$, $\Delta S_{\nu}$) or ($z$, $\Delta S_{\nu}$, $\theta$) have been measured. The first of these is relevant, e.g., to a sample of clusters detected in the interferometric SZE survey of Holder et al. (2000), or to the MAP/Planck/ACT cluster sample with X-ray follow-up and reliable temperatures; the second case is relevant to a sample of well-resolved SZE clusters (e.g., those of the ACT) that are too distant ($z > 1$) to obtain, e.g., reliable temperatures. Current cluster samples exist where a combination of cluster sizes and temperatures are measured and have been analyzed in the literature (see, e.g., Mohr & Evrard 1997; Verde et al. 2001b).

4. THE FUNDAMENTAL PLANE OF GALAXY CLUSTERS

4.1. The Fundamental Plane in the Fiducial Model

At any given redshift $z_0$, equations (6), (11), and (12) (i.e., in the deterministic scenario) express the three observables $T_X$, $\Delta S_{\nu}$, and $\theta$ in terms of the two variables $z_f$ and $M$. For a given frequency channel $\nu$ of the SZE survey, we assume that the ICM mass fraction has the functional form described in § 2.5 and that the cosmological parameters ($\Omega_0$, $\Omega_0$, and $\sigma_8$) and $\nu_{\text{ICM}}$ are known. These relations—three equations between the five variables ($T_X$, $\Delta S_{\nu}$, $\theta$, $M$, and $z_f$)—allow a study of the distribution of clusters in several useful projections of this five-dimensional parameter space. In particular, clusters define a three-dimensional manifold in the four-dimensional subspace of the four observables ($T_X$, $\Delta S_{\nu}$, $\theta$, and $z$). It is, however, more practical to consider the three-dimensional subspace ($T_X$, $\Delta S_{\nu}$, $\theta$, and $z$) and regard the cluster redshift as an evolutionary parameter. In this case, for a given redshift $z_0$, clusters can populate only a half-plane in ($T_X$, $\Delta S_{\nu}$, $\theta$)-space. The restriction to a half-plane arises from the requirement that clusters form prior to the redshift at which they are observed, $z_f > z_0$.

In order to visualize this half-plane, we will hereafter refer to the “fundamental plane” (FP), in Figure 1 we show an example of the distribution of clusters observed at the fixed redshift $z_0 = 0.1$ (points) and a portion of the FP (gray area). The figure also shows the projection of the FP and the cluster sample onto the “walls” of the box.
which define the three scaling relations $\Delta S_\theta - T_X$, $\theta - \Delta S_{\Delta}$, and $\theta - T_X$. Of course, not all locations in the FP are equally likely to be occupied: cluster temperatures, virial radii, and SZD cannot assume any arbitrary value between $-\infty$ and $+\infty$; smaller clusters are more numerous than high-temperature ones; and the width of the probability distribution of $z_f$ decreases monotonically for larger clusters. As a result, clusters preferably populate a portion of the FP. In Figure 1, the points show the distribution of 200 clusters ($M \gtrsim 10^{14} M_\odot$), selected randomly at $z_0 = 0.1$ using a Monte Carlo method.

If all observable quantities ($T_X$, $\Delta S_{\Delta}$, $\theta$, and $z$) are measured in a cluster sample and the top-hat collapse model is the correct description of the physical properties of clusters, then the clusters define the FP shown in Figure 1, determined solely by the cosmological parameters. Deviations from the top-hat collapse model or different choices of the cosmological parameters can cause a shift in the position and orientation of the FP and can also introduce a random scatter around it. We will argue that it is possible to quantify such deviations from the simple top-hat model, and gain insight into both cluster physics and cosmological parameters, by studying the departures of the FP from its position and orientation in our fiducial model. As an example, $\alpha < 1$ would modify the dependence of the FP on redshift $z$, while $x > 0$ would induce a scatter around the FP. In the rest of this paper, we will quantify these statements by concentrating on different projections of the FP.

4.2. The Fundamental Plane and Cluster Scaling Relations

As mentioned above, the projections of the FP define three scaling relations, $\Delta S_\theta - T_X$, $\theta - \Delta S_{\Delta}$, and $\theta - T_X$. The last of these relations can be analyzed using existing cluster samples and have been studied by various authors (e.g., Mohr & Evrard 1997; Verde et al. 2001b). In this paper, we focus on the usefulness of the first two scaling relations, which will be observationally available from future SZE cluster surveys.

Figures 2 and 3 show the theoretical expectations for the two projections of the FP that involve the SZD, together with the expected position of clusters in our fiducial model. Figure 2 shows the projection of the FP onto the $\Delta S_\theta - T_X$-plane. The solid line shows the location of clusters at redshift $z_0 = 0.1$ with masses in the range $10^{14} M_\odot \leq M \leq 3 \times 10^{15} M_\odot$ in this plane, assuming that these clusters formed at the redshift at which they are observed, $z_f = z_0 = 0.1$. The dotted arrow shows how the location of a $2 \times 10^{14} M_\odot$ cluster in this plane depends on its formation redshift for $0.1 < z_f < 5$. As the arrow demonstrates, both the temperature and SZD are increased for clusters that form earlier. Similarly, the dashed arrow shows how the location of this cluster would change with the Hubble constant for $0.2 < h < 0.9$. Both the temperature and SZD decrease if the Hubble constant is lower. Note that changes in $\Omega_0$ and $\sigma_8$ mainly affect how clusters are distributed in formation redshift, i.e., along the direction of the dotted arrow. Since this is nearly parallel to the solid line, a change in $\Omega_0$ or $\sigma_8$ is nearly degenerate with a change in cluster mass. This suggests that the expected scatter in the $\Delta S_\theta - T_X$ relation should be small and insensitive to $\Omega_0$ and $\sigma_8$. Notice also that low values of $h$ make clusters appear colder, mimicking an unphysical formation redshift $z_f < z_0$.

