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Cosmology with cluster surveys

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Abstract. Surveys of clusters of galaxies provide us with a powerful probe of the density and nature of the dark energy. The red-shift distribution of detected clusters is highly sensitive to the dark energy equation of state parameter w. Upcoming Sunyaev–Zel'dovich (SZ) surveys would provide us large yields of clusters to very high red-shifts. Self-calibration of cluster scaling relations, possible for such a huge sample, would be able to constrain systematic biases on mass estimators. Combining cluster red-shift abundance with limited mass follow-up and cluster mass power spectrum can then give constraints on w, as well as on σ_8 and Ω_M to a few per cents.

Keywords. Cosmology; cosmic microwave background; clusters.

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1. Introduction

Over the last few years, cosmological constraints from Type-Ia SNe [1,2], cluster baryon fractions [3], and the cosmic microwave background (CMB) anisotropy [4,5] have pointed to a dark energy dominated universe. An important question facing the astronomy community is the characteristics of such a dark energy (parametrized by its equation of state parameter w, where the pressure $p = w\rho$). Not long ago, it was also realized that with future galaxy cluster surveys in Sunyaev–Zel'dovich effect [6] or in X-ray, one would be able to do precision cosmology (especially probe w) by measuring the cluster red-shift distribution and their spatial and angular correlations [7].

2. The cluster red-shift distribution

The observed cluster red-shift distribution in a survey is the co-moving volume per unit red-shift and solid angle $\mathrm{d}V/\mathrm{d}z\,\mathrm{d}\Omega$ times the co-moving density of clusters n_{cl} with masses above the survey detection limit M_{lim}. This can be written as

$$\frac{\mathrm{d}N}{\mathrm{d}z\,\mathrm{d}\Omega} = \frac{\mathrm{d}V}{\mathrm{d}z\,\mathrm{d}\Omega} \; = \; \frac{c}{H(z)} d_A^2(z)\,(1+z)^2 \int_{M_{\mathrm{lim}}(z)}^{\infty} \mathrm{d}M\, \frac{\mathrm{d}n}{\mathrm{d}M}, \tag{1}$$

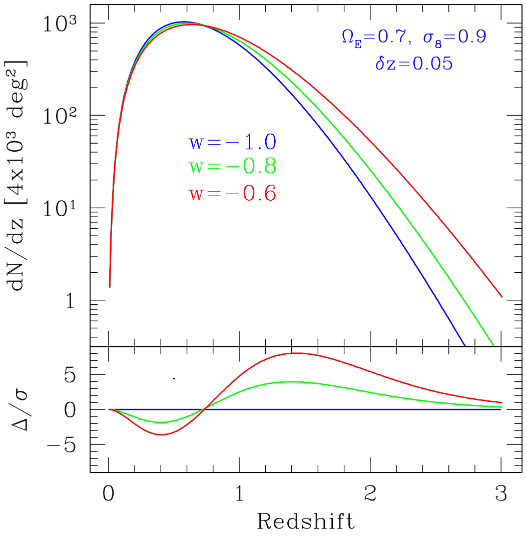

Figure 1. The sensitivity of cluster red-shift distribution for a 4000 deg^2 SZE survey to the dark energy equation of state w. Three models with different w are shown above. Their statistical differences are shown below. Figure courtesy: J Mohr.

where $\mathrm{d}n/\mathrm{d}M$ is the cluster mass function, $H(z)$ is the Hubble parameter as a function of red-shift and d_A is the angular diameter distance. The expansion history of the universe is given by $H(z) = H_0 E(z)$, where H_0 is the Hubble parameter and the parameter $E(z)$ describes its evolution such that $E^2(z) = \Omega_M\,(1+z)^3 + (1-\Omega_M-\Omega_E)\,(1+z)^2 + \Omega_E\,(1+z)^{3(1+w)}$. The expansion history of the universe bears the signature of dark energy and affects both the co-moving volume as well as the growth of structures. In figure 1 we show the effect of varying w on $\mathrm{d}N/\mathrm{d}z$. At low red-shifts the volume effect is important whereas at higher red-shifts the changes are due to change in growth of structures for different w's.

Other than the volume and the growth dependence, the survey yield depends sensitively on the mass limit. This is connected to the survey flux limit f_lim over which an instrument is capable of detecting clusters. The connection between these two are through the all important SZE (or X-ray) mass-observable [7a] relations and they depend on both cosmology as well as cluster physics. Striking regularity has been observed in the mass–luminosity relations for low red-shift clusters [8] and these are also known to persist to intermediate red-shifts [9]. However, a control over any systematic biases in the mass estimators at ∼10% level is required to do precision cosmology. Upcoming cluster surveys would contain enough information which would make possible the calibration of the mass-observable relations from the survey data itself without using inputs from targetted cluster observations. This has been termed ‘self-calibration’ in cluster surveys. One is, then, able to solve for cluster structure and do precision cosmology at the same time.

