

## CHANDRA CLUSTER COSMOLOGY PROJECT III: COSMOLOGICAL PARAMETER CONSTRAINTS

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### ABSTRACT

*Chandra* observations of large samples of galaxy clusters detected in X-rays by *ROSAT* provide a new, robust determination of the cluster mass functions at low and high redshifts. Statistical and systematic errors are now sufficiently small, and the redshift leverage sufficiently large for the mass function evolution to be used as a useful growth of structure based dark energy probe. In this paper, we present cosmological parameter constraints obtained from *Chandra* observations of 37 clusters with  $\langle z \rangle = 0.55$  derived from 400 deg<sup>2</sup> *ROSAT* serendipitous survey and 49 brightest  $z \approx 0.05$  clusters detected in the All-Sky Survey. Evolution of the mass function between these redshifts requires  $\Omega_\Lambda > 0$  with a  $\sim 5\sigma$  significance, and constrains the dark energy equation of state parameter to  $w_0 = -1.14 \pm 0.21$ , assuming constant  $w$  and flat universe. Cluster information also significantly improves constraints when combined with other methods. Fitting our cluster data jointly with the latest supernovae, WMAP, and baryonic acoustic oscillations measurements, we obtain  $w_0 = -0.991 \pm 0.045$  (stat)  $\pm 0.039$  (sys), a factor of 1.5 reduction in statistical uncertainties, and nearly a factor of 2 improvement in systematics compared to constraints that can be obtained without clusters. The joint analysis of these four datasets puts a conservative upper limit on the masses of light neutrinos,  $\sum m_\nu < 0.33$  eV at 95% CL. We also present updated measurements of  $\Omega_M h$  and  $\sigma_8$  from the low-redshift cluster mass function.

*Subject headings:* cosmology: observations, cosmological parameters, dark matter — clusters: general — surveys

### 1. DARK ENERGY AND CLUSTER MASS FUNCTION

Recent accelerated expansion of the Universe detected in the Hubble diagram for distant type Ia supernovae is one of the most significant discoveries of the past 10 years (Perlmutter et al. 1999; Riess et al. 1998). The acceleration can be attributed to the presence of a significant energy density component with negative pressure, hence the phenomenon is commonly referred to as Dark Energy. For a recent review of the dark energy discovery and related theoretical and observational issues, see Frieman, Turner & Huterer (2008) and references therein. Perhaps the simplest phenomenological model for dark energy is non-zero Einstein’s cosmological constant. The supernovae data indicated (and other cosmological datasets now generally agree) that a cosmological constant term currently dominates energy density in the Universe.

The next big question is whether Dark Energy really is the cosmological constant. The properties of dark energy are commonly characterized by its equation of state parameter,  $w$ , defined as  $p = w\rho$ , where  $\rho$  is the dark energy density and  $p$  is its pressure. A cosmological constant in the context of General Relativity corresponds to a non-evolving  $w = -1$ . It is proposed that departures from the cosmological constant model should be sought in the form of observed  $w$  being either  $\neq -1$ , or evolving with redshift. Combination of supernovae,

cosmic microwave background, and baryonic acoustic oscillations data currently constrain  $|1 + w| < 0.15$  at 95% CL (Komatsu et al. 2008). Observational signatures of such deviations of  $w$  from  $-1$  are very small, and hence the measurements are prone to systematic errors. For example, variations of  $w$  between  $-1$  and  $-0.9$  change fluxes of  $z = 0.75$  supernovae in a flat universe with  $\Omega_M = 0.25$  by only 0.03 magnitudes. Therefore, it is crucially important that the dark energy constraints at this level of accuracy are obtained from combination of several independent techniques. This not only reduces systematics but also improves statistical accuracy by breaking degeneracies in the cosmological parameter constraints.

One of the methods that has been little used so far is evolution in the number density of massive galaxy clusters. Evolution of the cluster mass function traces (with exponential magnification) growth of linear density perturbations. Growth of structure and distance-redshift relation are similarly sensitive to properties of dark energy, and also are mutually highly complementary methods (e.g., Linder & Jenkins 2003). Mapping between the linear power spectrum and cluster mass function relies on the model for nonlinear gravitational collapse. This model is now calibrated extensively by  $N$ -body simulations (see § 3). The cluster mass function models also use additional assumptions (e.g., that the mass density is dominated by cold dark matter in the recent past, and that the fluctuations have Gaussian distribution). However, corrections due to reasonable departures from these assumptions are negligible compared to statistical uncertainties in the current samples (we discuss these issues further in § 3). It is important also that the theory of nonlinear collapse is insensitive to the background cosmology. For example, the same model accurately describes the relation between the linear power spectrum and cluster mass function in the  $\Omega_M = 1$ ,  $\Omega_\Lambda = 0$ , low-density  $\Omega_M = 0.3$ ,  $\Omega_\Lambda = 0$ , and “concordant”  $\Omega_M = 0.3$ ,  $\Omega_\Lambda = 0.7$  cosmologies (Jenkins et al. 2001).

Fitting cosmological models to the real cluster mass func-

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tion measurements uses not only growth of structure but also the distance-redshift information because observed properties for objects of the same mass generally depend on the distance. Therefore, constraints on  $w$  derived from the cluster mass function internally make a combination of growth of structure and distance based cosmological tests, and thus potentially can be very accurate and competitive with any other technique (e.g., Albrecht et al. 2006).

Previous attempts to use evolution of the cluster mass function as a cosmological probe were limited by small sample sizes and either poor proxies for the cluster mass (e.g., the total X-ray flux) or inaccurate measurements (e.g., temperatures with large uncertainties). Despite these limitations, reasonable constraints could still be derived on  $\Omega_M$  (e.g., Borgani et al. 2001; Henry 2004). However, constraints on the dark energy equation of state from such studies are weak. For example, Henry (2004) derived the best-fit  $w = -0.42$ , only marginally inconsistent with  $w = -1$ , using the temperature function of the *Einstein* Medium Sensitivity Survey clusters; Mantz et al. (2007) determine  $w = -1.4 \pm 0.55$  with a larger sample of distant clusters (MACS survey, see Ebeling et al. 2001) but using the X-ray luminosity as a mass proxy.

The situation with the cluster mass function data has been dramatically improved in the past two years. A large sample of sufficiently massive clusters extending to  $z \sim 0.9$  has been derived from *ROSAT* PSPC pointed data covering 400 deg<sup>2</sup> (Burenin et al. 2007, Paper I hereafter). Distant clusters from the 400d sample were then observed with *Chandra*, providing high-quality X-ray data and much more accurate total mass indicators. *Chandra* coverage has also become available for a complete sample of low- $z$  clusters originally derived from the *ROSAT* All-Sky Survey. Results from deep *Chandra* pointings to a number of low- $z$  clusters have significantly improved our knowledge of the outer cluster regions and provided a much more reliable calibration of the  $M_{\text{tot}}$  vs. proxy relations than what was possible before. On the theoretical side, improved numerical simulations resulted in better understanding of measurement biases in the X-ray data analysis (Nagai et al. 2007; Rasia et al. 2006; Jeltama et al. 2007). Even more importantly, results from these simulations have been used to suggest new, more reliable X-ray proxies for the total mass (Kravtsov et al. 2006). We discuss all this issues in the previous paper (Vikhlinin et al. 2008, Paper II hereafter). The cluster mass functions derived in this paper are reproduced in Fig. 1. Overall, these results are an important step forward in providing observational foundation for cosmological work with the cluster mass functions.

In this work, we present cosmological constraints from the data discussed in Paper II. The cosmological information contained in the cluster mass function data and relevant to dark energy constraints can be approximately separated into 3 quasi-independent components:

- (1) Changes in the comoving number density at a fixed mass threshold constrain a combination of the perturbations growth factor and relative distances between low and high- $z$  samples; this by itself is a dark energy constraint (§8).
- (2) The overall normalization of the observed mass function constrains the amplitude of linear density perturbations at  $z \approx 0$ , usually expressed in terms of the  $\sigma_8$  parameter. Statistical and systematic errors in the  $\sigma_8$  measurement are now sufficiently small, and the ratio of  $\sigma_8$  and the amplitude of the CMB fluctuations power spectrum gives the total growth of perturbations between  $z \approx 1000$  and  $z = 0$  — a second powerful dark energy constraint (§8.1).

- (3) The slope of the mass function measures  $\Omega_M \times h$ ; this by itself is not a dark energy probe but can be used to break degeneracies present in other methods.

Our dark energy constraints were derived for the following cases. Assuming constant  $w$  and flat universe, we measure  $w_0 = -1.14 \pm 0.21$  using only cluster data (i.e., evolution of the mass function between our two redshift samples) and the HST prior on  $h$  (§8.2). Combining cluster and WMAP data, we obtain  $w_0 = -1.08 \pm 0.15$  but ( $w_0$  is constrained much more tightly for a fixed  $\Omega_M$  (§8.3). Finally, adding cluster data to the joint supernovae + WMAP + BAO constraint, we obtain  $w_0 = -0.991 \pm 0.045$  (§8.3), significantly reducing statistical and especially systematic (§8.4) uncertainties compared to the case without clusters. A large fraction of the extra constraining power comes from contrasting  $\sigma_8$  with normalization of the CMB power spectrum; this procedure is sensitive to non-zero mass of light neutrinos. Allowing for  $m_\nu > 0$ , we obtain a new conservative upper limit  $\sum m_\nu < 0.33$  eV (95% CL) while still improving the  $w_0$  measurement relative to the SN+WMAP+BAO-only case ( $w_0 = -1.02 \pm 0.055$ , §8.5). Adding clusters also improves equation of state constraints for evolving  $w$  in flat universe (§9.1) and constant  $w$  in non-flat universe (§9.2).

The paper is organized as follows. We start with a short summary of cluster data and systematic uncertainties (§2), discuss issues relevant for computing theoretical mass function models (§3) and describe our fitting procedure (§4). We then discuss constraints that can be obtained from low-redshift mass function only ( $\Omega_M h$  in §5 and  $\sigma_8$  in §6). We then consider as an example constraints from the cluster evolution in non-flat  $\Lambda$ CDM model (i.e.,  $w$  fixed at  $-1$ );  $\Omega_\Lambda > 0$  is required with  $\sim 5\sigma$  confidence (§7). Constraints on the dark energy equation of state are considered in §§8–9. Systematic errors are discussed in §8.4.

## 2. SUMMARY OF THE CLUSTER DATA AND SYSTEMATIC UNCERTAINTIES

This work is based on two cluster samples, originally compiled from *ROSAT* X-ray surveys (see Paper II for a complete description of the sample selection and data analysis). The low-redshift sample includes the 49 highest-flux clusters detected in the All-Sky Survey at Galactic latitudes  $|b| > 20^\circ$  and  $z > 0.025$ . The effective redshift depth of this sample is  $z < 0.15$ . The high-redshift sample includes 37  $z > 0.35$  objects detected in the 400d survey, with an additional flux cut applied; the redshift depth of this sample is  $z \approx 0.9$ . All the low and high- $z$  clusters were later observed with *Chandra*, providing good statistical precision spatially resolved spectral data thus yielding several high-quality  $M_{\text{tot}}$  estimators for each object. The combined cluster sample is a unique, uniformly observed dataset. The volume coverage and effective mass limits at low and high redshifts are similar (see the estimated mass functions in Fig. 1).

Because of the sufficiently high quality of the *Chandra* data, we employ advanced data analysis techniques going well beyond simple flux estimates and  $\beta$ -model fits commonly used in earlier studies. Cosmological cluster simulations has been used to test for the absence of significant observational biases in reconstructing the basic cluster parameters (Nagai et al. 2007). Using these simulations, we also tested which of the X-ray observables are best proxies for the total cluster mass (Kravtsov et al. 2006; Nagai et al. 2007) and concluded that the best three are the average temperature,  $T_X$ , measured in the annulus  $[0.15-1] r_{500}$  (thus excluding the central region often af-

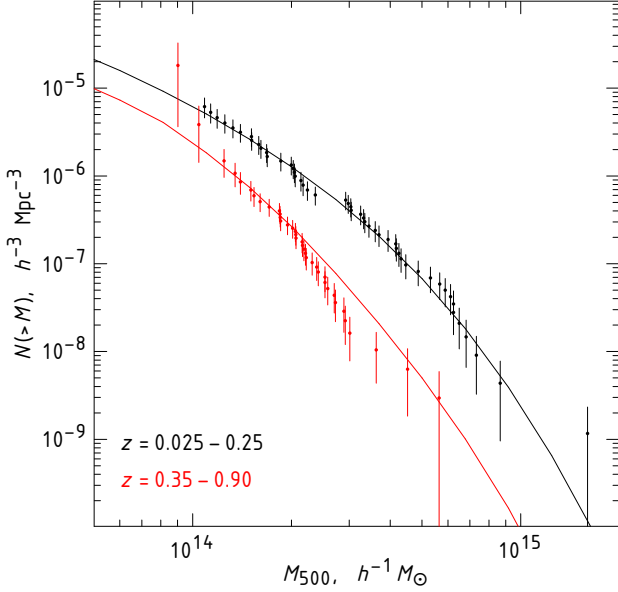


FIG. 1.— Estimated mass functions for our cluster samples computed for the  $\Omega_M = 0.25$ ,  $\Omega_\Lambda = 0.75$ ,  $h = 0.72$  cosmology. Solid lines show the mass function models (weighted with the survey volume as a function of  $M$  and  $z$ ), computed for the same cosmology with only the overall normalization,  $\sigma_8$ , fitted. The deficit of clusters in the distant sample near  $M_{500} = 3 \times 10^{14} h^{-1} M_\odot$  is a marginal statistical fluctuation — we observe 4 clusters where 9.5 are expected, a  $2\sigma$  deviation (cf. Fig. 17 in Paper II).

affected by radiative cooling and sometimes, by AGN activity in the central galaxy); the intracluster gas mass integrated within  $r_{500}$ ; and the combination of the two,  $Y_X = T_X \times M_{\text{gas}}$ . These parameters are low-scatter proxies of the total mass (in particular,  $Y_X$ , and  $M_{\text{gas}}$  is only slightly worse). Simulations and available data show that the scaling of these proxies with  $M_{\text{tot}}$ , including the redshift dependence, is very close to predictions of the simple self-similar model. In a sense, even though we use advanced numerical simulations which include multiple aspects of the cluster physics to test  $M_{\text{tot}}$  vs. proxy relations, the role of simulations is limited to providing small corrections to predictions of very basic and hence reliable theory. Application of these corrections as well as practical considerations for deriving  $T_X$ ,  $M_{\text{gas}}$ , and  $Y_X$  from the real data are discussed in Paper II.