Figure 3 shows the projection of the FP onto the $(\theta - T_X)$-plane. As in Figure 2, the solid line shows the location of clusters at redshift $z_0 = 0.1$ with masses in the range $10^{14} M_\odot \leq M \leq 3 \times 10^{15} M_\odot$, while the dotted and dashed arrows demonstrate the dependence of the location of a $2 \times 10^{14} M_\odot$ cluster on its formation redshift and on the Hubble constant. Note that in difference from Figure 2, the dotted arrow, representing increasing formation redshifts, is nearly orthogonal to the solid line. This suggests that the scatter in $\Delta S_\theta - \theta$ should be large, and sensitive to $\Omega_0 - \sigma_8$ and primordial non-Gaussianity (the same conclusion holds for the size-temperature relation, as can be seen from Figure 1; see also Verde et al. 2001b).

5. Probing the Internal Physics of Clusters

The idealized model for clusters described in §2.1 is based on the collapse of a spherical top-hat perturbation and is
the simplest model for relating cluster observables. It is important to have observational tests for departures from this model, both in order to understand the structure of clusters themselves and to allow clusters to be used as standard candles in cosmological studies. As discussed above, all four observables ($\Delta S_\nu$, $T$, $z$, and $\theta$) might not be available for every cluster. This prompts us to consider what constraints are possible both with and without knowing the angular size $\theta$. In this section we will assume that cosmological parameters are known and use the deformations of the FP to test whether clusters are standard candles.

5.1. Testing for the Origin of Scatter

A striking feature of the FP in our fiducial model, shown in Figure 1, is its orientation, which implies that the three projections have significantly different scatter. In particular, a relatively large scatter is predicted around the $\theta$-$\Delta S_\nu$ and $\theta$-$T_X$ scaling relations, while the $\Delta S_\nu$-$T_X$ relation remains much more tightly defined. Figures 2 and 3 reveal that this result follows from the deterministic nature of our fiducial model, where the only source of scatter in the observables is the distribution in formation redshift $z_f$ of clusters (which, ultimately, is a direct consequence of cosmological initial conditions). As discussed in § 2.4 above, the deterministic scenario, without any additional sources of scatter, might be consistent with existing data (i.e., the scatter in the $\theta$-$T_X$ and $M$-$T_X$ relations). Nevertheless, it is interesting to consider alternative options, those in between the two extreme deterministic and stochastic scenarios.

The parameters $x$ and $f_M$ introduced in § 2.4 above quantify how much of the observed scatter is caused by cosmological initial conditions or by random variations from cluster to cluster arising from their internal physics. To quantify this, we Monte Carlo–generate the $M$-$T_X$ relation of a mock catalog of 250 clusters, first in our deterministic fiducial model with $f_M = 0.75$, $x = 0$ and then for different combinations of $f_M$ and $x$. We then compare these to the fiducial model with a two-dimensional Kolmogorov-Smirnov (K-S) test (e.g., Press et al. 1992; Peacock 1983). This test computes the $D$ statistic, which is the maximum cumulative difference between the two distributions, and then gives $P_{D,P}$, the probability that $D$ could be greater than observed. Small values of $P_{D,P}$ indicate that it is extremely likely that the two distributions differ; for example, a conservative choice is usually $P_{D,P} < 0.01$, which implies that the two data sets are significantly different. We have checked with multiple realizations that if two data sets are drawn from the same underlying distribution (i.e., our fiducial model), $P_{D,P} > 0.317$ about 68% of the time, and $P_{D,P} > 0.046$ about 95% of the time. In what follows we will thus plot the equal probability contours corresponding to $P_{D,P} = 0.317$, 0.046, and 0.01.

Figure 4 shows these equal probability contours. Recall that the deterministic scenario corresponds to $f_M = 0.75$, $x = 0$, the stochastic scenario corresponds to $f_M = 1$, $x > 0$, and in-between cases are described by $f_M < 1$, $x > 0$. In particular, from Figure 4 it is clear that for the mass-temperature relation a (deterministic) model with $f_M = 0.75$ and $x = 0$ is virtually indistinguishable from a (stochastic) model with $f_M = 1$ and $x = 0.13$; thus, we adopt $f_M = 1$, $x = 0.13$ for our fiducial stochastic model.

Figure 4 has two important implications. First, the parameter space outside the central white area is excluded by the K-S test at the 68% confidence level ($P_{D,P} < 0.317$), indicating that the $M$-$T_X$ relation by itself can already be a useful discriminant for the source of scatter. Forthcoming data sets can yield a local sample of many more than 250 clusters with size, temperature, and mass estimates, in which case the constraints shown in Figure 4 can be significantly improved. Second, Figure 4 suggests that although their combination is tightly constrained from the $(M, T_X)$-distribution alone, a degeneracy appears to still remain between $f_M$ and $x$. A comparison with Figure 1 suggests that this degeneracy can be broken by considering, in addition, the distribution of clusters along the $\Delta S_\nu$-$T_X$ relation. For models where the scatter is cosmological ($f_M \approx 0.75$), this relation is significantly tighter than the $(\theta, T_X)$-distribution. On the other hand, in “stochastic” models ($f_M \approx 1$), the scatter in $\Delta S_\nu$-$T_X$ should be comparable to that in $M$-$T_X$.

