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A MEASUREMENT OF H_0 FROM THE SUNYAEV-ZELDOVICH EFFECT

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ABSTRACT

We present a determination of the Hubble constant, H_0, from measurements of the Sunyaev-Zeldovich effect in an orientation-unbiased sample of seven $z < 0.1$ galaxy clusters. With improved X-ray models and a more accurate 32 GHz calibration, we obtain $H_0 = 64^{+14}_{-11} \pm 14_{\rm sys}$ km s^{-1} Mpc^{-1} for a standard cold dark matter (CDM) cosmology, or $H_0 = 66^{+14}_{-11} \pm 15_{\rm sys}$ km s^{-1} Mpc^{-1} for a flat ΛCDM cosmology. In combination with X-ray cluster measurements and the big bang nucleosynthesis value for Ω_B, we find $\Omega_M = 0.32 \pm 0.05$.

Subject headings: cosmic microwave background — cosmology: observations — dark matter — distance scale — galaxies: clusters: individual (Abell 399, Abell 401, Abell 478, Abell 1651, Abell 2142, Abell 2256, Coma)

1. INTRODUCTION

The Sunyaev-Zeldovich effect (SZE) is a spectral distortion in the cosmic microwave background (CMB) due to inverse Compton scattering of the CMB photons off hot electrons; at radio frequencies, this distortion is manifested as a fractional decrement in intensity of order 10^{-4}. For over two decades it has been known (Silk & White 1978; Cavaliere, Danese, & De Zotti 1979) that the combination of X-ray and SZE observations of rich galaxy clusters, under the assumption of spherical symmetry, yields a direct measurement of the cosmic distance scale. Only in the past few years have reliable and accurate applications of this method become possible (e.g., Birkinshaw, Hughes, & Arnaud 1991; Herbig et al. 1995; Carlstrom, Joy, & Grego 1996; Grainge et al. 1996; Holzapfel et al. 1997). Due to the assumption of spherical symmetry, selection biases have been a great concern. To address this, Myers et al. (1997) defined an X-ray flux-limited sample of 11 $z < 0.1$ clusters and began a campaign to measure distances to these clusters. This yields an orientation-unbiased sample, and departures from spherical symmetry in individual clusters will average out in the determination of H_0 from the sample as a whole. Myers et al. obtain a Hubble constant of 54 ± 14 km s^{-1} Mpc^{-1} from observations of four clusters. The accuracy of this result is limited by a 7% radio calibration uncertainty and estimated 15%–30% X-ray model uncertainties for each cluster.

In this Letter, we present an improved measurement of H_0 based on the Herbig et al. and Myers et al. results on Coma, A478, A2142, and A2256, plus observations of three new clusters (A399, A401, A1651) from their complete sample. The results we present incorporate more accurate X-ray models (Mason & Myers 2000, hereafter MM2000) and a more accurate radio calibration (Mason et al. 1999). We also calculate the effect of intrinsic CMB anisotropies on our result and find them to be a limiting factor for a sample of this size. Throughout this Letter, we use $H_0 = 100\ h$ km s^{-1} Mpc^{-1} and consider two cosmologies: standard cold dark matter (SCDM; $\Omega_M = 1$, $\Omega_\Lambda = 0$) and ΛCDM ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$). Unless otherwise stated, we assume the SCDM cosmology.

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2. THE SUNYAEV-ZELDOVICH EFFECT, CLUSTER SAMPLE, AND X-RAY MODELS

2.1. *The Sunyaev-Zeldovich Effect*

The observed fractional change in antenna temperature induced by a cloud of electrons with a beam-averaged Compton y-parameter $y_{\rm obs}$ is (Sunyaev & Zeldovich 1980)

$$\frac{\Delta T_{\rm obs}}{T_{\rm cmb}} = \frac{x^2 e^x}{(e^x - 1)^2}\,[x \coth(x/2) - 4]\chi_{\rm rel}^{-1} y_{\rm obs}. \qquad (1)$$

Here $x = h\nu/kT_{\rm cmb}$, and $\chi_{\rm rel}^{-1}$ is a relativistic correction factor, which we compute using the analytic expression of Sazonov & Sunyaev (1998). We assume zero peculiar velocity, which introduces an ∼5% uncertainty but will average out over the sample. Along a given line of sight, the Compton y-parameter is

$$y = \frac{kT_e}{m_e c^2}\,\tau, \qquad (2)$$

where τ is the inverse Compton optical depth. At 32.0 GHz ($x = 0.563$), equation (1) takes the form

$$\frac{\Delta T_{\rm obs}}{T_{\rm cmb}} = -1.897 y_{\rm obs}\chi_{\rm rel}^{-1}. \qquad (3)$$

We follow the procedure of Myers et al. (1997) in correcting the observed Compton y-parameters for relativistic effects rather than the models.