Paper II also presents an observational calibration of the  $M_{\text{tot}}$  vs. proxy relations using an extremely well-observed sample of low- $z$  clusters. This discussion is crucial for understanding the systematic uncertainties in our cluster mass function measurements, and we urge interested readers to consult Paper II. Table 4 there gives a summary of the main sources of systematic uncertainties in the derived cluster mass functions. They can be separated into three quasi-independent components. First is the uncertainty in calibration of the absolute cluster mass scale by *Chandra* hydrostatic mass estimates in a sample of dynamically relaxed, well-observed low- $z$  clusters (Vikhlinin et al. 2006); the level of this uncertainty (9%) is estimated from comparison of *Chandra* masses with two recent weak lensing studies (Hoekstra 2007; Zhang et al. 2008). Second is uncertainties related to possible departures from standard evolution in  $M_{\text{tot}} - T_X$ ,  $M_{\text{tot}} - M_{\text{gas}}$ , and  $M_{\text{tot}} - Y_X$  relations. This uncertainty ( $\sim 5 - 6\%$  between  $z = 0$  and  $z = 0.5$ ) was estimated from general reliability of numerical models of the cluster formation and from the magnitude of corrections that had to be applied to the data (see § 4 in Paper II for de-

tails). The last major source of uncertainty is evolution in the  $L_X - M_{\text{tot}}$  relation, affecting computations of the 400d survey volume coverage; this uncertainty is mostly measurement in nature because we derive the  $L_X - M_{\text{tot}}$  relation internally from the same cluster set. Its effect is negligible for the high- $M$  end of the mass function and becomes comparable to Poisson errors for low- $M$  clusters. A representative compilation of the effects of  $L_X - M_{\text{tot}}$  uncertainties on the  $V(M)$  function is presented in Fig. 15 of Paper II.

The general reliability of our analysis is greatly enhanced by using independent, high-quality X-ray indicators of the total cluster mass —  $T_X$ ,  $M_{\text{gas}}$ ,  $Y_X$ . Since the masses estimated from these proxies depend differently on the distance to the object, the high- $z$  mass functions estimated with different proxies should agree only if the assumed background cosmology is correct. In principle, this can be used as an additional source of information for the distance-redshift relation and folded into the cosmological fit. However, this method is nearly equivalent to the  $f_{\text{gas}}(z)$  test, which is more reliably carried which is more reliably carried out using direct hydrostatic mass estimates in relaxed clusters (Allen et al. 2008), and therefore we ignore this information. Instead, we use the agreement between different proxies observed for the best-fit cosmology as a comforting indication that there are no serious errors in our results.

### 3. SUMMARY OF THEORY

In the current paradigm of structure formation, galaxy clusters form via gravitational collapse of matter around large peaks in the primordial density field (Kaiser 1984; Bardeen et al. 1986). Their abundance and spatial distribution in a co-moving volume will thus depend on the statistical properties of the initial density field, such as gaussianity<sup>9</sup> and power spectrum (and hence the cosmological parameters that determine it), and could depend on the details of non-linear amplification of the density perturbations by gravity. Indeed, semi-analytic models based on the linear primordial density field and a simple ansatz describing non-linear gravitational collapse of density peaks (Press & Schechter 1974; Bond et al. 1991; Lee & Shandarin 1998; Sheth et al. 2001) have proven to be quite successful in describing results of direct cosmological simulations of structure formation (e.g., Lee & Shandarin 1999; Sheth et al. 2001; Jenkins et al. 2001). The accuracy of the existing models, however, is limited and over the last several years the abundance of collapsed objects was calibrated by fitting appropriate fitting function to the results of direct cosmological simulations (Jenkins et al. 2001; Evrard et al. 2002; Warren et al. 2006). The fitting functions are expressed in the so-called universal form<sup>10</sup> as a function of the variance of the density field on the mass scale  $M$ . The fact that such universal expressions exist implies that there is a direct link between the the linearly evolving density field and cluster abundance.

In our analysis we use the most recent accurate calibration of the halo mass function by Tinker et al. (2008), which provides fitting formulas for halo abundance as a function of mass, defined in spherical apertures enclosing overdensities similar to the mass we derive from observational proxies for the observed clusters. The Tinker et al. fitting formulas are formally accurate to better than 5% for the cosmologies close to the concordance  $\Lambda$ CDM cosmology and for the mass and redshift range

<sup>9</sup> We note however, that the current constraints on non-gaussianity from the CMB anisotropy measurements imply that the expected effects on clusters are small (Grossi et al. 2007).

<sup>10</sup> In the sense that the same function and parameters could be used to predict halo abundance for different redshifts and cosmologies.

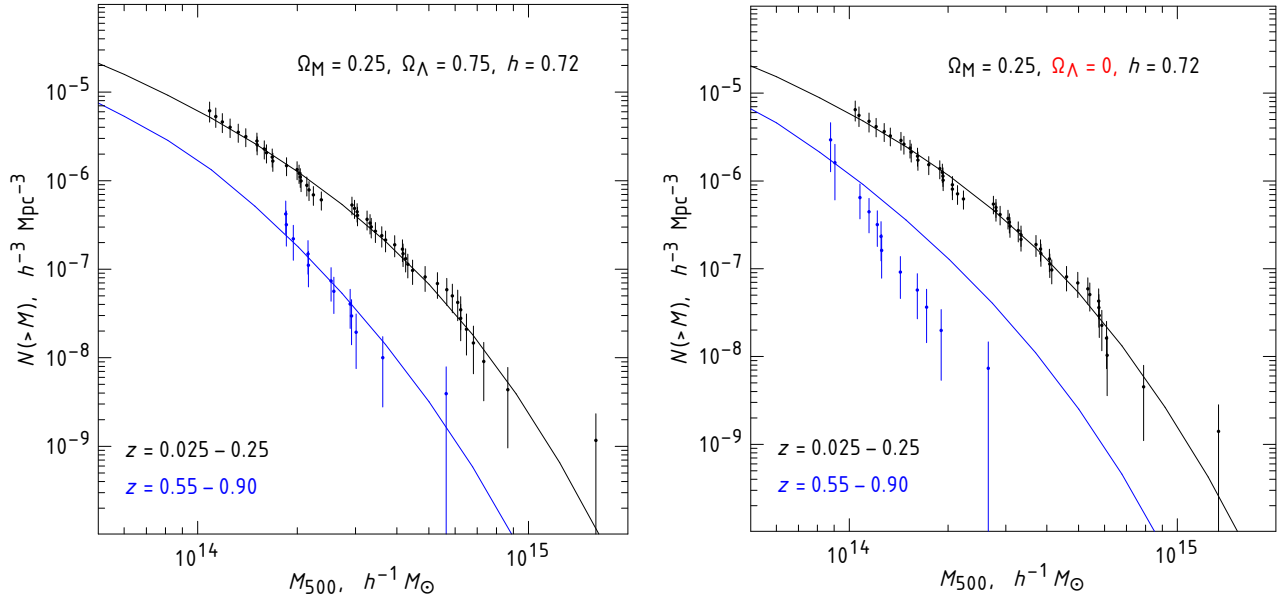


FIG. 2.— Illustration of sensitivity of the cluster mass function to the cosmological model. In the left panel, we show the measured mass function and predicted models (with only the overall normalization at  $z = 0$  adjusted) computed for a cosmology which is close to our best-fit model. The low- $z$  mass function is reproduced from Fig. 1, which for the high- $z$  cluster we show only the most distant subsample ( $z > 0.55$ ) to better illustrate the effects. In the right panel, both the data and the models are computed for a cosmology with  $\Omega_\Lambda = 0$ . Both the model and the data at high redshifts are changed relative to the  $\Omega_\Lambda = 0.75$  case. The measured mass function is changed because it is derived for a different distance-redshift relation. The model is changed because the predicted growth of structure and overdensity thresholds corresponding to  $\Delta_{\text{crit}} = 500$  are different. When the overall model normalization is adjusted to the low- $z$  mass function, the predicted number density of  $z > 0.55$  clusters is in strong disagreement with the data, and therefore this combination of  $\Omega_M$  and  $\Omega_\Lambda$  can be rejected.

of interest in our study; at this level, the theoretical uncertainties in the mass function do not contribute significantly to the systematic error budget. Although the formula has been calibrated using dissipationless  $N$ -body simulations (i.e. without effects of baryons), the expected effect of the internal redistribution of mass during baryon dissipation on halo mass function are expected to be  $< 5\%$  (Rudd et al. 2008) for a realistic fraction of baryons that condenses to form galaxies.

Similarly to Jenkins et al. (2001) and Warren et al. (2006), the Tinker et al. formulas for the halo mass function are presented as a function of variance of the density field on a mass scale  $M$ . The variance, in turn, depends on the linear power spectrum of the cosmological model,  $P(k)$ , which we calculate as a product of the initial power law spectrum,  $k^n$ , and the transfer function for the given mixture of CDM and baryons, computed using the analytic approximations of Eisenstein & Hu (1999). This analytic approximation is accurate to better than 2% for a wide range of cosmologies, including cosmologies with non-negligible neutrino contributions to the total matter density.

Our default analysis assumes that neutrinos have a negligibly small mass. The only component of our analysis that could be affected by this assumption is when we contrast the low-redshift value of  $\sigma_8$  derived from clusters with the CMB power spectrum normalization. This comparison uses evolution of purely CDM+baryons power spectra. The presence of light neutrinos affects the power spectrum at cluster scales; in terms of  $\sigma_8$ , the effect is roughly proportional to the total neutrino density, and is  $\approx 20\%$  for  $\sum m_\nu = 0.5$  eV (we calculate the effect of neutrinos using the transfer function model of Eisenstein & Hu 1999). Stringent upper limits on the neutrino mass were reported from comparison of the WMAP and Ly- $\alpha$  forest data,  $\sum m_\nu < 0.17$  eV at 95% CL (Seljak et al. 2006). If neutrino masses are indeed this low, they would have no effect on our analysis. However, possible issues with modeling of the Ly- $\alpha$  data have been noted in the literature (see, e.g., discussion in

§ 4.2.8 of Dunkley et al. 2008) and so we experiment also with neutrino masses outside the Ly- $\alpha$  forest bounds (§ 8.5).

#### 4. FITTING PROCEDURE

We obtain parameter constraints using the likelihood function computed on a full grid of cosmological parameters affecting cluster observables (and also those for external datasets). The relevant parameters for the cluster data are those that affect the distance-redshift relation, as well as the growth and power spectrum of linear density perturbations:  $\Omega_M$ ,  $\Omega_\Lambda$ ,  $w$  (dark energy equation of state parameter),  $\sigma_8$  (linear amplitude of density perturbations at the  $8 h^{-1}$  Mpc scale at  $z = 0$ ),  $h$ , tilt of the primordial fluctuations power spectrum, and potentially, the non-zero rest mass of light neutrinos. This is computationally demanding and we describe our approach below.