We therefore next examine constraints on $(f_M, x)$ that will be available from clusters with measured $z$ and $\Delta S_\nu$. In order to illustrate how the scatter in the $\Delta S_\nu$-$T_X$ relation differs in the stochastic and deterministic scenarios, in Figure 5 we show the distribution of clusters in this plane. We used Monte Carlo realizations of our fiducial model to generate a catalog of $\sim 100$ clusters with masses above $10^{14} h^{-1} M_\odot$ (see Holder et al. 2000), observed at each of the redshifts $z_0 = 0.1, 0.5$, and 1 (unless stated otherwise, in what follows we assume $z > M_{\min}$, where $M_{\min} = 10^{14} h^{-1} M_\odot$).

The left and right panels of Figure 5 show the distributions in the deterministic and stochastic scenarios, respectively. A comparison of the two panels reveals, as expected, that at any redshift, the scatter in the deterministic scenario is small, while in the stochastic scenario, it is significantly

\footnote{In principle, a change in $f_M$ also changes the normalization of the $M$-$T$ relation. In practice, we find that this change is small, and for a sample of 300 clusters with $M > 10^{14} h^{-1} M_\odot$, it can be neglected.}
larger. We find that the two scenarios differ increasingly toward higher redshifts (although this redshift trend is not apparent in Fig. 5). This is not surprising, since in the deterministic scenario, the scatter is reduced by the narrower distribution of cluster ages at high-$z$, while in the stochastic scenario, there is no similar trend.

In what follows, we find it useful to define a combination $\eta$ of the observables $\Delta S_v$, $T$, and $z$:

$$\eta = \frac{0.01553(T_X/\text{keV})^{3/2+0.266+1}}{(1+z)^{3/2}(\Delta S_v/\mu^2)/(\mu\text{Jy/GHz}^2)}.$$  \hfill (14)

In the fiducial model $\eta$ depends on cosmology: $\eta = ([1+z_f]/(1+z_0))^{3/2}f_M^{0.5}h^{0.5}(z_f)F^2(z_0)\Omega^{0.5}$.

We generate Monte Carlo mock catalogs of 300 clusters in the redshift range $0 \leq z \leq 1$. We impose the restriction $z \leq 1$ because of the increasing difficulty in obtaining accurate cluster redshifts for more distant clusters. The survey proposed by Holder et al. (2000) will yield about 300 clusters with $z \leq 1$. Similarly, in the ACT survey, about 300 of the detected SZE clusters will have redshifts measured in X-ray and/or optical follow-up observations. For each cluster in our mock catalog, we then compute $\eta$ using equation (14).

Using these mock catalogs, we can now determine constraints on $(f_M, x)$ by comparing mock catalogs with different combinations of $(x, f_M)$ in otherwise identical models. Instead of using the deterministic scenario for the benchmark model, we adopt $f_M = 0.85$ and $x = 0.065$. This combination lies approximately in the center of the degenerate parameter range shown in Figure 4, and hence it allows us to quantify the “distance” of both deterministic and stochastic scenarios from this intermediate case. The $P_{>D} = 0.317, 0.046$, and 0.01 probability contours obtained from these K-S tests are shown in Figure 6 (the constraints for the deterministic fiducial model would have the same orientation in the $(x, f_M)$-plane, but the $P_{>D} = 0.317$ contour would yield an error of $\pm 0.02$ in $x$ and $\pm 0.05$ in $f_M$).

The shaded contours (identical in both panels) reveal that tight constraints can be derived on a combination of $(x, f_M)$, similar to those from the $M$-$T$ relation, but tighter. In using these types of constraints, it is important to compare observational data with model catalogs extending down to the “correct” minimum mass, i.e., the true mass of the smallest observed cluster. The shaded confidence regions were obtained by implicitly assuming the right minimum mass ($M_{\text{min}}$) of the survey. To demonstrate the sensitivity of this method to the limiting mass, in the left panel of Figure 6 the set of transparent contours shows $P_{>D} = 0.01$, obtained assuming a value for $M_{\text{min}}$ that is too low by a factor of 2. Similarly, the transparent contours in the right panel show the results that we obtain, $P_{>D} = 0.046, 0.01$, if we assume the wrong value of $h$ by $\pm 5\%$. A larger error on either of these two parameters would result in all combinations of $(x, f_M)$ producing a $(\eta, x)$-distribution that is inconsistent with the distribution in our benchmark model. This conclusion does not change if we reverse the sign of the change in $M_{\text{min}}$ and $h$. This suggests that this type of study can be used to simultaneously constrain $(x, f_M)$, as well as $M_{\text{min}}$ and $h$. Our results in Figure 6 also suggest that if one marginalizes over the allowed ranges of $M_{\text{min}}$ and $h$, the errors on $x$ and $f_M$ will not be significantly increased.

5.2. Cluster Evolution and Feedback

In § 2.3 we introduced two parameters that describe deviations arising from energy injection or other feedback ($\xi$) and from lack of full virialization or redshift evolution due to other reasons ($\alpha$). In our fiducial model, $\xi = 1.5$ and $\alpha = 1.0$. It is interesting to quantify the effects on the cluster scaling relations of different choices for both parameters. As suggested in the previous section, an inadequacy in our fiducial model will show up as a systematic dependence of $\eta$ (eq. [14]) on $z$ and/or $T_X$.