Given a model for the cluster density and temperature profiles from X-ray observations, we predict the SZE decrement in terms of the Compton y-parameter averaged over the telescope beam and switching patterns:

$$y_{\rm pred} = \frac{1}{\Omega_{\rm beam}} \int d\Omega\, y_{\rm model}(\hat{\Omega}) R_{N,\,{\rm sw}}(\hat{\Omega}). \qquad (4)$$

Here $\Omega_{\rm beam}$ is the solid angle of the telescope beam, $y_{\rm model}$ is the predicted y along a given line of sight, and $R_{N,\,{\rm sw}}(\hat{\Omega})$ is the normalized beam response, including the effects of switching. It is easily shown that $y_{\rm pred}$, as determined from X-ray observations and equation (4), is proportional to $h^{-1/2}$, so that

TABLE 1
Cluster Model Parameters

Cluster	z	θ_0 (arcmin)	β	n_{e0} ($\times 10^{-3}\ h^{1/2}\ \mathrm{cm}^{-3}$)	kT_e (keV)	τ_{sw} ($\times 10^{-3}\ h^{-1/2}$)
A399	0.0715	4.33 ± 0.45	0.742 ± 0.042	3.23 ± 0.18	7.0 ± 0.2	2.50 ± 0.13
A401	0.0748	2.26 ± 0.41	0.636 ± 0.047	7.90 ± 0.81	8.0 ± 0.2	3.17 ± 0.18
A478	0.0900	1.00 ± 0.15	0.638 ± 0.014	27.81 ± 9.7	8.4 ± 0.7	3.68 ± 0.15
A1651	0.0825	2.16 ± 0.36	0.712 ± 0.036	7.14 ± 3.20	6.1 ± 0.2	2.44 ± 0.11
Coma	0.0232	9.32 ± 0.10	0.670 ± 0.003	4.52 ± 0.04	9.1 ± 0.4	2.76 ± 0.16
A2142	0.0899	1.60 ± 0.12	0.635 ± 0.012	14.95 ± 1.0	9.7 ± 0.8	4.28 ± 0.18
A2256	0.0601	5.49 ± 0.21	0.847 ± 0.024	4.08 ± 0.08	6.6 ± 0.2	3.19 ± 0.16

Note.—τ_{sw}, θ_0, β, and n_{e0} are from MM2000; T_e-values are from Markevitch et al. 1998; redshifts are from Struble & Rood 1991. Uncertainties are 1 σ.

if $y_{obs} = q$ and $y_{pred} = ph^{-1/2}$, the Hubble constant is given by

$$h = \left(\frac{p}{q}\right)^2. \quad (5)$$

Note that the τ_{sw}-values presented in MM2000 are simply the model inverse Compton optical depths convolved with the telescope beam-switching pattern as per equation (4). For an isothermal cluster, $y_{pred} = \tau_{sw} kT_e / m_e c^2$.

2.2. *Cluster Sample*

In MM2000 we define a larger, X-ray flux-limited cluster sample that expands upon that presented by Myers et al. (1997). This is a 90% volume-complete sample selected from the X-ray Brightest Abell-type Cluster (XBAC) catalog (Ebeling et al. 1996) with $z < 0.1$ and $F_X > 1.0 \times 10^{-11}$ ergs cm^{-2} s^{-1}. At $z = 0.1$, the volume-completeness criterion corresponds to $L_X > 1.13 \times 10^{44}\ h^{-2}$ ergs s^{-1} (0.1–2.4 keV). The resulting set of 31 clusters contains the Myers et al. (1997) sample. While the seven clusters for which we present measurements here are all members of the smaller Myers et al. sample, this work is part of an ongoing project to survey distances to the objects in our expanded sample. MM2000 discusses in detail the completeness of this XBAC-derived catalog.