The computation of the likelihood function for a single combination of parameters is relatively straightforward. Our procedure (described in Paper II) uses the full information contained in the dataset, without any binning in mass or redshift, takes into account the scatter in the  $M_{\text{tot}}$  vs. proxy relations and measurement errors, and so on. We should note, however, that since the measurement of the  $M_{\text{gas}}$  and  $Y_X$  proxies depends on the assumed distance to the cluster, the mass functions must be re-derived for each new combination of the cosmological parameters that affect the distance-redshift relation —  $\Omega_M$ ,  $w$ ,  $\Omega_\Lambda$ , etc. Variations of  $h$  lead to trivial rescalings of the mass function and do not require re-computing the mass estimates. Computation of the survey volume uses a model for the evolving  $L_X - M_{\text{tot}}$  relation (see § 5 in Paper II), which is measured internally from the data and thus also depends on the assumed  $d(z)$  function. Therefore, we refit the  $L_X - M_{\text{tot}}$  relation for each new cosmology and recompute  $V(M)$ . Sensitivity of the derived mass function to the background cosmology is illustrated in Fig. 2. The entire procedure, although equivalent to full reanalysis of the *Chandra* and *ROSAT* data,

TABLE 1  
COSMOLOGICAL CONSTRAINTS FROM X-RAY CLUSTER DATA

| Parameter                               | Value             | Determined by  | Systematic errors | Dominant source of systematic uncertainties |
|---|-------------------|--|-------------------|---|
| $\Omega_M h$ .....                      | $0.184 \pm 0.024$ | Shape of the local mass function, § 5                        | $\pm 0.027$       | Slope of the $L - M$ relation.              |
| $\Omega_M$ .....                        | $0.255 \pm 0.043$ | Shape of the local mass function plus HST prior on $h$ , § 5 | $\pm 0.037$       | Slope of the $L - M$ relation.              |
| $\sigma_8 (\Omega_M/0.25)^{0.47}$ ..... | $0.813 \pm 0.013$ | Normalization of the local mass function, § 6                | $\pm 0.024$       | Absolute mass calibration at $z = 0$ .      |
| $\Omega_M$ .....                        | $0.34 \pm 0.08$   | Evolution of the $T_X$ -based mass function, § 7             | $\pm 0.055$       | Evolution of the $M - T$ relation           |

can be organized very efficiently if one stores the derived  $\rho_g(r)$  and  $T(r)$  computed in some reference cosmology. It takes  $\approx 20$  sec on a single CPU to re-estimate all masses, refit the  $L_X - M_{\text{tot}}$  relation, and recompute volumes for each new combination of the cosmological parameters.

The next step is to compute, for each combination of  $\Omega_M$ ,  $\Omega_\Lambda$  etc., the likelihood function on a grid of those parameters which do not affect the distance-redshift relation. In our case, these are  $\sigma_8$ ,  $h$ , and when required, the power spectrum tilt or neutrino mass. The cluster data are extremely sensitive to  $\sigma_8$  and so we need a fine grid for this parameter. Fortunately, the mass function codes compute the mass functions for different values of  $\sigma_8$  with other parameters fixed at almost no extra expense. The sensitivity of the cluster data to  $h$  and tilt is much weaker, therefore the likelihood can be computed on a coarse grid for these parameters and then interpolated.

With the acceleration strategies outlined above, it took us  $\sim 9600$  CPU-hours (or 20 days using multiple workstations) to compute the cluster likelihood functions on full parameter grids for several generic models (non-flat  $\Lambda$ CDM, constant dark energy equation of state in a flat universe, constant  $w$  with non-zero neutrino mass, linearly evolving  $w$  in flat universe, constant  $w$  in non-flat universe). Alternatively, simulating the Markov chains (Lewis & Bridle 2002) with sufficient statistics for all these cases would require approximately the same computing time.

After the cluster likelihood function was computed, we also computed  $\chi^2$  for external cosmological datasets — WMAP (5-year results), Baryonic Acoustic Oscillations, and Supernovae Ia bolometric distances. Since we basically use analytic Gaussian priors for these datasets (see § 8.1 below), these computations are fast and can be made on a fine parameter grid. We also use a Gaussian prior for the Hubble constant,  $h = 0.72 \pm 0.08$ , based on the results from the HST Key Project (Freedman et al. 2001). This prior is important only when the constraints from the shape of the mass function (§ 5) come into play and when external cosmological datasets are not used in the constraints. When fitting the cluster data, we also keep the absolute baryon density fixed at the best-fit WMAP value,  $\Omega_b h^2 = 0.0227$  (Dunkley et al. 2008). This parameter slightly affects the calculation of the linear power spectrum (Eisenstein & Hu 1998). When we add the WMAP information to the total constraints, we marginalize the WMAP likelihood component over this parameter. If not stated otherwise, our cosmological fits also assume a primordial density fluctuation power spectrum with  $n = 0.95$  (Spergel et al. 2007). Our results are completely insensitive to variations of  $n$  within the WMAP measurement uncertainties and even to setting  $n = 1$ .

Once the combined likelihood as a function of cosmological parameters is available, we use the quantity  $-2 \ln L$ , whose statistical properties are equivalent to the  $\chi^2$  distribution (Cash 1979), to find the best fit parameters and confidence intervals.

In addition to statistical uncertainties, we also consider different sources of systematics. We do not include systematic errors in the likelihood function but instead refit parameters with the relations affected by systematics varied within the estimated  $1\sigma$  uncertainties. This approach allows as not only to estimate how the confidence intervals are expanded from combination of all systematic errors, but also to track the most important source of uncertainty for each case. A full analysis of systematic errors is presented in § 8.4 for the case of constraints on constant  $w$  in a flat universe; in other cases the systematic uncertainties contribute approximately the same fraction of the total error budget. We also verified that in the constant  $w$  case, our method of estimating the systematic errors produces the results which are very close to the more accurate procedure using the Markov chain analysis.

#### 5. CONSTRAINTS FROM THE SHAPE OF THE LOCAL MASS FUNCTION: $\Omega_M h$

The shape of the cluster mass function reflects the shape of the linear power spectrum in the relevant range of scales, approximately  $10 h^{-1}$  Mpc in our case. This shape, for a reasonable range of parameters in the CDM cosmology is controlled (Bardeen et al. 1986) mostly by the quantity  $\Omega_M h$ . It is useful to consider constraints on this combination separately because they are nearly independent of the rest of the cosmological parameters we are trying to measure with the cluster data.

Fixing the primordial power spectrum index to the WMAP value,  $n = 0.95$ , the fit to the local mass function<sup>11</sup> gives  $\Omega_M h = 0.184 \pm 0.024$  (purely statistical 68% CL uncertainties). The best fit value is degenerate with the assumed primordial power spectrum index, and the variation approximately follows the relation  $\Delta \Omega_M h = -0.31 \Delta n$ . The variations of  $n$  within the range constrained by the WMAP data,  $\pm 0.015$ , lead to negligibly small changes in our derived  $\Omega_M h$ .

An additional source of statistical uncertainty is that related to the derivation of the  $L - M$  relation, since we derive this relation from the same set of clusters. Uncertainties in the  $L - M$  relation are translated into those of the survey volume and hence the cluster mass function. Most of our cosmological constraints are primarily sensitive to the cluster number density near the median mass of the sample. This median mass, the  $V(M)$  uncertainties are small compared to statistics (see § 6 in Paper II). The  $\Omega_M h$  determination, however, is based on

<sup>11</sup> Including the high-redshift data, we obtain a consistent value,  $\Omega_M h = 0.198 \pm 0.022$ . Combined with the HST prior on  $h$ , this leads to a measurement of  $\Omega_M = 0.275 \pm 0.043$ . However, using the high- $z$  data makes the  $\Omega_M h$  constraints dependent on the background cosmology and therefore we prefer to base this measurement only on the local mass function. Also, we use the  $Y_X$ -based mass estimates for this and  $\sigma_8$  analyses. The other observables,  $T_X$  or  $M_{\text{gas}}$ , give essentially identical results, because all of them were normalized using the same set of low- $z$  clusters (see Paper II, for details). The difference between mass proxies is only important for the measurements based on the evolution of the high- $z$  mass function (§ 7).

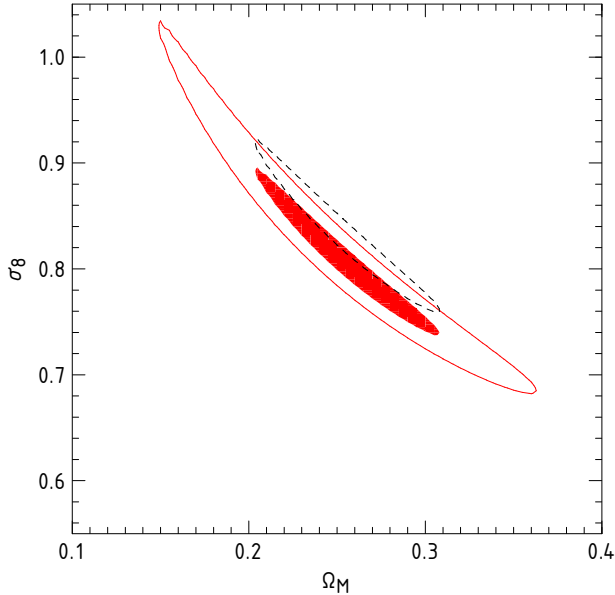


FIG. 3.— Constraints on the  $\sigma_8$  and  $\Omega_M$  parameters in a flat  $\Lambda$ CDM cosmology from the total (both low and high-redshift) cluster sample. The inner solid region corresponds to  $-2\Delta \ln L = 1$  from the best-fit model (indicates the 68% CL intervals for one interesting parameter, see footnote 13) and the solid contour shows the one-parameter 95% CL region ( $-2\Delta \ln L = 4$ ). The dashed contour shows how the inner solid confidence region is modified if the normalization of the absolute cluster mass vs. observable relations is changed by +9% (our estimate of the systematic errors).

the relative number density of clusters near the high and low mass ends of the sample. Since the volume is a fast-decreasing function at low  $M$ 's, the  $V(M)$  variations are important. The most important parameter of the  $L - M$  relation in our case is the power law slope,  $\alpha$  (see eq. 20 in Paper II). Variations of  $\alpha$  within the errorbars ( $\pm 0.14$ ) of the best fit value lead to changes in the derived  $\Omega_M h$  of  $\pm 0.027$ . Adding this in quadrature to the formal statistical errors quoted above, we obtain a total uncertainty of  $\pm 0.035$ . We have verified that other sources of systematics in the  $\Omega_M h$  determination are much less important than those related to the  $L - M$  relation.

In principle, a non-zero mass of light neutrinos has some effect on the perturbation power spectrum at low redshifts. We checked, however, that their effect on the *shape* of the cluster mass function is negligible for any  $\sum m_\nu$  within the range allowed by the CMB data (Komatsu et al. 2008). Therefore, neutrinos do not affect our results on  $\Omega_M h$ .

Our determination of  $\Omega_M h = 0.184 \pm 0.035$  compares well with the previous measurements using cluster data and galaxy power spectra. Of the previous cluster results especially noteworthy is the work of Schuecker et al. (2003) whose constraints are based not only on the shape of the mass function but also on the clustering of low- $z$  clusters. Their value is  $\Omega_M h = 0.239 \pm 0.056$  (errors dominated by uncertainties in the conversion of cluster X-ray luminosities into mass; this source of uncertainty is avoided in our work by using high-quality X-ray mass proxies).  $\Omega_M h$  is measured accurately also by galaxy redshift surveys. The results from the 2dF and SDSS surveys are  $\Omega_M h = 0.178 \pm 0.016$  and  $0.223 \pm 0.023$ , respectively (Cole et al. 2005; Tegmark et al. 2004, —we rescaled to  $n = 0.95$  their best fit values reported for  $n = 1$ ). The individual errorbars in galaxy survey results are smaller than those from the cluster data; however, a recent work by Percival et al. (2007c) suggests that the previous galaxy redshift results may be affected

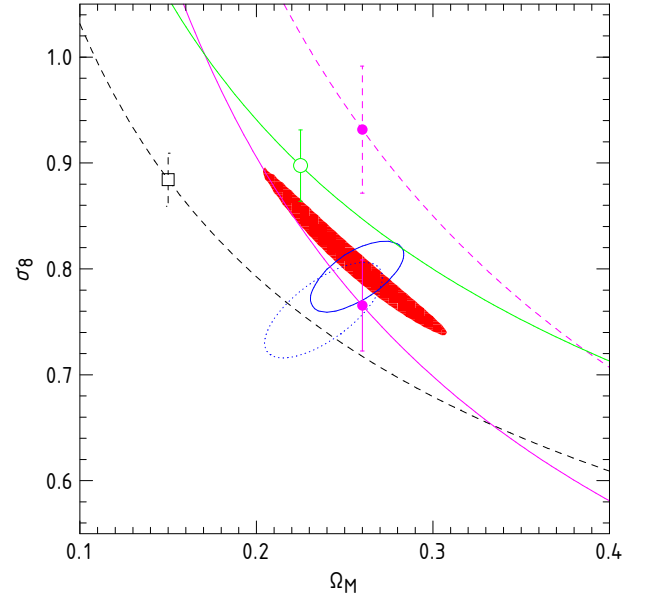


FIG. 4.— Comparison with other  $\sigma_8$  measurements. Solid region is our 68% CL region reproduced from Fig. 3 (this and all other confidence regions correspond to  $\Delta\chi^2 = 1$ , see footnote 13 on page 7). Blue contours show the WMAP 3 and 5-year results from Spergel et al. (2007) and Dunkley et al. (2008) (dotted and solid contours, respectively). For other measurements, we show the general direction of degeneracy as a solid line and a 68% uncertainty in  $\sigma_8$  at a representative value of  $\Omega_M$ . Filled circles show the weak lensing shear results from Hoekstra et al. (2006) and Fu et al. (2008) (dashed and solid lines, respectively). Open circle shows results from a cluster sample with galaxy dynamics mass measurements (Rines et al. 2007). Finally, open square shows the results from Reiprich & Böhringer (2002, approximately the lower bound of recently published X-ray cluster measurements).

by scale-dependent biases on large scales. Indeed, there is a tension between the SDSS and 2dF values at  $\approx 90\%$  CL and the difference is comparable to the errorbars of our measurement.