In order to quantify the minimal level of deviations that can be measured in future SZE surveys, we performed a two-dimensional K-S test in the $(\eta, z)$-distribution for the $\alpha$ parameter using Monte Carlo simulations of 300 clusters. We find that deviations from $\alpha = 1$ by $\pm 0.03$ are detectable at the 68% confidence level. Performing the same test in the $(\eta, T_X)$-plane for the $\xi$ parameter, we find that deviations from the value $\xi = 1.5$ by $\xi = 1.5^{+0.05}_{-0.1}$ are detectable at the same significance.
If angular sizes of ~300 clusters in a survey are available, in addition to \( \Delta S_{\nu} \), \( T \), and \( z \), the values of \( x \) and \( f_M \) and the cosmological parameters can be accurately determined. From equation (13) we obtain

\[
\frac{h}{F(z)} = \frac{(\Delta S_{\nu}/\mu\text{Jy})f_M}{15.6(\nu/\text{GHz})^2f_{\text{ICM}}(T_X/\text{keV})^2(\theta/\text{arcmin})^2}.
\]  

(15)

If we consider this combination of observables as a function of \( z_0 \), we find that (1) the scatter around this relation is not sensitive to \( f_M \), and hence it can only be due to a nonzero value for the parameter \( x \), and (2) the absolute normalization of the relation depends on the cosmology and \( f_M \). In particular, if cosmological parameters are known, the latter depends only on \( f_M \).

These properties of the combination of observables in equation (15) allow a unique combination of \((x, f_M)\) to be measured. Figure 7 shows the equal probability contours \( (P_{\Delta S_{\nu}} = 0.317, 0.046, 0.01) \) in the \((f_M, x)\)-plane for a sample of 300 clusters: the “product” of the probability contours of Figures 6 and 7 allows a unique combination of \((x, f_M)\) to be determined. In addition, the redshift dependence of equation (15) directly probes the redshift evolution of the angular-diameter distance and therefore can be further utilized to measure cosmological parameters, as we will discuss in § 6.3.

6. PROBING COSMOLOGICAL PARAMETERS

In this section, we will assume that clusters can be used as standard candles, i.e., that our fiducial deterministic model of cluster physics is accurate. The deformations of the FP relative to its shape in the fiducial model can then be used to determine cosmological parameters.

6.1. Constraints from \( \Delta S_{\nu}, T_X \), and \( z_0 \)

Assuming that only \( \Delta S_{\nu}, T_X \), and \( z_0 \) are available, a two-dimensional K-S test applied to the \((\eta, z)\)-distribution can be used to constrain \( \Omega \) and \( h \). It is important to note here that this measurement of the Hubble constant, based on a combination SZE and X-ray data, is different from the existing method proposed by, e.g., Gunn (1978), Silk & White (1978), and Birkinshaw (1979). The latter method, by combining the central SZD with X-ray central temperature, yields an estimate of the length of the cluster; assuming that the cluster is spherical, this can be used as an angular diameter distance test. By averaging over a large cluster sample, effects of cluster asphericity can be averaged out. In this method clusters are used as standard rulers. The method presented here is complementary; it uses the total observed SZD, which can be directly measured, requires data that is easier to obtain (no detailed SZ and X-ray maps of the cluster are needed), and by making use of the whole cluster.
SZD, should therefore be less sensitive to the details of cluster physics near the center. This method relies on different assumptions; in particular, it assumes clusters are virialized (although deviations from virialization can be parameterized, as discussed in §§ 2.3 and 2.4). In our method, clusters are used as standard candles. The expected statistical errors for a cluster sample of the same size are comparable for the two methods, but the possible systematics are of an entirely different nature.

The results of applying a two-dimensional K-S test to the \((\eta, z)\)-distribution to determine \(\Omega\) and \(h\) are shown in Figure 8. The parameter space outside the light gray area is excluded by the K-S test at the 68% level \((P_{S,D} = 0.317)\); the other two contours correspond to \(P_{S,D} = 0.046\) and \(P_{S,D} = 0.01\). The “true” underlying value is indicated by the plus sign. The solid and dashed contours show the first two likelihood contours \((P_{S,D} = 0.317 \text{ and } 0.046)\), obtained by assuming a minimum mass for the survey \(M_{\text{min}}\) 50% lower and 50% higher, respectively, than the \(10^{14} h^{-1} M_{\odot}\) used in the mock catalog. The estimates of \(h\) are not strongly affected by the choice of \(M_{\text{min}}\). In practice, one will marginalize over \(M_{\text{min}}\): this will increase the uncertainty in the recovered \(\Omega_0\) but not in \(h\). The two dotted lines show the constraint \(\Omega_0 h^2 = \text{constant } \pm 5\%\), expected from forthcoming CMB experiments. This suggests that the two constraints are sufficiently different and can be combined together to break the degeneracy between \(\Omega_0\) and \(h\). We also note that constraints in the \((\Omega, h)\)-plane obtained from the redshift distribution \(dN/dz\) of clusters \((\text{dot-dashed line; Haiman et al. 2001})\) is complementary to the degeneracy with \(M_{\text{min}}\) as shown in Figure 8; thus, this degeneracy can be removed using, e.g., \(dN/dz\) information.