2.3. *X-Ray Models*

MM2000 also presents X-ray models for the 22 clusters in our sample that had public *ROSAT* Position Sensitive Proportional Counter data as of 1999 May. The primary focus of this analysis was to quantify the uncertainty in the beam-convolved inverse Compton optical depth, τ_{sw}, a quantity that we find is robustly constrained by the *ROSAT* data. We adopt the Markevitch et al. (1998) measurements of the cluster gas temperature T_e, which—except for the Coma Cluster—we assume to be isothermal. For the Coma Cluster, following Hughes, Gorenstein, & Fabricant (1988), we adopt a hybrid model, which is isothermal inside a radius of 500 h^{-1} kpc, outside of which the temperature follows the density profile with an adiabatic index of $\gamma = 1.5$. For A478 and A2142, we use the fits that have been corrected for the spectral bias induced by the cooling flow emission. Table 1 summarizes our cluster models and the resulting beam-averaged Compton y-values, y_{pred}. In § 4, we discuss the impact on H_0 of our choices for the cluster models.

3. SZE OBSERVATIONS

In this section we report on observations of seven clusters from our sample. Two of these, A399 and A401, are in close proximity. The effects of this are included in our model predictions (see § 4).

3.1. *New Observations*

For the observations reported here, the Owens Valley Radio Observatory (OVRO) 5.5 m (5 m) telescope was outfitted with a high electron mobility transistor (HEMT) receiver having a center frequency of 32 GHz and a bandwidth of 6.5 GHz. The HEMT input is Dicke-switched every millisecond between two ambient-temperature corrugated feeds that give rise to two 7$'$.35 FWHM Gaussian beams [each having a main-beam volume of $\Omega_{beam} = (5.21 \pm 0.03) \times 10^{-6}$ sr] separated by 22$'$.16 in azimuth. To remove systematic effects due primarily to atmosphere and ground, we employ a triple-differencing technique. Two levels of differencing are provided by the Dicke-switching between the target (ON) position and a reference (REF) position and by nodding the telescope in azimuth at a rate of ∼0.1 Hz. The third level is provided by observing blank leading (LEAD) and trailing (TRAIL) fields over the same range of azimuth and elevation as the MAIN field, so that ground-based signals are cancelled in the difference. The cluster signal is given by the MAIN field signal minus the average of the LEAD and TRAIL signals (MLT). The LEAD-TRAIL field difference (LTD) provides a diagnosis of possible residual signals due, e.g., to unsubtracted ground emission or intrinsic CMB fluctuations.

Flux density calibration is accomplished with reference to Cassiopeia A using an epoch 1998 flux of 194 ± 4 Jy (Mason et al. 1999), with the secular variation of Cas A modeled as per Baars et al. (1977). Data are edited by automatic filtering algorithms that use the scatter of the data and their standard deviations as rejection criteria. More discussion of our observing strategy and data filters is given in Readhead et al. (1989) and Myers et al. (1997); more details on the instrument are in Leitch et al. (2000).

3.1.1. *Discrete Source Removal*

The brightest contaminating discrete sources in A399 and A1651, selected from the 87GB catalog (Gregory & Condon 1991), were monitored at 18.5 GHz with the OVRO 40 m telescope in 1996 November and December, concurrent with cluster SZE observations. In the fall of 1997 we used the OVRO 40 m telescope to survey all NRAO VLA Sky Survey (Condon et al. 1998) sources in these fields and those for A401 which, assuming a flat spectrum, would give a peak signal of greater than 16 μK at 32 GHz. We also observed *all* sources within 12$'$ of any of the field centers and having 1.4 GHz flux densities greater than 50 mJy. Sources that showed indications of variability were extrapolated to 32 GHz assuming a flat spectrum; otherwise the two-point spectral index between 1.4 and 32 GHz was used. The overall corrections in μK are given for each cluster in § 3.1.2.

3.1.2. *A399, A401, and A1651*

Observations of A399 were taken from 1996 October through 1997 March. For these observations, the LEAD and TRAIL fields were separated from the MAIN by 26 minutes of right ascension. After statistical filters and weighting of the data, we acquired 40 hr of total integration time including LEAD and TRAIL fields, and time spent on the REF beams. To account for source contamination, 24 ± 5 μK was subtracted from the observed signal. We then determine a decrement of $\Delta T_{\rm obs} = -164 \pm 21$ μK (MLT). The LEAD-TRAIL difference is $\Delta T_{\rm LTD} = 15 \pm 21$ μK. The observed ΔT corresponds to $y_{\rm obs} = (3.28 \pm 0.42) \times 10^{-5}$, including the relativistic correction $\chi_{\rm rel} = 1.027$.