The cluster results can be improved in the future by extending the range of the mass function measurements. Not only can this improve statistical errors in the mass function measurements but it can also improve the accuracy of the  $L - M$  relation, a significant source of uncertainty in our case. We note that it is more advantageous to increase statistics in the high- $M$  range than to extend the mass function into the galaxy group regime. In addition to greater reliability of the X-ray mass estimates in the high- $M$  systems, the surveys become dominated by cosmic variance approximately below the lower mass cut in our sample (the cosmic variance is estimated in §7.1 of Paper II using the prescription of Hu & Kravtsov 2003).

Combined with the HST prior on the Hubble constant, our constraint on  $\Omega_M h$  becomes a measurement for the matter density parameter,  $\Omega_M = 0.255 \pm 0.043$  (stat)  $\pm 0.037$  (sys), where systematic errors are also dominated by the slope of the  $L - M$  relation. This agrees within the errors with other independent determinations, such as a combination of BAO and CMB acoustic scales,  $\Omega_M = 0.256 \pm 0.027$  (Percival et al. 2007b), and a combination of gas fraction measurements in massive clusters with the average baryon density from Big Bang Nucleosynthesis,  $\Omega_M = 0.28 \pm 0.06$  (Allen et al. 2008). It also agrees with another independent measurement based on our data,  $\Omega_M = 0.30 \pm 0.05$  from evolution of the cluster temperature function, see (§7 below).

## 6. CONSTRAINTS FROM THE NORMALIZATION OF THE CLUSTER MASS FUNCTION: $\sigma_8 - \Omega_M$

The normalization of the cluster mass function is exponentially sensitive to  $\sigma_8$ , the amplitude of linear perturbations at the length scale  $8 h^{-1}$  Mpc, approximately corresponding to the cluster mass scale (Frenk et al. 1990). Measuring this parameter with the cluster data has been a popular topic of research, especially using statistics of X-ray clusters (Frenk et al. 1990; Henry & Arnaud 1991; Lilje 1992; White et al. 1993, and many others thereafter). The strong sensitivity of the predicted cluster number density to  $\sigma_8$  makes the determination of this parameter relatively insensitive to the details of the sample selection. Historically, different studies using very different cluster catalogs yielded similar results, if the data were analyzed uniformly. Determination of  $\sigma_8$  is more sensitive to calibration of the absolute mass scale. For example Pierpaoli et al. (2003) show that if  $M_{\text{tot}}$  for a fixed value of  $T_X$  is varied by a factor of 1.5,  $\sigma_8$  derived from the local cluster temperature function is changed by  $\Delta\sigma_8 \approx 0.13$ . Smaller biases are introduced if the effects of scatter in deriving the mass-luminosity relation are neglected resulting in incorrect computations of the survey volume (Stanek et al. 2006). Our present work includes advances in both of these areas and thus it is worth presenting an updated measurement of  $\sigma_8$ .

Determination of  $\sigma_8$  from the cluster abundance data usually shows a strong degeneracy with the  $\Omega_M$  parameter, typically,  $\sigma_8 \propto \Omega_M^{-0.6}$  (e.g., Huterer & White 2002). The nature of this degeneracy is that the mass function determines the rms amplitude of fluctuations at the given  $M_{\text{tot}}$  scale. The corresponding length scale is a function of  $\Omega_M$  ( $M \sim \Omega_M l^3$ ) and thus the derived  $\sigma_8$  depends also on  $\Omega_M$  and more weakly on the local slope of the linear power spectrum (see discussion in White et al. 1993). We need, therefore, to constrain  $\sigma_8$  and  $\Omega_M$  jointly. We used a grid of parameters of the flat<sup>12</sup>  $\Lambda$ CDM model ( $\Omega_M$ ,  $h$ ,  $\sigma_8$ ), and computed the cluster likelihood using the mass function for the local sample. We then add the Hubble constant prior (§ 4), and marginalized the combined likelihood over  $h$ .

The results are shown in Fig 3<sup>13</sup>. For a fixed  $\Omega_M$ , the value of  $\sigma_8$  is constrained to within  $\pm 0.012$  (statistical). The degeneracy between  $\sigma_8$  and  $\Omega_M$  can be accurately described as  $\sigma_8 = 0.813(\Omega_M/0.25)^{-0.47}$ . The  $\Omega_M$  range along this line is constrained by the shape of the local mass function combined with the HST prior on the Hubble constant (§ 5). Including the high-redshift data, we obtain very similar results. For example, for  $\Omega_M = 0.25$ , the total sample gives  $\sigma_8 = 0.803 \pm 0.0105$ , to be compared to  $\sigma_8 = 0.813 \pm 0.012$  from low- $z$  clusters only. This implies that the  $\sigma_8$  measurement is dominated by the more accurate local cluster data, as expected.

Systematic errors of the  $\sigma_8$  measurement are dominated by the uncertainties in the absolute mass calibration. To test the effect of these uncertainties, we changed the normalization of the mass vs. proxy relations by  $\pm 9\%$  (our estimate of systematic errors in the mass scale calibration, see § 2). The effect, shown

by the dotted contour in Fig. 3, is to shift the estimated values of  $\sigma_8$  by  $\pm 0.02$ , just outside the statistical 68% CL uncertainties. This range can be considered as a systematic uncertainty in our  $\sigma_8$  determination for a fixed  $\Omega_M$ .

Our cluster constraints on  $\sigma_8$  are more accurate (for a fixed  $\Omega_M$ ) than any other method, even including systematic errors (Fig. 4). It is encouraging that our results are in very good agreement with recent results from other methods. The measurements based on lensing shear surveys, cluster mass function with  $M_{\text{tot}}$  estimated from galaxy dynamics, and WMAP (5-year results assuming flat  $\Lambda$ CDM cosmology) are all within their respective 68% CL uncertainties from our best fit. This independently confirms that our calibration of the cluster mass scale is not strongly biased. Furthermore, the present systematic errors in the cluster analysis are smaller than the statistical accuracy provided by WMAP-5 and other methods. This allows us to effectively use the  $\sigma_8$  information in the dark energy equation of state constraints (§ 8.3).

We now move to models where the crucial role is played by the high-redshift cluster mass function data. The first case to consider is combined constraints for  $\Omega_M$  and  $\Omega_\Lambda$  in the non-flat  $\Lambda$ CDM cosmology. To better demonstrate what role the different components of the information provided by the cluster mass function play in the combined constraints, we consider two cases: a) when the full cluster mass function information is used, and b) when the shape information is artificially removed thus leaving only the evolutionary information.

## 7. CONSTRAINTS FOR NON-FLAT $\Lambda$ CDM COSMOLOGY: $\Omega_M - \Omega_\Lambda$

In the first case, for each combination of parameters, we compute the full likelihood for the low and high- $z$  mass functions and add the HST prior on the Hubble constant (this is necessary for effective use of the mass function shape information, see § 4 and § 5). We then marginalize the combined likelihood over non-essential parameters ( $\sigma_8$  and  $h$  in this case) keeping the primordial power spectrum index fixed at the WMAP best-fit value,  $n = 0.95$ . Removal of the shape information (our second case) is achieved by letting  $n$  vary and marginalizing over it. This is approximately equivalent to using a free shape parameter for the CDM power spectra, the approach often used in earlier cluster studies (e.g., Borgani et al. 2001). Constraints for both cases were obtained for mass functions estimated using all our three proxies,  $T_X$ ,  $M_{\text{gas}}$ , and  $Y_X$ .

The results are presented in Figs. 5 and 6. First, we can easily identify the role of using the mass function shape information (illustrated for the  $M_{\text{gas}}$  and  $Y_X$  proxies). Clearly, it mostly breaks the degeneracies along the  $\Omega_M$  axis. The best fit values and statistical uncertainties for  $\Omega_M$  are very close to those derived from the shape of the local mass function (and nearly identical to those from the total sample, § 5).

For a fixed  $\Omega_M$ , the observed evolution in the cluster mass function provides a constraint on  $\Omega_\Lambda$ . Degeneracies in the  $\Omega_M - \Omega_\Lambda$  plane provided by different mass proxies applied to the same set of clusters differ because of the different distance dependence of the  $M_{\text{tot}}$  estimates via  $T_X$ ,  $M_{\text{gas}}$ , and  $Y_X$  (see below). Even without the shape information, evolution in the  $Y_X$  and  $M_{\text{gas}}$ -based mass functions requires  $\Omega_\Lambda > 0$  at the 85% and 99.7% CL, respectively. Including the shape information, we obtain  $\Omega_M = 0.28 \pm 0.04$ ,  $\Omega_\Lambda = 0.78 \pm 0.25$  (and  $\Omega_\Lambda > 0$  is required at the 99% CL) from the  $Y_X$ -based analysis. The evolution of the  $M_{\text{gas}}$ -based mass function gives  $\Omega_M = 0.27 \pm 0.04$ ,  $\Omega_\Lambda = 0.83 \pm 0.15$ , and  $\Omega_\Lambda > 0$  at 99.98% CL. The  $T_X$ -based mass function does not strongly constrain  $\Omega_\Lambda$  but provides an

<sup>12</sup> The assumption of flatness (and background cosmology in general) has a minor effect on determination of  $\sigma_8$  because the measurement is dominated by the low-redshift sample. However, we note that when we use the  $\sigma_8$  information in the dark energy constraints (§ 8 and thereafter), we do not use the results from this section directly. When we fit  $w$ ,  $\sigma_8$  is effectively re-measured from the cluster data for each background cosmology.

<sup>13</sup> The contours in these and subsequent figures correspond to the 95% CL region for one interesting parameter ( $\Delta\chi^2 = 4$ ). The inner solid region corresponds to  $\Delta\chi^2 = 1$ . This choice is made to facilitate quick estimates of the single-parameter uncertainty intervals directly from the plots. The total extent of the  $\Delta\chi^2 = 1$  region in either direction is a good estimate for the 1-parameter 68% CL interval (Cash 1976). Similarly, the width of this region is a 68% CL interval assuming that the second parameter is fixed.

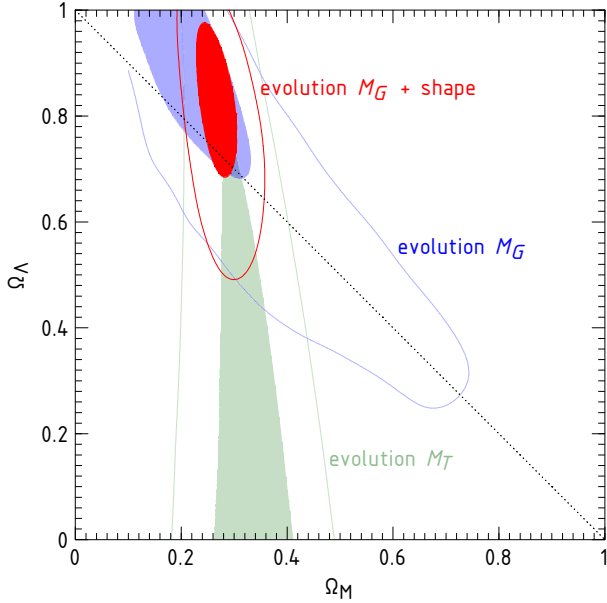


FIG. 5.— Constraints for non-flat  $\Lambda$ CDM cosmology from evolution of the cluster mass function. The results using only the evolution information (change in the number density of clusters between  $z = 0$  and  $z \approx 0.55$ ) are shown in blue and green from the  $M_{\text{gas}}$  and  $T_X$ -based total mass estimates. The degeneracies in these cases are different because these proxies result in very different distance-dependence of the estimated masses (see text for details). The constraints from the  $Y_X$ -based mass function are between those for  $M_{\text{gas}}$  and  $T_X$  (Fig. 6). Adding the shape of the mass function information breaks degeneracies with  $\Omega_M$ , significantly improving constraints from  $M_{\text{gas}}$  and  $Y_X$  with little effect on the  $T_X$  results.

independent measurement of  $\Omega_M$  with almost no degeneracy with  $\Omega_\Lambda$ :  $\Omega_M = 0.34 \pm 0.08$ , in good agreement with the mass function shape results (and also previous measurements based on evolution of the cluster temperature function, see Henry 2004). In a flat  $\Lambda$ CDM model (the one with  $\Omega_M + \Omega_\Lambda = 1$ ), the constraint is slightly tighter,  $\Omega_M = 0.30 \pm 0.05$ .