6.2. Constraints from \(\Delta S_{\nu}, \theta, \text{and } z\)

Assuming that clusters in the sample are resolved and that their angular sizes \((\theta)\) are measured, a two-dimensional K-S test applied to the \((\Delta S_{\nu}, \theta)\)-distribution can be used to constrain \(\Omega_0\) and \(\sigma_8\). In Figure 9, we illustrate the dependence of the \((\Delta S_{\nu}, \theta)\)-distribution on \(\sigma_8\) \((\Delta S_{\nu}/\nu^2)\) is in units of \(\mu\text{Jy GHz}^{-2}\). The diamonds show a Monte Carlo sample of 25 clusters at \(z = 0.3\) with \(\theta \geq 2\'\) for \(\Omega_0 = 0.4, \Lambda_0 = 0.6, h = 0.65, \text{ and } \sigma_8 = 0.99\); the dots show the \((\Delta S_{\nu}, \theta)\)-distribution of \(\sim 100\) Monte Carlo–simulated clusters for different choices of \(\sigma_8\). It is clear that a too large/small \(\sigma_8\) gives rise to a too large/small scatter in the \(\Delta S_{\nu}, \theta\) relation. The results are demonstrated in Figure 10, where we show the equal probability contours in the \((\sigma_8, \Omega_0)\)-plane obtained from the \(\Delta S_{\nu}, \theta\) relation. The fiducial model is indicated by the plus sign (here we have dropped the constraint \(\sigma_8 = 0.495 \Omega_0^{-0.07}\)). As before, the parameter space outside the light gray area is excluded at the 68% level by the K-S test, and the other two sets of contours correspond to 95% and 99% confidence levels. The constraint obtained from the \(\Delta S_{\nu}, \theta\) relation can be approximated by \(\sigma_8 = 0.92 \Omega_0^{-0.11}\). For comparison, the solid line shows the constraint in the \((\sigma_8, \Omega_0)\)-plane obtained from the local abundance of clusters at \(z = 0.3\) with \(\theta \geq 2\’\).
massive clusters. A comparison of these two methods suggests that the two constraints can be used together to measure both \( \Omega_0 \) and \( \sigma_8 \).

6.3. Constraints from \( \Delta S_{\nu}, \theta, T, \) and \( z \)

As already mentioned in § 5.2 above, if all observables are known for a cluster sample and if \( f_{\rm M} \) and \( x \) are reasonably well constrained, then equation (15) yields the angular diameter distance as a function of redshift. This quantity depends on \( \Omega_0, \Lambda, h \), and the equation of state parameterized by \( w \); it can thus be used to constrain these parameters. Several other observables have already been used to measure the angular diameter distance as a function of redshift, such as Type Ia supernovae (e.g., Riess et al. 1998; Perlmutter et al. 1999) or the redshift evolution of the linear power spectrum shape (e.g., McDonald & Miralda-Escude 1999; Roukema & Mamon 2002). Galaxy clusters potentially offer an independent test. The accuracy with which the angular diameter distance can be measured will strongly depend on the observational uncertainties in \( \Delta S_{\nu}, \theta, \Gamma \), and \( T \) and will be addressed in a subsequent work.

7. A COMPARISON OF TWO DIFFERENT STATISTICS

Throughout this paper, we have adopted the two-dimensional K-S test to quantify the discriminating power of the scaling relations between different models. In our study, we have focused on the shapes of the scaling relations and have not explored constraints from the total number of detected clusters, which itself is a function of cosmological parameters. The cosmology dependence of the number counts has been recently studied by Haiman et al. (2001) and Holder, Haiman, & Mohr (2001) to forecast precision constraints that will be available on the equation of state parameter \( w \), as well as the parameters \( \Omega_0, \Omega_\Lambda, \) and \( \sigma_8 \). These constraints are complementary to those that derive from the shape of the scaling relations, and the two methods will also have different systematic errors. For example, the fundamental plane approach requires extensive X-ray/optical follow-up of SZ surveys or requires the temperatures of SZ-selected clusters to be obtained from different catalogs. This can introduce selection effects that affect the number of detected clusters but not the shape of the scaling relations. The K-S test has several attractive features, such as its distribution independence and the fact that it is a robust and computationally direct method. It is a particularly appropriate statistic for the present application, since it distinguishes distributions based only on their shape, independent of their overall normalization. Nevertheless, one must bear in mind that the K-S test is optimized to detect “shifts” in distributions and is less well suited in distinguishing among distributions with significant “tails” (e.g., Press et al. 1992). In order to assess the robustness of our results to the choice of statistic, we here compare our analysis of the constraint on the Hubble constant \( h \) with constraints obtained from a maximum likelihood method.

In applying both types of statistics, we utilize the distribution of clusters in the \((\nu, z)\)-plane, as defined in § 5.1 above, to derive constraints on the Hubble constant.