A1651 was also observed during this period, with LEAD and TRAIL field separations of $20^{\rm m}30^{\rm s}$ from the MAIN field; the effective total integration time was 25 hr. We subtract 5 ± 1 μK from the observed decrement to correct for discrete sources. These are mostly in the REF beam of the LEAD field. With the source correction, we determine a decrement $\Delta T_{\rm obs} = -247 \pm 30$ μK (MLT). The LTD is $\Delta T_{\rm LTD} = -92 \pm 36$ μK. The Compton y-parameter is $y_{\rm obs} = (4.88 \pm 0.59) \times 10^{-5}$ including the relativistic correction $\chi_{\rm rel} = 1.023$.

A401 was observed from 1997 October to 1998 March, giving an effective total integration time of 43 hr. The LEAD and TRAIL field separations were $16^{\rm m}36^{\rm s}$. Discrete sources contribute 16 ± 11 μK. The source-corrected decrement is $\Delta T_{\rm obs} = -338 \pm 20$ μK (MLT); the LTD is $\Delta T_{\rm LTD} = 133 \pm 24$ μK. This gives (with $\chi_{\rm rel} = 1.031$) $y_{\rm obs} = (6.33 \pm 0.43) \times 10^{-5}$. The statistically significant LTD's for A401 and A1651 are discussed in § 4.

3.2. *Coma Cluster*

Herbig et al. (1995) used the OVRO 5 m telescope to determine the SZE decrement toward the Coma Cluster (Abell 1656) during the observing seasons of 1992 and 1993 and found a Rayleigh-Jeans temperature decrement of $\Delta T_{\rm obs} = -302 \pm 48$ μK. These data were calibrated relative to DR 21 assuming $S_{\rm DR\,21} = 18.24 \pm 0.55$ Jy and referenced to the telescope main beam assuming $\Omega_{\rm beam} = (5.16 \pm 0.15) \times 10^{-6}$ sr. From the Mason et al. (1999) flux density scale and $\chi_{\rm rel} = 1.035$, we determine a beam-averaged Compton y-parameter of $y_{\rm sw} = (6.38 \pm 1.01) \times 10^{-5}$.

3.3. *A478, A2142, and A2256*

A478, A2142, and A2256 were observed by Myers et al. (1997) from July 1993 to March 1994 resulting in decrements of $-375 \pm 28, -437 \pm 25$, and -243 ± 29 μK, respectively; these temperature are referred to the main beam, and have been corrected for point-source contamination. These data were calibrated using a brightness temperature of $T_{\rm J} = 144 \pm 8$ K for Jupiter. After including the correction for the main-beam area [Myers et al. 1997 use $(5.12 \pm 0.14) \times 10^{-6}$ sr], we find an overall correction of $f = 1.037$ for the Myers et al. data. The stated decrements yield switched, beam-averaged Compton y-parameters of $(7.25 \pm 0.54) \times 10^{-5}$, $(8.44 \pm 0.48) \times 10^{-5}$, and $(4.70 \pm 0.56) \times 10^{-5}$, respectively. We apply relativistic corrections ($\chi_{\rm rel} = 1.033$, 1.037, and 1.026) together with our calibration correction, and find Compton y-values of $(7.77 \pm 0.58) \times 10^{-5}$, $(9.10 \pm 0.52) \times 10^{-5}$, and $(5.00 \pm 0.60) \times 10^{-5}$.