Systematic uncertainties of the  $\Omega_\Lambda$  measurements are dominated by possible departures of evolution in the  $M_{\text{tot}}$  vs. proxy relations. This issue is discussed in detail below in connection with the dark energy equation of state constraint (§ 8.4); here we note only that the systematic uncertainties are approximately 50% of the purely statistical errorbars on the dark energy parameters ( $\Omega_\Lambda$ ,  $w$ ). Therefore, our cluster data provide a clear independent confirmation for non-zero  $\Omega_\Lambda$ .

*Comments on the role of geometric information in the cluster mass function test* — Cosmological constraints based on fitting the cluster mass function generally use not only information from growth of structure but also that from the distance-redshift relation because derivation of the high- $z$  mass functions from the data assumes the  $d(z)$  and  $E(z)$  functions. Quite generally, the estimated mass is a power law function of these dependencies,  $\bar{M} \propto d(z)^\beta E(z)^{-\epsilon}$ . Different mass proxies have different  $\beta$  and  $\epsilon$ , and thus combine the geometric and growth of structure information in different ways and lead to different degeneracies in the derived cosmological parameters. We find that strongly distance-dependent proxies (such as  $M_{\text{gas}}$ , see Paper II) are intrinsically more powerful in constraining the dark energy parameters ( $\Omega_\Lambda$ ,  $w$ ). By contrast, distance-independent proxies such as  $T_X$  result in poor sensitivity to dark energy but instead better constrain  $\Omega_M$ . This is well illustrated by the results in Fig. 5. The  $M_{\text{gas}}$  based estimates for  $M_{\text{tot}}$  result (if we ignore the shape of the mass function information)

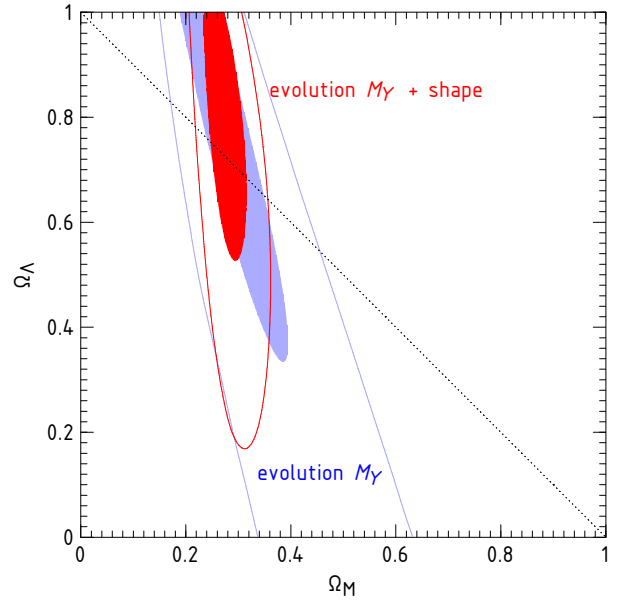


FIG. 6.— Same as Fig. 5 but for  $Y_X$ -based mass estimates.

in degeneracy approximately along the line  $\Omega_M + \Omega_\Lambda = 1$ . In fact, the evolution of the cluster mass functions derived from  $M_{\text{gas}}$  can be made broadly consistent with the  $\Omega_M \approx 1$ ,  $\Omega_\Lambda \approx 0$  cosmology if one allows for strong deviations from the CDM-type initial power spectra (Nuza & Blanchard 2006). However, the mass functions estimated from the temperatures of the same clusters are grossly inconsistent with such a cosmology, irrespective of the assumptions on the initial power spectrum ( $\Omega_M = 1$  is  $8.3\sigma$  away from the best fit to the temperature-based mass function, Fig. 5). It is encouraging that the 68% CL regions for all three mass proxies overlap near the “concordance” point at  $\Omega_M = 0.25 - 0.3$  and  $\Omega_\Lambda = 0.7 - 0.75$ .

## 8. FLAT UNIVERSE WITH CONSTANT DARK ENERGY EQUATION OF STATE: $w_0 - \Omega_X$

Next, we study constraints on a constant dark energy equation of state,  $w_0 \equiv p_X/\rho_X$ , in a spatially flat universe. The analysis using cluster data only is equivalent to the  $\Omega_M - \Omega_\Lambda$  case (§ 7). We compute the likelihood for the cluster mass functions on a grid of parameters: present dark energy density  $\Omega_X (= 1 - \Omega_M)$ ,  $w_0$ ,  $h$ , and  $\sigma_8$ , then add the HST prior on the Hubble constant (§ 4). Marginalization over non-essential parameters,  $h$  and  $\sigma_8$ , gives the likelihood as a function of  $\Omega_M$  and  $w_0$ . We also obtain the equation of state constraints combining our cluster data with the three external cosmological data sets (following the reasoning of Dunkley et al. 2008, for the choice of these datasets):

### 8.1. External Cosmological Datasets

*SN Ia* — We use the distance moduli estimated for the Type Ia supernovae from the HST sample of Riess et al. (2007), SNLS survey (Astier et al. 2006), and ESSENCE survey (Wood-Vasey et al. 2007), combined with the nearby supernova sample (we used a combination of all these samples compiled by Davis et al. 2007). Calculation of the SN Ia component of the likelihood function for the given cosmological model is standard and can be found in any of the above references.

TABLE 2  
PARAMETER CONSTRAINTS FROM COMBINATION OF CLUSTERS WITH OTHER COSMOLOGICAL DATASETS

| Parameter   | Value                                    | Dataset  | Systematic errors      | Dominant source of systematics  |
|---|--|--|------------------------|---|
| <i>Flat (<math>\Omega_k = 0</math>), constant <math>w</math> (<math>w = w_0</math>)</i>                         |  |  |                        |   |
| $w_0$ .....   | $-1.14 \pm 0.21$                         | evol+shape+h, § 8.2                                  | $\pm 0.10, \pm 0.08$ , | Evolution of $M_{\text{tot}}$ vs. proxy relations, evolution in $L_X - M_{\text{tot}}$ , respectively |
| $w_0$ .....   | $-1.08 \pm 0.15$                         | evol+cmb, § 8.3                                      | $\pm 0.025$            | Evolution of $M_{\text{tot}}$ vs. proxy relations   |
| $w_0$ .....   | $-0.97 \pm 0.12$                         | evol+cmb+ $\sigma_8$ +bao, § 8.3                     | $\pm 0.038$            | Absolute cluster mass calibration   |
| $\Omega_X$ .....  | $0.732 \pm 0.016$                        | cmb+bao+sn, § 8.3                                    |                        |   |
| $w_0$ .....   | $-0.995 \pm 0.067$                       | cmb+bao+sn, § 8.3                                    | $\pm 0.076$            | SN systematics  |
| $w_0$ .....   | <b><math>-0.991 \pm 0.045</math></b>     | cmb+bao+sn+evol+ $\sigma_8$ , § 8.3                  | $\pm 0.022, \pm 0.033$ | SN systematics, cluster masses  |
| $\Omega_X$ .....  | <b><math>0.740 \pm 0.012</math></b>      | cmb+bao+sn+evol+ $\sigma_8$ , § 8.3                  |                        |   |
| $h$ .....   | <b><math>0.715 \pm 0.012</math></b>      | cmb+bao+sn+evol+ $\sigma_8$ , § 8.3                  |                        |   |
| $\sigma_8$ .....  | <b><math>0.786 \pm 0.011</math></b>      | cmb+bao+sn+evol+ $\sigma_8$ , § 8.3                  |                        |   |
| <i>Flat (<math>\Omega_k = 0</math>), constant <math>w</math> (<math>w = w_0</math>), non-zero neutrino mass</i> |  |  |                        |   |
| $w_0$ .....   | $-1.02 \pm 0.055$                        | $\sigma_8$ +cmb <sub>v</sub> +cmb+bao+sn+evol, § 8.5 | $\pm 0.064$            | SN systematics.   |
| $\sum m_\nu$ .....  | $0.1 \pm 0.12$ eV,<br>< 0.33 eV (95% CL) | $\sigma_8$ +cmb <sub>v</sub> +cmb+bao+sn+evol, § 8.5 | $\pm 0.1$ eV           | SN systematics, cluster masses  |
| <i>Flat (<math>\Omega_k = 0</math>), evolving <math>w</math>: <math>w = w_0 + w_a(1 - a)</math></i>             |  |  |                        |   |
| $w_a + 3.64(1 + w_0)$ .....   | $0.05 \pm 0.17$                          | cmb+bao+sn+evol+ $\sigma_8$ , § 9.1                  |                        |   |
| <i>Constant <math>w</math> (<math>w = w_0</math>), non-flat (<math>\Omega_k \neq 0</math>)</i>                  |  |  |                        |   |
| $w_0$ .....   | $-1.03 \pm 0.06$                         | cmb+bao+sn+evol+ $\sigma_8$ , § 9.2                  |                        |   |

NOTE. — Codes used in column 3: *evol* — evolution of the cluster mass function; *h* — HST prior on Hubble constant; *shape* — shape of the cluster mass function; *cmb* — WMAP-5 distance priors;  $\sigma_8$  — comparison of the cluster-derived  $\sigma_8$  with the CMB power spectrum normalization (reflecting growth of perturbations between  $z_{\text{CMB}}$  and  $z = 0$ ); *bao* — BAO distance prior; *sn* — SN Ia luminosity distances; *cmb<sub>v</sub>* — WMAP-5+BAO+SN constraints on neutrino mass (§ 8.5).

**Baryonic Acoustic Oscillations** — Detection of the baryonic acoustic peak in the correlation function for large red galaxies in the SDSS survey leads to a good measurement of the combination

$$\left[ \frac{d_A(z)^2}{(cz)^2 H(z)} \right]^{1/3} \sqrt{\Omega_M H_0^2} \left[ \frac{n}{0.98} \right]^{0.35} = 0.469 \pm 0.017 \quad (1)$$

at  $z = 0.35$  (Eisenstein et al. 2005, “SDSS LRG sample”). This prior mostly constrains  $\Omega_M$  but has some sensitivity also to the dark energy equation of state.

A more recent measurement of the BAO peaks in the combined SDSS and 2dF survey data is presented in Percival et al. (2007a) who determine the BAO distance measure at two redshifts ( $z = 0.2$  and  $z = 0.35$ ) instead of one in Eisenstein et al. (2005). These new data are somewhat in tension ( $\sim 2\sigma$ ) with the SN+WMAP results (see, e.g., Fig. 11 in Percival et al. 2007a), which may artificially tighten the constraints when the BAO data are combined with SN Ia, WMAP, and clusters. We checked, however, that from the combination of SN Ia, WMAP, and SDSS-LRG BAO, we derive the parameter constraints that are essentially equivalent to those in Komatsu et al. (2008), who used the Percival et al. priors. Therefore, the choice of the BAO dataset is unimportant in the combined constraints.

**WMAP-5** — The likelihood for WMAP 5-year data is computed using a simplified approach described in § 5.4 of Komatsu et al. (2008). This involves a computation, for a given set of cosmological parameters, of three CMB parameters — angular scale of the first acoustic peak,  $\ell_A$ ; the so called shift parameter,  $R$ ; and the recombination redshift,  $z_*$ . The likelihood for the WMAP-5 data is then computed using the covariance matrix for  $\ell_A$ ,  $R$ , and  $z_*$  provided in Komatsu et al. This method is almost as accurate as direct computation of the WMAP likelihood (Wang & Mukherjee 2007) but is much faster, which allowed us to explore the entire multi-

dimensional grid of the cosmological parameters instead of running Markov chain simulations. One additional note is that to compute the CMB likelihood, we had to add the absolute baryon density,  $\Omega_b h^2$ , to our usual set of cosmological parameters and then marginalize over it. The reason is that while the average baryon density has very little impact on the rest of our analysis, the CMB data are very sensitive to  $\Omega_b h^2$ , thus any variation of  $h$  must be accompanied by the corresponding variation of  $\Omega_b$  without which the computation of the CMB likelihood would be inadequate.

The method outlined above recovers essentially the entire information from the location and relative amplitudes of the peaks in the CMB power spectrum (Wang & Mukherjee 2007). One additional piece of information is the absolute normalization of the CMB power spectra, reflecting the amplitude of density perturbations at the recombination redshift,  $z_* \approx 1090$ . Contrasted with  $\sigma_8$  determined from our cluster data at  $z \approx 0$ , it constrains the total growth of density perturbations between the CMB epoch and the present, and thus is a powerful additional dark energy constraint.