In general, a maximum likelihood analysis is not directly comparable to the K-S test, since the former utilizes information from the total number of clusters, while the latter is insensitive to it. However, in the case of constraining the Hubble constant, we find that the total number of clusters is insensitive to the value of \( h \). As an example, in our fiducial model with \( h = 0.65 \), we predict, by construction, 300 clusters in the redshift range \( 0.1 < z < 1 \), in a solid angle of \( \sim 20 \) deg\(^2\), above the limiting mass \( M_{\min} = 10^{14} \) \( h^{-1} \) \( M_\odot \). Assuming that the minimum mass \( M_{\min} \) scales as \( M_{\min} \propto h^{-1} \) (e.g., from mass determinations from X-ray profiles or weak lensing) and assuming further that the power spectrum has been independently measured, we find that the total count is essentially independent of \( h \). Lack of a priori knowledge of the power spectrum introduces a small \( h \)-dependence through the “shape parameter” \( T \sim \Omega h \); we find 297.3 clusters for \( h = 0.64 \). Finally, assuming a fixed \( f_{\text{ICM}} \), the mass corresponding to a constant SZD scales more strongly, as \( M_{\min} \propto h^{-8/3} \) (with the \( f_{\text{ICM}} \)-dependence used in this paper, the dependence would be weaker). Under this scaling, including the \( h \)-dependence of the power spectrum, we find 291.5 clusters for \( h = 0.64 \), implying that based on the number counts alone, models with \( h = 0.64 \) and \( h = 0.65 \) would be only 0.5 \( \sigma \) apart. We conclude that in the case of constraints on \( h \), we can directly compare the likelihood and the two-dimensional K-S test performances, both of which will test primarily the shapes rather than the normalizations of the underlying distributions.

The observation of a discrete number \( N \) of clusters is a Poisson process, the probability of which is given by the product

\[
P = \prod_{i=1}^{N} \left( e_i^n \exp(-e_i/i) / n! \right),
\]

where \( n_i \) is the number of clusters observed in the \( i \)th experimental bin and \( e_i \) is the expected number in that bin in a given model: \( e_i = I(x_i) \Delta x_i \). Here \( I \) is proportional to the probability distribution, and \( x_i \) denotes the set of observables, in the present case, \( x = (\nu_i, z_i) \). Following Cash (1979), for unbounded data (or equivalently, for very small
bins that have only 0 or 1 counts) we define the quantity

\[ C = -2 \ln P = 2 \left( E - \sum_{i=1}^{N} \ln I_i \right), \]

where \( N = 300 \) is the total number of observed clusters (i.e., the number of clusters in the mock catalog for our fiducial model with \( h = 0.65 \)) and \( E \) is the expected number of clusters in models with arbitrary \( h \). We have omitted all terms that involve \( \delta x_i \) since they do not depend on \( h \). The quantity \( \Delta C \), defined in two models with different \( h \), has a \( \chi^2 \)-distribution (e.g., Cash 1979). Both the two-dimensional K-S test and the maximum likelihood test are performed in the \((\eta, z_0)\)-plane, where \( I(\eta, z_0) \) is given by

\[ I(\eta, z_0) = \frac{d^2N}{d\eta dz_0} \equiv \frac{dn}{d\eta dz_0} \frac{dV}{d\eta dz_0} \Delta \Omega. \]

Here \( dn/dN \) is the Press-Schechter mass function, \( dP/dz \) is the formation redshift distribution from Lacey \\& Cole (1993), and \( dV/d\eta dz \) is the comoving cosmological volume. We have assumed a solid angle \( \Delta \Omega = 20 \, \text{deg}^2 \) and included clusters at redshifts \( 0.1 < z < 1 \) in our analysis. Recall also that

\[ \eta = h^{-0.5} \frac{(1 + z_f)^{3/2}}{(1 + z_0)^{3/2}} f_M \sigma_\nu^{1/2}(z_f) P^2(z_0)\Omega^{1/2}. \]

In Figure 11, we show the comparison between the likelihoods obtained from \( \Delta C \) and from the two-dimensional K-S confidence levels, as a function of \( h \). Since the likelihood is non-Gaussian, the confidence levels have been obtained by numerically integrating the likelihood curve. The figure reveals that the likelihood method is more sensitive than the K-S test. For example, in the K-S case, the test puts this model at the significance. This finding suggests that a maximum likelihood method better captures the shape of the \( \eta \) versus \( z \) distribution of clusters and can significantly improve on the statistical constraints quoted here. We expect that a similarly improved use of the distribution shapes may be possible in other cases (e.g., in the measurements of \( \Omega_b \)). However, constraints obtained from a likelihood analysis can be dominated by the information available from the total cluster abundance rather than the shape. In those cases, an improved utilization of the shapes can result in only marginal improvements of the overall constraints, and, at the same time, the use of the maximum likelihood method would subject the results to additional systematic errors. A systematic study of the best statistic in each case is beyond the scope of the present paper and is deferred to a future publication.

8. DISCUSSION

In anticipation of extensive data on a large sample of galaxy clusters, it is important to analyze cluster properties to reduce systematic errors, to test whether physical properties of the local cluster sample are preserved at high redshift, and, if necessary, to model their evolution. We present a first attempt to do so self-consistently from cluster data.

The approach presented here assumes that the primordial fluctuation field was Gaussian. However, clusters are rare peaks of the density fluctuation and are therefore extremely sensitive to small deviations from Gaussianity. Nevertheless, this assumption is not crucial: a parameterization of non-Gaussianity could easily be included in the model as an additional free parameter (e.g., Robinson, Gawiser, \\& Silk 2000; Matarrese, Verde, \\& Jimenez 2000; Verde et al. 2001a, 2001b), and constraints on the non-Gaussianity parameter can be obtained from the cluster sample (Benson et al. 2002).

We have used four observables: the redshift, the X-ray temperature, the total observed SZD, and the cluster angular size. A particular worry in our approach is that we estimate the angular size based on the virial radius. Current numerical simulations of cluster formation (see, e.g., Bryan \\& Norman 1998) indeed indicate the presence of virialization shocks, as expected from the top-hat collapse model. However, the shock tends to be weaker and located at larger radii, which can make its detection in the SZE maps difficult or impossible. Cluster angular sizes can also be estimated from X-ray maps, which, however, effectively probe only radii smaller than the virial radius.