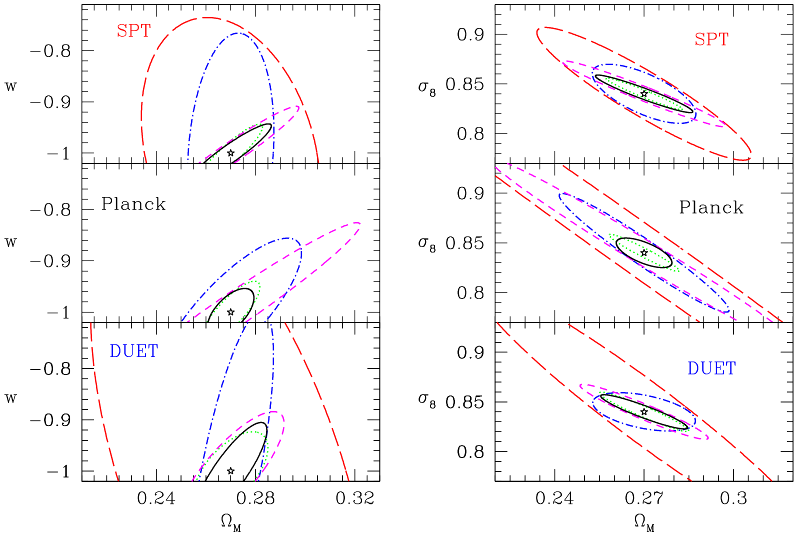

Figure 2. Left panel: 1-σ constraints on w and Ω_M for an SZE SPT survey (top), SZE Planck survey (middle) and an X-ray DUET survey (bottom) for five scenarios: 'Only Cosmology' (dotted); constraints from $\mathrm{d}N/\mathrm{d}z$ for 'Non-Std Evol' case (long-dashed); constraints from $\mathrm{d}N/\mathrm{d}z+\bar{P}_{\mathrm{cl}}$, (dot-dashed); $\mathrm{d}N/\mathrm{d}z$ + 100 cluster follow-up (short-dashed) and finally constraints from $\mathrm{d}N/\mathrm{d}z + \bar{P}_{\mathrm{cl}}$ + follow-up (solid). Right-panel: The corresponding constraints on σ_8 and Ω_M.

3. Self-calibration in cluster surveys

It was already shown [10,11] that precison cosmology with cluster surveys are possible. Diego *et al* [12] in an analysis of a small sample of cluster showed that it may be possible to solve for cluster structure from within the survey. Levine *et al* [13] examined a temperature limited survey, showing that a sufficiently large survey allows one to measure cosmological parameters and constrain the cluster mass-observable relation simultaneously if one assumes perfect knowledge of the red-shift evolution of the galaxy cluster structure. In the subsequent years, different authors have developed this very important idea and many calculations have been made underscoring the importance of incorporating information from multiple observables into the future cluster surveys, and they demonstrate that cluster surveys are essentially self-calibrating – containing enough information to solve for the mass-observable relation at every red-shift and constrain cosmological parameters.

Although self-calibration was found to occur for no evolution, it was subsequently shown [14] that if one allows for an imperfect understanding of galaxy cluster evolution, then the constraints on w are seriously weakened. In the same paper it was demonstrated that self-calibration can be regained by doing partial mass follow up at other wavelengths. As another solution to overcome the evolution-cosmology degeneracy, Hu [15] showed that there is potential for internal calibration by using the shape of the mass function of clusters in red-shift slices. Lima and Hu [16] used information from excess variance in counts in cell to reduce uncertainties. Recently, it was shown that from the survey data it is trivial to obtain the red-shift averaged cluster mass power spectrum $\bar{P}_{\rm cl}(k)$. Addition of this extra information, which is free without any extra observational effort, can help break any cosmology-cluster physics degeneracy and restore 'self-calibration' [17,18]. In figure 2, we show how self-calibration helps in tightening cosmological constraints for three future surveys (SPT [19] and Planck [20] in SZ effect and DUET [21] in X-rays). These surveys typically detect 20,000 or more clusters. We have shown the cases where there is no evolution (dotted lines). Note that the constraints degrade hugely if we have an evolution and when one has to solve for both cosmology and cluster structure and evolution (long-dashed lines). Self-calibration is restored by adding complementary information such as $\bar{P}_{\rm cl}(k)$ (dot–dashed lines) or doing a limited 100 cluster follow-up using archival data to calibrate the mass–luminosity relation (short-dashed lines). Combining all the information (solid lines) can give us 4–6% constraints on w and $\sim$2% constraints on σ_8 and Ω_M. These are from cluster surveys alone. Addition of complementary informations from SNIa and CMB studies can further tighten the constraints.

Thus we see that in the presence of 'self-calibration', cluster survey is a powerful technique for studying the nature of the dark energy as well as any other characteristic of the universe that affects the expansion history, growth of density perturbations or the nature of the transfer function (through $\bar{P}_{\rm cl}(k)$). In addition, cluster surveys generate cosmological constraints from different physical properties of the universe than from other techniques (i.e. surveys probe the growth of density perturbations whereas SNIa distance measurements only probe the expansion history) and hence enhance our understanding of the evolving universe.

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