**WMAP-5 plus local  $\sigma_8$**  — The WMAP team provides the amplitude of the curvature perturbations at the  $k = 0.02 \text{ Mpc}^{-1}$  scale,

$$\Delta_{\mathcal{R}}^2 = (2.21 \pm 0.09) \times 10^{-9} \quad (2)$$

Section 5.5 in Komatsu et al. (2008) gives the prescription of how to predict this observable for a given set of cosmological parameters and  $\sigma_8$ . A useful accurate fitting formula can also

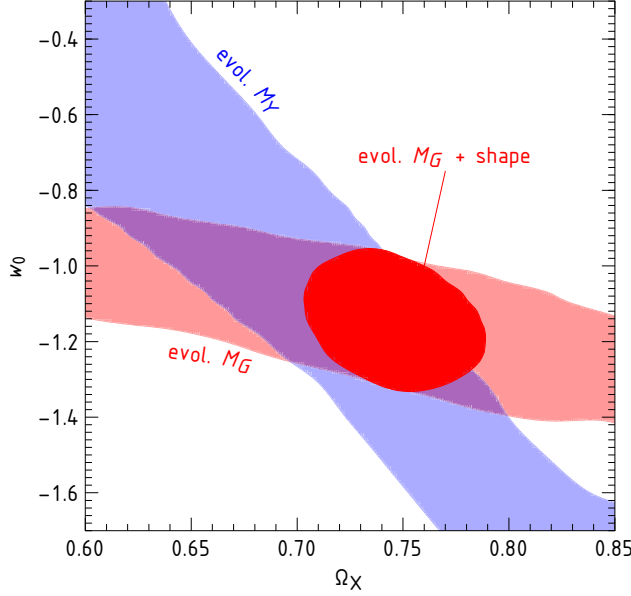


FIG. 7.— Constraints on the present dark energy density  $\Omega_X$  and constant equation of state parameter  $w_0$  derived from cluster mass function evolution in a spatially flat Universe. The results for  $M_{\text{gas}}$  and  $Y_X$ -based total mass estimates are shown in red and blue, respectively. The inner solid red region shows the effect of adding the mass function shape information (§5) to the evolution of the  $M_{\text{gas}}$ -based mass function.

be found in Hu & Jain (2004):

$$\tilde{\Delta}_{\mathfrak{R}} \approx \frac{\sigma_8}{1.79 \times 10^4} \left( \frac{\Omega_b h^2}{0.024} \right)^{1/3} \left( \frac{\Omega_M h^2}{0.14} \right)^{-0.563} \times (7.808 h)^{(1-n)/2} \left( \frac{h}{0.72} \right)^{-0.693} \frac{0.76}{G_0} \quad (3)$$

(we adjusted numerical coefficients to take into account that the Hu & Jain approximation uses the CMB amplitude at  $k = 0.05 \text{ Mpc}^{-1}$  while the WMAP-5 results are reported for  $k = 0.02 \text{ Mpc}^{-1}$ ). In this equation,  $G_0$  is the perturbation growth factor between the CMB redshift and the present, normalized to the growth function in the matter-dominated universe:  $G(z) \equiv (1+z) \delta(z)/\delta(z_{\text{CMB}})$ . This fitting formula helps to understand the nature of the  $\sigma_8$  vs. CMB amplitude constraint. The relation between  $\sigma_8$  and  $\tilde{\Delta}_{\mathfrak{R}}$  depends on the absolute matter and baryon densities,  $\Omega_M h^2$  and  $\Omega_b h^2$  (well-measured by the CMB data alone), and on the total growth factor,  $G_0$ , and the absolute value of the Hubble constant,  $h$ . Both of these quantities provide powerful constraints on any parametrization of the dark energy equation of state (Hu 2005), and their combination does so as well.

Inclusion of this information in the total likelihood is straightforward. Given the usual set of cosmological parameters ( $\Omega_X$ ,  $w_0$ ,  $h$ ) plus  $\sigma_8$ , one computes

$$\chi_{\text{CMBnorm}}^2 = (\tilde{\Delta}_{\mathfrak{R}}^2 \times 10^9 - 2.21)^2 / 0.09^2, \quad (4)$$

where  $\tilde{\Delta}_{\mathfrak{R}}$  can be obtained either from eq.[3] or as described in Komatsu et al. (2008). The  $\chi_{\text{CMBnorm}}^2$  component is then added to the cluster  $\chi^2$  and the sum marginalized over  $\sigma_8$ .

### 8.2. $w_0$ from Cluster Data Only

Constraints on the present dark energy density  $\Omega_X$  and constant equation of state are presented in Fig. 7. For compar-

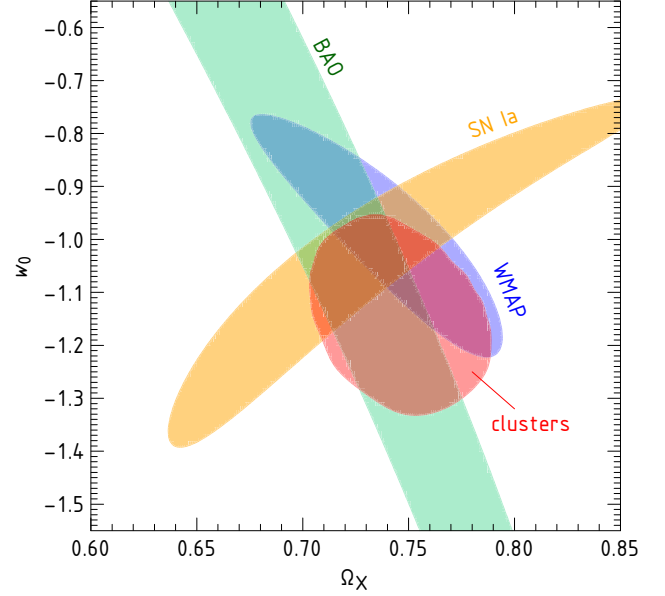


FIG. 8.— Comparison of the dark energy constraints from X-ray clusters and from other individual methods (supernovae, baryonic acoustic oscillations, and WMAP).

ison, we show separately the results derived only from evolution of the  $M_{\text{gas}}$  and  $Y_X$ -based mass functions, and the effect of including the mass function shape information (§7 describes the procedure for removing shape information from the cluster likelihood function). We do not consider here the  $T_X$  based mass estimates because they provide little sensitivity to the dark energy parameters (§7). Just like in the  $\Omega_M - \Omega_\Lambda$  case, evolution of the  $M_{\text{gas}}$  and  $Y_X$ -based mass functions constrains different combinations of  $w_0$  and  $\Omega_X$ . The width of the confidence regions across the degeneracy direction is similar but the gas-based results are less inclined giving a little more sensitivity to  $w_0$  for a fixed dark energy density —  $\Delta w_0 = \pm 0.17$  from the  $M_{\text{gas}}$ -based functions and  $\Delta w_0 = \pm 0.26$  from  $Y_X$ .

Adding the mass function information combined with the HST prior on  $h$  breaks the degeneracy along the  $\Omega_X$  direction. For example, the ellipse in Fig. 7 shows the 68% CL region from fitting both the evolution and shape of the  $M_{\text{gas}}$ -based mass function. The one-parameter confidence intervals in this case are  $\Omega_X = 0.75 \pm 0.04$  and  $w_0 = -1.14 \pm 0.21$ . These results compare favorably with those from other individual methods — supernovae, BAO, WMAP (Fig. 8), although the supernovae and CMB data provide tighter constraints on  $w_0$  for a fixed  $\Omega_X$ . The real strength of the cluster data is, however, when they are combined with the CMB and other cosmological datasets. The combined constraints are very similar for the  $M_{\text{gas}}$  and  $Y_X$ -based cluster mass functions, and therefore we discuss only the former hereafter.

### 8.3. $w_0$ from the Combination of Clusters with Other Data

First, we consider a combination of the cluster data with the WMAP distance priors (see §5.4 in Komatsu et al. 2008). Cluster data bring information on growth of density perturbations and normalized distances in the  $z \simeq 0.0 - 0.9$  interval, and — weakly — on the  $\Omega_M h$  parameter. Adding this information reduces the WMAP-only uncertainties on  $w_0$  and  $\Omega_X$  approximately by a factor of 2 (dark blue region in Fig. 9):  $w_0 = -1.08 \pm 0.15$ ,  $\Omega_X = 0.76 \pm 0.04$ .

A much more significant improvement of the constraints

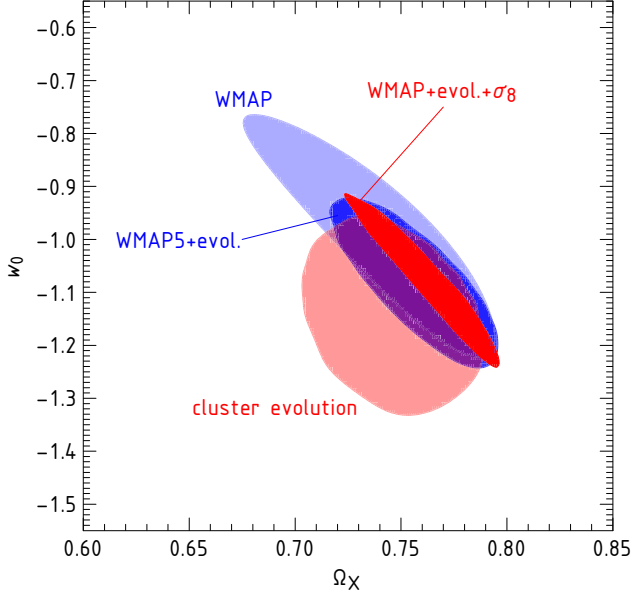


FIG. 9.— Dark energy constraints in a flat universe from the combination of the CMB and cluster data (dark blue region). Adding the  $\sigma_8$  vs. CMB normalization information significantly improves constraints on  $w_0$  for a fixed  $\Omega_X$  (inner red region).

arises from the  $\sigma_8$  determination from low-redshift clusters (dark red region in Fig. 9). Comparison of the local determination of  $\sigma_8$  with the CMB normalization mostly provides a measurement of the total perturbation growth factor between  $z_{\text{CMB}}$  and the present. This depends more sensitively on  $w_0$  than the evolution of the cluster mass function because of, first, larger redshift leverage, and second, because the perturbation amplitude at high  $z$  is measured more accurately by CMB than by 37 clusters from the 400d survey.

Is it appropriate to use the  $\sigma_8$  vs. CMB normalization information in the dark energy constraints or does it require unreasonable interpolation of the dark energy parametrization to high redshifts? We note in this regard that for any combination of the cosmological parameters in the vicinity of the “concordance” model,  $w_0 \simeq -1$ ,  $\Omega_X = 0.25 - 0.3$ , the Universe becomes matter-dominated and enters the deceleration stage by  $z \sim 1.5 - 2$ ; the growth of perturbations is basically fixed after that at  $G(z) = 1$ . In other words, the CMB data can be used to safely predict the amplitude of density perturbations at  $z = 1.5 - 2$  almost independently of the exact dark energy properties. As long as it is appropriate to use a particular dark energy parametrization in the  $z = 0 - 2$  interval, it is therefore appropriate to use the same model for the joint clusters+WMAP fit.

By itself, adding the  $\sigma_8$  information does not significantly improve the  $w_0$  and  $\Omega_X$  constraints (the total extent of the  $1\sigma$  confidence regions is similar to the WMAP+evolution case), but the confidence region becomes much more degenerate with  $\Omega_X$  (see inner red region in Fig. 9), which increases the potential for improvement when we combine these results with other cosmological datasets, BAO and supernovae.

The combined constraints from all four cosmological datasets are shown in Fig. 10 (inner dark red region). The 68% one-parameter confidence intervals are  $\Omega_X = 0.740 \pm 0.012$  and  $w_0 = -0.991 \pm 0.045$ . The importance of adding information from our cluster samples is illustrated by a factor of  $\sim 1.5$  reduction of the measurement uncertainties with respect to the

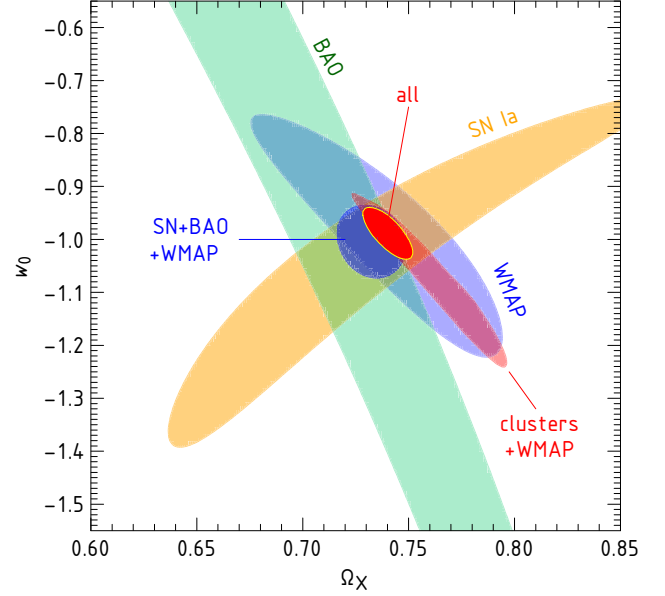


FIG. 10.— Dark energy constraints in flat universe from combination of all cosmological datasets. We find  $w_0 = -0.991 \pm 0.045$  ( $\pm 0.04$  systematic) and  $\Omega_X = 0.740 \pm 0.012$ , see Table 2 and § 8.3.