Alternatively, similar scaling relations could be obtained by considering other observables, in addition to those that we have considered here. The fundamental plane approach can be generalized to include, for example, the X-ray luminosity, the velocity dispersion, or estimates of the cluster masses (e.g., from weak lensing). This opens up many interesting possibilities. The constraints on cluster physics and cosmological parameters are complementary to constraints obtained from other observables; they could thus be combined with constraints obtained from X-ray cluster abundances, total Sunyaev-Zeldovich effect decrement cluster

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**Fig. 11.**—Comparison of two-dimensional K-S and maximum likelihood confidence levels. Since the cluster abundance is insensitive to \( h \), it is possible to directly compare the performances of the two tests for a sample of 300 clusters in our fiducial (deterministic) model. The likelihood is obtained following eqs. (17) and (20). The maximum likelihood method is much more sensitive than the K-S test, but it requires good knowledge of the cluster mass function and of mask and selection effects of the survey.
abundances, or analyses of kinetic SZE and weak lensing statistics.

9. CONCLUSIONS

In view of the advent of high-precision cosmology and the expected avalanche of cluster data available with SZE experiments in conjunction with X-ray missions, it is vital to be able to extract the maximum amount of information from these cluster samples.

We have investigated the scientific potential of obtaining total observed SZDs ($\Delta S_T$) in the context of a well-studied cluster sample, for which X-ray and optical follow-up are available. In particular, for cosmological studies, one would ideally like to use clusters as “standard candles”; the use of large future galaxy cluster surveys for cosmological studies is likely to be limited by the validity of this assumption rather than by statistical uncertainties (Haiman et al. 2001).

We have used a semianalytic model to study the expected distribution of galaxy clusters in redshift ($\Delta z$), virial temperature ($T$), Sunyaev-Zel’dovich decrement ($\Delta S_T$), and angular size ($\theta$). In the simplest models, clusters are identified with virialized, spherical halos. In this case, at every redshift, clusters define a “fundamental plane” in the three-dimensional parameter space ($T$, $\Delta S_T$, $\theta$). The FP and its redshift evolution are sensitive to both the internal evolution of clusters and to the underlying cosmological parameters and can be used to obtain useful constraints on both. We have parameterized possible deviations from this model to include effects of energy injection or feedback, stochastic scatter in the observables $T$, $\Delta S_T$, and $\theta$, and deviations from virial equilibrium. We have shown that their effect is to create measurable deformations in the FP. Our results show that the choice of statistics can have a significant impact on the derived constraints, at the level of a factor of several on the accuracies of constrained parameters.

We have derived predictions for cluster scaling relations that involve the SZE and studied how these scaling relations depend on assumptions about the cluster physics and structure (i.e., on the assumption that clusters are standard candles), as well as on the underlying cosmological parameters. In particular, we find that, if clusters are virialized objects, the cluster distribution in the ($\Delta S_T$, $T$)-plane should be narrow. The predicted tightness of the $\Delta S_T$-$T$ relation makes it especially useful for quantifying clusters’ physical properties and possible deviations from virialization and to detect the presence of stochastic scatter in ($T$, $\Delta S_T$, $\theta$); i.e., it is a useful tool to test whether clusters can be used as standard candles.

On the other hand, under the assumption that clusters can be used as standard candles, we show that deformations of the FP and of cluster scaling relations that involve $\Delta S_T$ can be used to determine cosmological parameters. The constraints on cosmological parameters so obtained are complementary to those obtained, e.g., from CMB primary anisotropies, cluster abundances, or clusters’ central SZE.

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REFERENCES

Bahcall, N. A., & Cen, R. Y. 1992, ApJ, 398, L81

Bennett, C. L., et al. 1995, BAAS, 187, 71.09

Bahcall, N. A. & Fan, X. 1998, ApJ, 531, 71

Bahcall, N. A., & Cen, R. Y. 1992, ApJ, 398, L81

Birkinshaw, M. 1979, MNRAS, 187, 847

Bialek, J. J., Evrard, A. E., & Mohr, J. J. 2001, ApJ, 555, 597

Bryan, G. L. 2000, ApJ, 544, L1

Bryan, G. L., & Norman, M. L. 1998, ApJ, 495, 80

Carlstrom, J. E., et al. 2002, in IAU Symp. 201, New Cosmological Data and the Values of the Fundamental Parameters, ed. A. Lasenby, A. Wilkinson, & A. W. Jones (San Francisco: ASP), in press

Cosh, W. 1979, ApJ, 228, 939

de Bernardis, P., et al. 2000, Nature, 404, 955

Eke, V. R., Navarro, J. F., & Steinmetz, M. 2001, MNRAS, 321, 559

Evrard, A. E. 1989, ApJ, 341, L71

1990, ApJ, 363, 349

Evrard, A. E., & Halverson, J. P. 1991, ApJ, 383, 95

Evans, N. R., & Frenk, C. S. 1996, MNRAS, 282, 263

Eke, V. R., Navarro, J. F., & Frenk, C. S. 1998, ApJ, 503, 569

Eke, V. R., Navarro, J. F., & Steinmetz, M. 2001, ApJ, 554, 114

Evrard, A. E., & Henry, J. P. 1991, ApJ, 379, 85

Ek, V. R., Cole, S. W., & Frenk, C. S. 1999, MNRAS, 300, 146

Nakajima, T., Suto, Y., & Kneisel, R. 2001, MNRAS, 328, 783

Lacey, C., & Cole, S. 1993, MNRAS, 262, 627

1994, MNRAS, 271, 676

Lilje, P. B. 1991, ApJ, 386, L33

Mandolesi, N. et al. 1998, Low-Frequency Instrument for Planck (proposal submitted to ESA)