4. INTERPRETATION

For SZE observations at our frequencies and angular scales, intrinsic CMB anisotropies are a significant source of uncertainty. We use the RING5M measurements (Leitch et al. 2000) to determine the impact of this on our H_0 results. In measurements taken with the OVRO 5 m telescope at 32 GHz, Leitch et al. determined an rms temperature difference on 22′ scales of $\delta T_{22'} = 79^{+11}_{-10}$ μK. In order to determine the degree to which parallactic angle averaging during a track on a cluster reduces this, we generated 10^3 realizations of 4 deg^2 patches of sky from a ΛCDM power spectrum. Each realization was convolved with the 5 m telescope main beam and the switching pattern characteristic of a typical SZE observation. We find (including the LEAD/TRAIL differencing) a residual CMB signal of $81.6\% \times \delta T_{22'}$, or 64 μK ($\sigma_y = 1.24 \times 10^{-5}$) assuming the RING5M power level. The rms of LTD predicted by this analysis is 90 μK, close to the observed rms of 79 μK in our seven clusters. On this basis, the nonzero LTD's seen in A1651 and A401 are not unexpected.

While this noise level is not small compared to the signal in fainter clusters such as A399, we leave these clusters in our sample to avoid an orientation bias and perform a maximum likelihood analysis to determine H_0. Assume that we have N observed Compton y-parameters q_i and N predicted y-parameters (as per eq. [5]) p_i determined from X-ray observations. The SZE observations are corrupted with random Gaussian noise $\sigma_{q,\,i}$ (including thermal noise and point-source subtraction uncertainties) and the predictions are corrupted with random Gaussian noise $\sigma_{p,\,i}$; the rms residual CMB signal is $\sigma_{\rm cmb} = 64$ μK. In addition, there are N "true" predictions $\hat{p}_i$, which are the predictions that we would have in the absence of errors in the X-ray models. Then we can determine h by minimizing

$$\chi^2 = \sum_{i=1}^{N} \frac{(q_i - h^{-1/2}\hat{p}_i)^2}{\sigma_{q,\,i}^2 + \sigma_{\rm cmb}^2} + \frac{(p_i - \hat{p}_i)^2}{\sigma_{p,\,i}^2}, \qquad (6)$$

where $\chi^2 \equiv -2 \ln L$. The unconstrained $\hat{p}_i$ must also be minimized in this process, but these can be projected out analytically. Setting the derivatives of χ^2 with respect to the $\hat{p}_i$ equal to zero, we find

$$\hat{p}_i = \frac{q_i + f_i h^{1/2} p_i}{h^{-1/2} + f_i h^{1/2}}, \qquad (7)$$

with $f_i = (\sigma_{q,\,i}^2 + \sigma_{\rm cmb}^2)/\sigma_{p,\,i}^2$. This leaves a one-dimensional parameter space. The value of h that minimizes equation (6) is the most probable value; two-sided 68% confidence intervals are determined about this value by integrating the likelihood function L. We impose the prior $0.01 < h < 5$; our upper bound on H_0 for A399 is slightly affected by our choice of prior, but other results are not. Monte Carlo tests with the estimator of equation (6) show that within the range of power levels allowed by RING5M, our result is not affected by the uncertainty in $\sigma_{\rm cmb}$.

Table 2 shows the measured and predicted values of the Compton y-parameter for our seven clusters along with the maximum likelihood values for and 68% confidence limits on H_0. A399 and A401 are in close spatial proximity with the result that the observed decrement on either is reduced somewhat due to signal

TABLE 2
H_0 RESULTS ON FIVE CLUSTERS

Cluster	y_{obs} ($\times 10^{-5}$)	y_{pred} ($\times 10^{-5}\ h^{-1/2}$)	H_0 (km s^{-1} Mpc^{-1})
A399	3.24 ± 0.41	3.27 ± 0.20	102^{+116}_{-53}
A401	6.93 ± 0.46	4.82 ± 0.32	48^{+28}_{-16}
A478	7.77 ± 0.58	6.05 ± 0.54	61^{+33}_{-20}
A1651	4.88 ± 0.59	2.92 ± 0.17	36^{+35}_{-15}
Coma	6.38 ± 1.01	5.00 ± 0.38	62^{+49}_{-24}
A2142	9.10 ± 0.52	8.12 ± 0.74	79^{+34}_{-24}
A2256	5.00 ± 0.60	4.11 ± 0.26	67^{+62}_{-28}
Sample	…	…	64^{+14}_{-11}

NOTE.—Uncertainties are 1 σ random errors only.