WMAP+SN+BAO data alone: we obtain  $w_0 = -0.995 \pm 0.067$  without clusters (dark blue region in Fig. 10; these results are essentially identical to those reported in Komatsu et al. 2008). Perhaps more importantly, including the cluster data also reduces systematic uncertainties by a similar amount (§ 8.4).

The best-fit values of the Hubble constant and  $\sigma_8$  from the combination of all datasets are  $h = 0.715 \pm 0.012$  and  $\sigma_8 = 0.786 \pm 0.011$ . These values are within 68% confidence intervals of their determination by direct measurements (HST Key Project results for  $h$  and fitting the low- $z$  cluster mass function for  $\sigma_8$ ). The best-fit combination of the dark energy parameters is also within the  $1\sigma$  confidence regions for each individual dataset included in the constraints (Fig. 10). Therefore, the best-fit cosmological model is a *good fit* to the data. In particular, Fig. 17 from Paper II shows that the mass function models computed in the  $\Lambda$ CDM cosmology ( $w_0 = -1$ ) provide a very good description of the data.

#### 8.4. Systematic Uncertainties in the $w_0$ Measurements

We estimate the effect of known sources of systematics on the cosmological constraints by varying the corresponding individual sets of data or internal relations (e.g., evolution in  $L_X - M_{\text{tot}}$  entering the survey volume computations) within the estimated  $1\sigma$  interval. We assume, optimistically, that the current WMAP and BAO data are free from significant systematics (i.e., that they are smaller than statistical uncertainties), and consider systematic errors only in the SN Ia and cluster datasets. In most cases, a single source clearly dominates the systematic error budget for a particular measurement, so we report on only those dominant sources.

The largest known source of systematic error in the SN Ia analysis is the correction for extinction in host galaxies and uncertainties in intrinsic colors of SN Ia (e.g., Frieman et al. 2008). As a measure of systematic uncertainty in the combined SN sample we use  $\pm 0.13$  in  $w_0$  for fixed  $\Omega_X$ , quoted by Wood-Vasey et al. (2007). We implement these errors by computing the SN likelihood in our experiments for  $(\Omega_X, w_0 + 0.13)$  and  $(\Omega_X, w_0 - 0.13)$  instead of  $(\Omega_X, w_0)$ .

#### 8.4.1. Main Sources of Cluster Systematics

The largest sources of systematic errors in the cluster analysis are those in the normalization of the  $M_{\text{tot}}$  vs. proxy relations. They can be separated into two almost independent components: 1) how accurately is the *absolute* cluster mass scale established by X-ray hydrostatic  $M_{\text{tot}}$  estimates in the low-redshift clusters, and 2) how accurately can we predict evolution in the  $M_{\text{tot}}$  vs. proxy relations, i.e., the *relative* mass scale between low and high redshift clusters. The first component mainly affects the  $\sigma_8$  measurements and associated dark energy constraints, while the second component affects the results derived from using only evolution in the cluster mass function (those in Fig. 7). Our estimates of the  $M_{\text{tot}}$  systematics are discussed extensively in Paper II. For the absolute mass scale ( $M_{\text{tot}}$  for fixed  $Y_X$ ,  $T_X$ , or  $M_{\text{gas}}$ ) at  $z \approx 0$ , we estimate  $\Delta M_{\text{sys}}/M \lesssim 9\%$  mainly from comparison of the X-ray and weak lensing mass estimates in representative samples. This source of error is implemented by changing the normalization of the  $M_{\text{tot}}$  vs.  $Y_X$ ,  $M_{\text{gas}}$ , or  $T_X$  relations at  $z = 0$  by  $\pm 9\%$ . For uncertainties in the evolution of the  $M_{\text{tot}}$  vs. proxy relations, we estimate  $\Delta M/M \approx 5\%$  at  $z = 0.5$ , mainly from comparison of the prediction of different models describing observed small deviations of the cluster scaling relations from self-similar predictions, and from the magnitude of these deviations and corresponding corrections we apply to the data. These uncertainties are implemented by multiplying the standard scaling relations by factors of  $(1+z)^{\pm 0.12}$ .

Comparable to the evolution in the  $M_{\text{tot}}$  vs. proxy relation are measurement uncertainties in the evolution factor for the  $L_X - M_{\text{tot}}$  relation. We do not use  $L_X$  to estimate the cluster masses, but the relation is required to compute the survey volume for the high- $z$  sample. The resulting volume uncertainty depends on the mass scale, and can become comparable to the Poisson error for the comoving cluster number density (see § 5.1.3 in Paper II). We tested how this influences the cosmological fit by varying the parameters of the  $L_X - M_{\text{tot}}$  relation within their measurement errors around the best fit [the evolution of  $L_X$  for fixed  $M_{\text{tot}}$  in our model is parametrized as  $E(z)^\gamma$  and  $\gamma$  is measured to  $\pm 0.33$ , see § 5.1.3 in Paper II].

Other sources of systematics in the cluster analysis (summarized in Paper II) are negligible compared to those outlined above. We verified also that uncertainties in the intrinsic scatter in the  $M_{\text{tot}}$ -proxy relations are not important. The main reason is that in the dark energy constraints, we use high-quality mass proxies ( $Y_X$  and  $M_{\text{gas}}$ ), which should provide mass estimates with small, 7–10% scatter. Variations of this scatter by up to  $\pm 50\%$  with respect to the nominal values do not significantly change the best fit cosmological parameters. This conclusion is seemingly different from Lima & Hu (2005) because in that paper, they consider proxies with larger scatter (the effect on the cosmological parameter constraints is proportional to scatter squared), and also they assumed that the normalizations in the  $M_{\text{tot}}$  vs. proxy relation are obtained from self-calibration while we use direct mass measurements for a well-observed subsample.

The variations of the best-fit parameters due to the systematics discussed above are reported in Table 2 along with the dominant source of error for each combination of cosmological datasets. For example, variations in the evolution of the  $M_{\text{tot}} - M_{\text{gas}}$  and  $M_{\text{tot}} - Y_X$  relations affect the best fit to the cluster data only by  $\Delta w_0 = \pm 0.1$ , while statistical uncertainties are  $\pm 0.2$  to  $\pm 0.3$  for fixed  $\Omega_X$  (§ 8.2); unless the systematics in this case are a factor of two larger than our estimates, they are unimportant.

#### 8.4.2. Systematics in the Combined Constraints

The most interesting case to consider is reduction in the systematic errors from combining both SN and cluster data with the WMAP and BAO priors. In the SN+CMB+BAO case, the supernovae systematics cause variations in the best-fit  $w_0$  by  $\pm 0.076$  (reduced from  $\pm 0.13$  for the SN-only case mainly by including WMAP priors). Cluster systematics affects the  $w_0$  constraints from the clusters+WMAP+BAO combination by  $\pm 0.04$  (dominated by the  $\pm 9\%$  uncertainties in the absolute mass scale). The influence of both sources of error is significantly reduced in the combined constraints. We find that the best fit  $w_0$  from SN+clusters+WMAP+BAO is affected by  $\pm 0.022$  by SN systematics, and by  $\pm 0.033$  by cluster systematics. The total systematic error in the combined constraint is thus  $\Delta w_0 = \pm 0.04$ , almost a factor of 2 reduction from  $\pm 0.076$  achievable without clusters.

We also note that if we significantly underestimate the cluster systematics, the most likely direction is that the cluster total masses are underestimated<sup>14</sup>. If cluster  $M_{\text{tot}}$  are revised high, this would lead to an increase in the derived  $\sigma_8$ , and decrease in  $w_0$  when cluster data are combined with the CMB priors. Dark energy models predicting the equation of state parameter significantly above  $w_0 = -1$  will be even less consistent with observations in this case.

#### 8.4.3. Prospects for Further Reduction of Systematic Errors

It is reassuring that all sources of systematic errors we considered affect the dark energy equation of state constraints within the statistical measurement errors. This implies that while systematic errors are important, they do not yet dominate the current error budget. The situation will reverse in the future as the datasets expand. More effort will be needed then to reduce the systematics still further. We briefly outline the prospects for reducing the cluster-related systematics. Some of this will happen automatically as the high- $z$  surveys become deeper and cover a larger area. For example, the  $V(M)$  uncertainties for our range of redshifts can be eliminated simply by decreasing the flux threshold by a factor of  $\sim 4$  compared to the 400d limit, making the sample volume-limited; such an extension will provide also a more accurate measurement of the  $L_X - M_{\text{tot}}$  relation. The absolute calibration of  $M_{\text{tot}}$  in low- $z$  clusters can be improved by constraining sources of non-thermal pressure (e.g., if turbulence is of any importance for the  $M_{\text{tot}}$  estimates, it is easily detectable with an X-ray microcalorimeter), or through stacked weak lensing analysis (e.g., measuring average lensing shear profiles for a large set of clusters with the same  $Y_X$ ). To improve limits on non-standard evolution in the  $M_{\text{tot}}$  vs. proxy relations, we cannot use direct mass measurements of the high- $z$  objects because they will be degenerate with the assumed distance-redshift relation. Instead, we should improve reliability of numerical models for cluster evolution. The biggest uncertainties in these models at present are related to the processes of gas cooling and star formation, and also to energy feedback from the central AGN. The strategy for future progress can be based on the fact that these processes most strongly affect cluster cores, which we do not use for the mass estimates. We

<sup>14</sup> The X-ray hydrostatic analysis includes only the gas thermal pressure and assumes that the cluster gas body is close to being spherically symmetric. The presence of additional components in the pressure, clumpiness and turbulent motions in the gas all lead to underestimation of  $M_{\text{tot}}$  derived from X-ray data. Probably the only possibility for *overestimation* of  $M_{\text{tot}}$  in the X-ray analysis is a gross miscalibration of the *Chandra* spectral response, for which strong experimental limits are available.

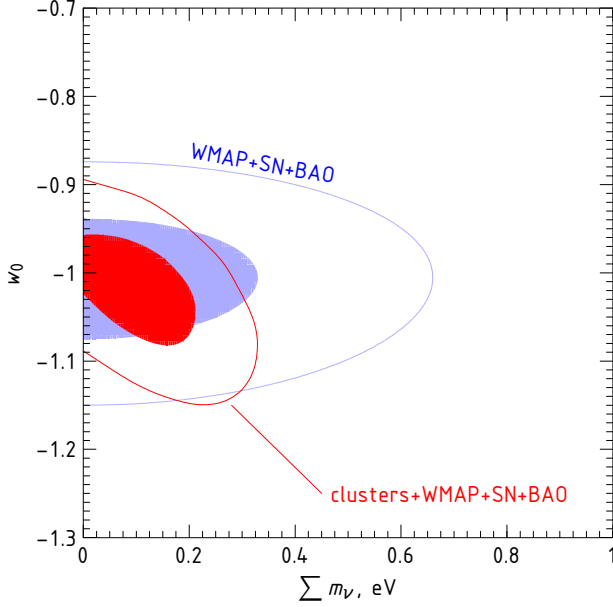


FIG. 11.— Equation of states from WMAP, BAO, SN Ia, and clusters in the case of non-zero neutrino mass.

can, therefore, use the data from the central regions to bracket a likely range of uncertainty in the model predictions for the cluster outer regions, where we derive the  $M_{\text{tot}}$  proxies. However, even with the current estimated uncertainties, the samples can grow by a factor of  $\sim 4$  before the systematics start to dominate. Ultimately, as the cluster surveys detect  $\sim 10^4$  clusters with accurately measured X-ray parameters, the so-called self-calibration techniques (Majumdar & Mohr 2004; Lima & Hu 2004) can be employed to further constrain the evolution in the  $M_{\text{tot}}$  vs. proxy relations.

### 8.5. Effects of Non-Zero Neutrino Mass

If light neutrinos have masses in the range of a few 0.1 eV, they become non-relativistic between  $z_{\text{CMB}}$  and  $z = 0$ , and this transition produces distortions in the matter perturbations power spectrum relative to prediction of the pure CDM+baryons model. Using approximations of the transfer function from Eisenstein & Hu (1999), it is easy to verify that the effect is approximately proportional to the total mass of neutrinos (more exactly, to  $\sum m_\nu / \Omega_M$ ), and the rms fluctuations at cluster scales today are suppressed by approximately 20% if  $\sum m_\nu = 0.5$  eV and  $\Omega_M = 0.26$ . This effect is far outside the measurement uncertainties in  $\sigma_8$  from clusters (we quote systematic errors of 3% from uncertainties in the  $M_{\text{tot}}$  calibration and statistical uncertainties are even smaller, see Table 1). Therefore, neutrino masses in this range a) may affect the dark energy constraints when cluster data are combined with WMAP (because they will effectively change the relation between  $\sigma_8$  and the CMB normalization, eq. 3), and b) can be tightly constrained by our cluster data.