Mason, B. S., Myers, S. T., & Readhead, A. C. S. 2001, ApJ, 555, L11

Matarrese, S., Verde, L., & Zucca, D. 2000, MNRAS, 328, 783

Mathieson, B. F. 2001, MNRAS, 326, L1

McDonald, P. D., et al. 2000, ApJ, 536, L59

Mohr, J. J., Evrard, A. E., Couchman, H. M. P., & Evrard, A. E. 1999, ApJ, 520, 78

Mukhopadhyay, P. D., & Erlandson, E. D., Lewis, A. D., & Evrard, A. E. 2000, ApJ, 544, 109

Myers, S. T., & Bower, G. 2000, MNRAS, 300, 146

Myers, S. T., & Bower, G. 2000, MNRAS, 300, L27

Nanayonik, A., Couchman, H. M. P., & Evrard, A. E. 1999, ApJ, 520, 78

Peacock, J. A. 1983, MNRAS, 202, 615

Press, W. R. 1973, ApJ, 300, 2

Reichardt, C., & Kamionkowski, M. 2002, MNRAS, 331, 71

Reese, E. D., & Mohr, J. J. 2001, ApJ, 565, L5

Schechter, P. L., & Fan, X. 1995, ApJ, 456, 5

Soifer, B. T., et al. 1998, ApJ, 500, 99

Spitzer, L. 1978, Physics of Fully Ionized Gases (New York: Interscience), 2nd ed.

Spergel, D. N., et al. 2003, ApJS, 148, 175

Stanek, K. Z., & Suntzeff, N. B. 1996, ApJ, 469, 100

Steinmetz, M., & Navarro, J. F. 2001, MNRAS, 321, 372

Tegmark, M., et al. 2004, ApJ, 610, 775

Thomsen, P., et al. 2002, A&A, 382, 8

Vogelsberger, M., et al. 2009, ApJ, 706, 1

Wright, E. L., et al. 2006, ApJ, 652, 77

Xue, J. Z., et al. 2010, ApJ, 710, 186

Yee, H. K. C., et al. 1996, ApJ, 469, 567

Zentner, A. R., & Bullock, J. S. 2003, ApJ, 582, 7

Zucker, J. M., & Steinhardt, P. J. 2003, Phys. Rev. D, 67, 023507

Zucca, D., et al. 2000, ApJ, 536, 10

Zucca, D., et al. 2000, ApJ, 540, 99

Zucca, D., et al. 2000, ApJ, 536, 10

Zucca, D., et al. 2000, ApJ, 540, 99

Zucca, D., et al. 2000, ApJ, 536, 10

Zucca, D., et al. 2000, ApJ, 540, 99

Zucca, D., et al. 2000, ApJ, 540, 99
Peebles, P. J. E. 1980, Large-Scale Structure of the Universe (Princeton: Princeton Univ. Press)
Pen, U. 1999, ApJS, 120, 49
Perlmutter, S., et al. 1999, ApJ, 517, 565
Pierpaoli, E., Scott, D., & White, M. 2001, MNRAS, 325, 77
Press, W. H., & Schechter, P. L. 1974, ApJ, 187, 425
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical Recipes in FORTRAN (2d ed.; Cambridge: Cambridge Univ. Press)
Reese, E. D., et al. 2000, ApJ, 533, 38
Riess, A. G., et al. 1998, AJ, 116, 1009
Robinson, J., Gawiser, E., & Silk, J. 2000, ApJ, 532, 1
Roettiger, K., Loken, C., & Burns, J. 1997, ApJS, 109, 307
Roukema, B. F., & Mamon, G. A. 2002, in IAU Symp. 201, New Cosmological Data and the Values of the Fundamental Parameters, ed. A. Lasenby, A. Wilkinson, & A. W. Jones (San Francisco: ASP), in press
Sasaki, S. 1994, PASJ, 46, 427
Sheth, R., Mo, H. J., & Tormen, G. 1999, MNRAS, submitted (astro-ph/9907024)
Silk, J., & White, S. D. M. 1978, ApJ, 226, L103
Sugiyama, N. 1995, ApJS, 100, 281
Sunyaev, R. A., & Zeldovich, Ya. B. 1980, ARA&A, 18, 537
Tucker, W., et al. 1998, ApJ, 496, L5
Verde, L., Jimenez, R., Kamionkowski, M., & Matarrese, S. 2001a, MNRAS, 325, 412
Verde, L., Kamionkowski, M., Mohr, J. J., & Benson, A. J. 2001b, MNRAS, 321, L7
Viana, P. T. P., & Liddle, A. R. 1996, MNRAS, 281, 323
———. 1999, MNRAS, 303, 535
Voit, G. M., & Donahue, M. 1998, ApJ, 500, L111
Wang, L., & Steinhardt, P. J. 1998, ApJ, 508, 483
Wechsler, R. H., Bullock, J. S., Primack, J. R., Kravtsov, A. V., & Dekel, A. 2002, ApJ, 568, 52
White, S. D. M., Efstathiou, G., & Frenk, C. S. 1993, MNRAS, 262, 1023
Willick, J. A. 2000, ApJ, 530, 80
Xu, H., Jin, G., & Wu, X.-P. 2001, ApJ, 553, 78