from the other in the reference beam; this is accounted for in the stated values of y_{pred}. Averaged over a track, we find a decrease in the predicted y for A399 of $(0.15 \pm 0.05) \times 10^{-5}\ h^{-1/2}$ and for A401 of $(0.13 \pm 0.05) \times 10^{-5}\ h^{-1/2}$. For an SCDM cosmology, the sample average is 64^{+14}_{-11} km s^{-1} Mpc^{-1}. The *scatter* of the H_0-values gives an error in the mean of only 8 km s^{-1} Mpc^{-1}, which is less than that given by our maximum likelihood analysis. The minimum of χ^2 corresponds to $\chi^2_\nu = 0.32$ for $\nu = 6$; there is an ~5% chance of obtaining a χ^2_ν-value this low by chance for 6 degrees of freedom. We therefore think it likely that the scatter in these seven clusters is fortuitously small. Since our observing and modeling errors have been well quantified, the maximum likelihood method gives a more reliable estimate of the uncertainty than the data scatter for a small sample such as ours. Our result is not sensitive to the model we choose for the cluster temperature profile: adopting hybrid models for all five clusters reduces the sample average by only 4%. Although more extreme models for the temperature profiles would have a larger effect on our result, such models are not motivated by current X-ray analyses (Irwin, Bregman, & Evrard 1999; White 2000). For a ΛCDM cosmology, the sample average is 66^{+14}_{-11} km s^{-1} Mpc^{-1}. The calibration uncertainties are 3% (radio) and 8% (X-ray), and we estimate a 10% uncertainty in the SZE predictions due to the possibility of substructure and nonisothermality in the intracluster medium (ICM). Altogether, we have a systematic error budget of $\pm 14_{sys}$ km s^{-1} Mpc^{-1}, or $\pm 15_{sys}$ km s^{-1} Mpc^{-1} for ΛCDM.

The increase in H_0 relative to the Myers et al. (1997) result is due primarily to differences in the updated X-ray models. As a check on our *ROSAT*-derived density models, we have compared the baryonic masses that we obtain inside 500 h^{-} kpc to those obtained by Mohr, Mathiesen, & Evrard (1999) for 20 of the 22 clusters in common to our analyses: we find that the mean mass ratio is equal to unity at better than 1% accuracy. See MM2000 for more discussion of this analysis. Also the T_e-values we have used tend to be higher than the Myers et al. values due to the correction for the spectral bias of the cooling flows. Using the Myers et al. temperatures increases the fractional scatter in the H_0-values by over a factor of 2 and decreases the sample mean to 55 km s^{-1} Mpc^{-1}. The fact that the uncertainty in our result is comparable to that of Myers et al.—in spite of improved X-ray models, better calibration, and three more clusters—is due to our inclusion of intrinsic anisotropy in the analysis.

5. CONCLUSIONS

We have presented a determination of H_0 resulting from measuring the SZE in five clusters from an unbiased, low-redshift sample. For an SCDM cosmology we find $H_0 = 64^{+14}_{-11} \pm 14_{sys}$ km s^{-1} Mpc^{-1}, while for a ΛCDM cosmology we obtain $H_0 = 66^{+14}_{-11} \pm 15_{sys}$ km s^{-1} Mpc^{-1}. This result is in good agreement with other recent measurements. Madore et al. (1999), using Cepheid variables as distance indicators, find $72 \pm 5 \pm 7_{sys}$ km s^{-1} Mpc^{-1}. Gravitational lens time delays give results consistent with these (e.g., Fassnacht et al. 1999).

Our value of H_0 implies an age for the universe ranging from $(10.2 \pm 3.2) \times 10^9$ yr for an SCDM universe to $(14.2 \pm 4.5) \times 10^9$ yr for ΛCDM. These are both consistent with recent age determinations from main-sequence fitting, which give ages of $(>12 \pm 1) \times 10^9$ yr (Chaboyer et al. 1998). In the X-ray cluster analysis of MM2000 we find a mean ICM mass fraction $f_{ICM} \equiv M_{bary}/M_{tot} = (7.02 \pm 0.28)\ h^{-3/2} \times 10^{-2}$ (within $R_{500} \sim 1\ h^{-1}$ Mpc) in a sample of 22 nearby clusters. We combine this result with the big bang nucleosynthesis constraint $\Omega_B h^2 = 0.019 \pm 0.001$ (Burles & Tytler 1998) and our value for H_0 to find a total matter density $\Omega_M = 0.32 \pm 0.05$, arguing against SCDM cosmologies.

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