To test the effect of neutrinos, we ran an additional set of models in which the total neutrino mass was allowed to vary between 0 and 1 eV. For simplicity we assumed that there are 3 neutrino species with the same mass, but the final results are not very sensitive to this assumption. The only component of our procedure which is significantly affected by non-zero neutrino mass is contrasting the cluster-derived  $\sigma_8$  with the WMAP normalization of the CMB power spectrum. We can no longer rely on eq.(3) and should instead use the full proce-

dure described in § 5.5 of Komatsu et al. (2008). Otherwise, the analysis is equivalent to the  $\sum m_\nu = 0$  case. The likelihood for all cosmological datasets was computed on our usual grid plus  $\sum m_\nu$  as an additional free parameter, and then marginalized over  $\Omega_X$ ,  $h$ , and  $\sigma_8$ . Finally, we took into account that a combination of WMAP, BAO, and SN data provides some sensitivity to neutrino mass through the so-called early integrated Sachs-Wolfe effect (see discussion in § 6.1.3 of Komatsu et al. 2008, and references therein). From this analysis, Komatsu et al. derive a 95% upper limit of  $\sum m_\nu < 0.66$  eV. Since our procedure of using WMAP priors (§ 8.1) ignores this additional information, we included it approximately by adding a Gaussian prior  $\sum m_\nu = 0 \pm 0.33$  eV to the final marginalized likelihood.

The derived constraints on  $\sum m_\nu$  and  $w_0$  are shown in Fig. 11. As expected, when the  $\sigma_8$  vs. CMB normalization constraint is added, there is a degeneracy between the best-fit  $w_0$  and total neutrino mass. If we were using only clusters and WMAP, the degeneracy would approximately follow the line  $w_0 + 1 = -0.4 \sum m_\nu$  and would extend to  $\sum m_\nu \approx 1.3$  eV (the WMAP-only bound on neutrino mass, Dunkley et al. 2008). This degeneracy is broken, however, when we add the BAO and SN information: low values of  $w_0$  required by clusters+CMB for high values of neutrino mass are inconsistent with these two datasets. Therefore, a combination of all four datasets can be used to constrain both  $w_0$  and neutrino mass. The best fit value is  $\sum m_\nu = 0.10 \pm 0.12$  eV, with a 95% CL upper limit of  $\sum m_\nu < 0.33$  eV. This limit is significantly tighter than that achievable without clusters ( $< 0.66$  eV at 95% CL). The constraint on  $w_0$  degrades somewhat compared to the  $m_\nu = 0$  case:  $w_0 = -1.02 \pm 0.055$  (compared to  $\pm 0.045$  for  $m_\nu = 0$ ), but is still better than  $\pm 0.067$  without clusters (see Table 2). To conclude, adding the cluster information allows us to set tight limits on the neutrino mass while still improving the  $w_0$  measurements with respect to the SN+WMAP+BAO case.

Our constraints on neutrino mass are still weaker than the published results from Ly- $\alpha$  forest data,  $\sum m_\nu < 0.17$  eV (Seljak et al. 2006). Both the cluster and Ly- $\alpha$  based constraints use the same effect — suppression of the power spectrum at small scales by neutrinos, — but they have completely different systematics. The main unknown in the Ly- $\alpha$  analysis is the thermal state of the low-density IGM, usually estimated from numerical simulations; it has been suggested that the thermal state may be more complex than assumed in previous work thus significantly weakening the  $m_\nu$  bounds (Bolton et al. 2008). For clusters, the main uncertainty is the absolute mass calibration for low-redshift objects which affects the measurement of  $\sigma_8$  (§ 6). The 9% systematic uncertainties on  $\Delta M/M$  that we quote would translate into approximately  $\pm 0.075$  eV for  $\sum m_\nu$ , negligible compared to the current statistical uncertainties. We note that if the X-ray cluster mass measurements are wrong by more than 9%, it is almost certainly in the sense that they are underestimated (see footnote 14 on page 12); the true value of  $\sigma_8$  will then be higher than our measurement and the bound on neutrino mass will be even tighter. Therefore, our 95% CL bound of  $\sum m_\nu < 0.33$  eV can be considered as a conservative upper limit.

## 9. MORE GENERAL DARK ENERGY MODELS

Finally, we demonstrate how our cluster data improves parameter constraints for more general dark energy models. We consider two cases — evolving equation of state,  $w = w(z)$ , and constant equation of state in a non-flat universe. The results are presented less completely than for the case of constant  $w$  in a flat universe. We also do not discuss systematic uncertainties

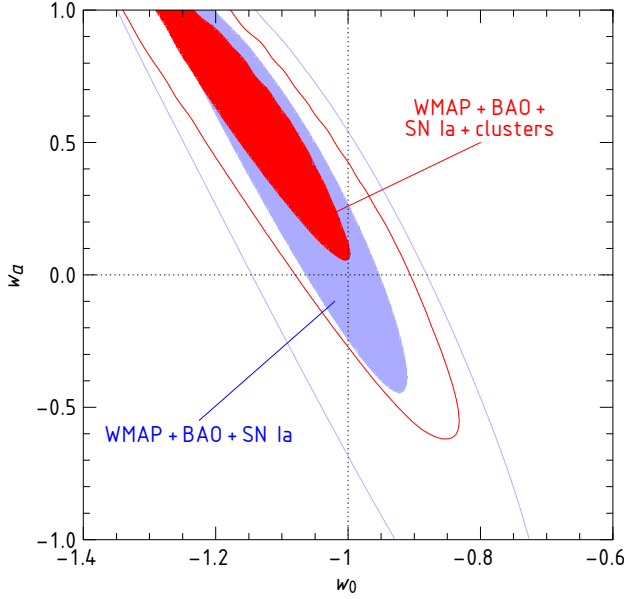


FIG. 12.— Constraints on evolving equation of state,  $w(z) = w_0 + w_a z / (1+z)$ , in flat universe.

separately for these cases; we checked that the importance of different sources of systematics and their fraction of statistical uncertainties is approximately the same as reported in § 8.4 for the constant  $w$ , flat universe case.

### 9.1. $w(z)$ in Flat Universe

We consider an often used parametrization of the equation of state evolution in which  $w$  changes linearly with the expansion factor,  $w(a) = w_0 + w_a(1 - a)$ , or equivalently,  $w(z) = w_0 + w_a z / (1 + z)$ . We do not consider more complex parametrizations because constraints on the evolution term are still weak, and because neither parametrization has a clear physical motivation.

The likelihood function is computed on the  $\Omega_M, w_0, w_a, h, \sigma_8$  grid and then marginalized over  $\Omega_M, h$ , and  $\sigma_8$ , leading to constraints in the  $w_0 - w_a$  plane shown in Fig. 12. Constraints on  $w_a$  are weak with or without clusters. For example, the model with  $w_0 = -1.2$  and  $w_a = 1$  (leading to  $w = -0.7$  by  $z = 1$ ) is perfectly consistent with the data. However, clusters make the confidence region substantially narrower (improve  $w_a$  constraints for a fixed  $w_0$ ). A cosmological constant model ( $w_0 = -1, w_a = 0$ ) is still consistent with the data.

Finally, we note that in either case, the degeneracy between  $w_0$  and  $w_a$  is almost linear,  $w_a = A + B w_0$ . For such degeneracies, constraints on constant  $w$  are equivalent to those for evolving  $w$  at the pivot redshift,  $a_p = (1 + z_p)^{-1} = 1 + 1/B$  (Hu & Jain 2004). From the slopes of degeneracies in Fig. 12, we find  $z_p \approx 0.29$  without clusters and  $z_p \approx 0.38$  when cluster information is included. Therefore, our combined constraints on constant  $w$  (§ 8) can also be interpreted as those for evolving  $w$  at this pivot redshift.

### 9.2. $w_0$ in Non-Flat Universe

The final case we consider is constant  $w$  in a non-flat universe. The cosmological grid in this case is  $(\Omega_k, \Omega_M, w_0, h, \sigma_8)$  with the requirement that the dark energy density is  $\Omega_X = 1 - \Omega_M - \Omega_k$ . The likelihood is marginalized over  $\Omega_M, h, \sigma_8$ , and the constraints on  $\Omega_k$  and  $w_0$  are shown in Fig. 13. Including clusters does not noticeably improve the measurement of  $\Omega_k$ ;

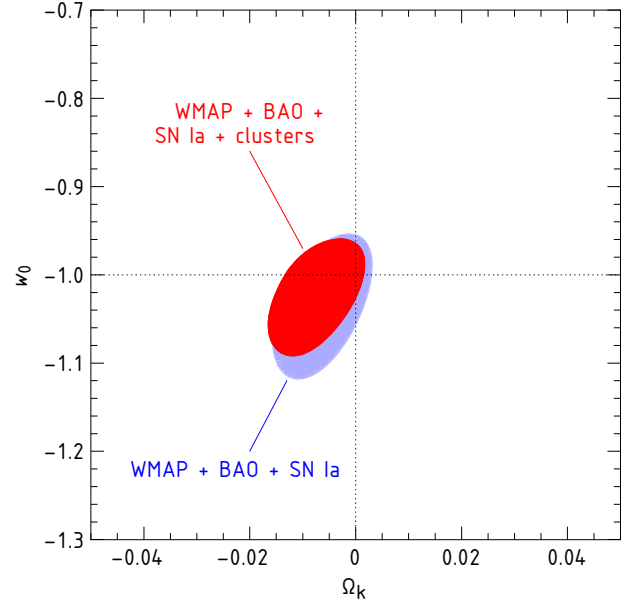


FIG. 13.— Equation of state constraints from WMAP, BAO, SN Ia, and clusters in the case of non-flat universe. We find  $w_0 = -1.03 \pm 0.06$  and  $\Omega_k = -0.008 \pm 0.009$  with all the data combined.

by far the most significant contribution to the  $\Omega_k$  constraint is from combination of WMAP and BAO data (Komatsu et al. 2008). However, clusters do substantially improve the equation of state measurement:  $w_0 = -1.03 \pm 0.06$  to be compared with  $\pm 0.085$  without clusters. A flat  $\Lambda$ CDM model ( $\Omega_k = 0, w_0 = -1$ ) is still consistent with the data within 68% CL.

## 10. SUMMARY AND CONCLUSIONS

We presented constraints on the cosmological parameters from a new measurement on the galaxy cluster mass function in the redshift range  $z = 0 - 0.9$ . All major sources of information contained in the cluster mass function — its overall normalization and slope at  $z = 0$ , and evolution at high redshifts — are determined with our new data with a higher statistical accuracy and smaller systematic errors than before. This leads to much improved and more reliable constraints on the cosmological parameters.

From the normalization of the mass function estimated at low redshifts, we derive the  $\sigma_8$  parameter degenerate with  $\Omega_M$ :  $\sigma_8(\Omega_M/0.25)^{0.47} = 0.813 \pm 0.013$  (stat)  $\pm 0.024$  (sys). The slope of the low- $z$  mass function is a measure of  $\Omega_M h$ :  $\Omega_M h = 0.184 \pm 0.037$ ; combined with the HST prior on  $h$ , this is an independent measurement of  $\Omega_M = 0.255 \pm 0.043$ . The matter density can be independently measured with our cluster data using evolution of the temperature function, yielding consistent results,  $\Omega_M = 0.30 \pm 0.05$  in a flat  $\Lambda$ CDM model and  $0.34 \pm 0.08$  in a general cosmology.

Evolution of the mass functions between  $z = 0$  and  $0.5$  (median redshift for our high- $z$  sample) constrains  $\Omega_\Lambda = 0.83 \pm 0.15$  in non-flat  $\Lambda$ CDM cosmology, or the dark energy equation of state parameter,  $w_0 = -1.14 \pm 0.21$ , in a spatially flat Universe. Inclusion of the information provided by our cluster data also significantly improves the equation of state constraints obtained from combination of multiple cosmological datasets. For example, by combining the 5-year WMAP, most recent supernovae measurements, and detection of baryonic acoustic oscillations in the SDSS with our cluster data, we obtain  $w_0 = -0.991 \pm 0.045$  (stat)  $\pm 0.040$  (sys); both the statistical

and systematic errors in the combined constraint are a factor of 1.5–2 smaller than those without clusters. Including cluster information also improves results for an evolving equation of state parameter and for constant  $w$  in a non-flat universe. A spatially flat  $\Lambda$ CDM model is within the 68% CL interval from the best fit in all cases that we tested.

A good agreement between the geometric and growth of structure-based measurements of  $w$  in principle can be used to place limits on modified gravity theories which attempt to explain cosmic acceleration without dark energy (e.g., Wang et al. 2007). When self-consistent models of non-linear collapse in such theories become available, it could be straightforward to use our cluster data in such tests also.

Comparison of the power spectrum normalization at  $z = 0$  obtained from clusters with the amplitude of the CMB fluctuations is a sensitive measure of the mass of light neutrinos. We constrain  $\sum m_\nu < 0.33$  eV at 95% CL, at the expense of slightly weakening the measurement of  $w_0$  obtained assuming that the neutrino masses are negligibly small.

<sup>15</sup> <http://hea-www.harvard.edu/400d/CCCC>

To facilitate the use of our cluster results in our cosmological studies, we provide at the project WWW site<sup>15</sup> machine readable tables of the likelihood function computed on several cosmological grids.

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