Subaru lensing survey of dark matter in supermassive galaxy clusters

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The primary purpose of our observation is to obtain the first precision measurement of the *scatter* between the X-ray observables and the true projected mass, determined via weak gravitational lensing. Knowledge of this scatter is essential for the use of galaxy cluster abundances to constrain dark energy with upcoming cluster surveys such as Planck and SPT (Albrecht et al. 2006), and is a stringent test of cluster-physics models (*e.g.* Stanek et al. 2006). This requires a complete sample of clusters, with errors in weak lensing (WL) masses of each cluster below the intrinsic scatter. This project will be the first to achieve that goal for a sufficiently large and fairly-selected cluster sample. The targets are the 20 most massive galaxy clusters in the northern hemisphere in the redshift range $0.15 < z < 0.3$, selected by X-ray temperature, with $M > 10^{15} h^{-1} M_{\odot}$.

We request 1 night to obtain single-band Subaru Suprime-cam images of those sample clusters that are visible this semester (and will submit a similar proposal for S08A). We will measure the shapes of ~ 20 background galaxies per arcmin^2 to map the cluster mass distribution via weak gravitational lensing, a task for which Subaru is the best facility in existence due to its combination of large FOV, small seeing, and well-sampled PSF. The Suprime-cam offers a unique opportunity to map the dark matter in these clusters at high enough S/N ratio to study the relation between visible and dark matter in detail on a *cluster-by-cluster basis.* This imaging will extend to a cluster radius of $\sim 2-3h^{-1}$Mpc. **All** of the Subaru targets have pre-existing *Chandra and/or XMM x-ray data* with well-determined *ASCA temperatures*; *HST WFPC2 and/or ACS imaging* of the cluster cores to reveal any strongly lensed features; and will have *multi-band optical photometry* from proposed Kitt Peak National Observatory imaging to yield photometric redshifts (in most cases supplemented by Spitzer IRAC data). The creation of this valuable, homogeneous dataset for supermassive clusters is not only necessary for determination of the $M-T$ distribution, but will be a resource for many investigations beyond this, many of course unforeseen at this time.

To obtain cosmological constraints from halo abundances, past studies have had to assume a mean relation *and* scatter between halo mass and X-ray observable (*e.g.*, Ikebe et al. 2002). Our work will determine both the mean relation and the scatter at the high-mass end to high precision, constraining the theory of cluster formation and allowing future cluster-count cosmology.

The expected intrinsic scatter in mass is $\sigma_M \approx 20\%$, and we want to measure this scatter to 1 part in 5 to test cluster theories and constrain dark energy. This means that (a) a sample of ≥ 20 clusters is needed, as the statistical error on the scatter is $\geq \sigma_M/\sqrt{2N}$ (if Gaussian). This is particularly true given that it may be necessary to divide the sample into relaxed and unrelaxed subsets. (b) The mass measurement error per cluster should be well below σ_M, and should be well characterized so it can be accurately removed. (c) Systematic errors in the mass determination must be held to a few percent so they do not contribute significantly to the scatter. One implication is that all survey data should be homogeneous, to avoid spurious scatter due to calibration offsets from heterogeneous lensing or photo-z data. Our survey will have all lensing data (and r photometry) from Subaru, and all other photometry bands from Kitt Peak.

We also will undertake work to validate the gravity + hydrodynamics model of cluster formation, via comparison of the matter distribution (from lensing) and hot gas (from X-rays), with sufficient S/N to conduct meaningful statistical tests on a cluster-by-cluster basis. We can test cluster-formation models in ways beyond investigating bulk cluster properties, by quantifying morphological parameters and comparing the measured distributions to those predicted in the N-body models. One example statistic is the misalignment between the principle axis of the projected X-ray and dark-matter distributions, which we will determine to within $\sim 20°$, providing the first meaningful statistical comparison with numerical models.

Weak gravitational lensing: We first note that the statistical error in WL mass reconstruction scales as $n_{\rm eff}^{-1/2}$, where $n_{\rm eff}$ is the density of well-resolved, high-S/N background galaxy detections. Subaru can resolve $n_{\rm eff} \sim 20$ arcmin^{-2} even when down-weighting low S/N or poorly-resolved sources. We also restrict our survey to the most massive clusters, which have the largest shear signals and hence the smallest fractional errors in mass. Only these supermassive clusters will have individual mass-measurement errors that are below the expected intrinsic scatter.

The project requires very low *systematic* errors in WL measurement. Understanding of the technical aspects of WL has significantly improved even in the past 2 years, bringing the field from the regime of 25% accuracy to of order 1% accuracy, as demonstrated by the recent STEP2 results (Massey et al. 2006). Co-I's on this proposal have developed *three* of the highest-performing WL pipelines in the STEP tests. Many lensing-based cluster mass estimates have large errors due to ignorance of the redshift distribution of source galaxies; we will obtain extensive photo-z data to firm up this calibration, and reliably identify foreground and cluster galaxies. Without photo-z's, these contaminants can affect the lensing signal in the inner regions at the 30% level in a radius-dependent way (Limousin et al. 2006), making determination of the mass profile parameters unreliable. The photo-z data will also ameliorate one significant problem with past cluster lensing analyses: projection of other structures along the line of sight. Using photo-z's to estimate optical richness, smaller foreground clusters or massive groups can be identified and their contribution to the shear can be modeled out.

Cluster structure: WL data can be used either to constrain a parametric model of the cluster mass, or to produce non-parametric mass maps. Comparison of the model with the non-parametric reconstruction will show any systematic model failure. Strongly lensed features place crucial constraints on the mass within the Einstein radius, typically $\sim 30''$. All target clusters have HST publicly available HST imaging of the strong-lensing regions. This survey will provide the first and best opportunity to use algorithms for combining strong and weak lensing data (*e.g.*, Bradac et al. 2005) on a large, homogeneous dataset of the most massive clusters.

We consider modeling the matter profile as a generalized NFW profile with inner slope α, concentration c, and virial mass M, using a Fisher matrix analysis to predict the errors on model parameters. With a strong lensing constraint giving $\pm 10\%$ measure of the Einstein radius, plus Subaru WL data to $2h^{-1}$Mpc, we find a fractional error on α and M of 22% and 13% *per cluster*. Thus, the ensemble mean values of α and M can be determined at the 10% and 6% level (respectively) with 20 clusters, now with errors dominated by the expected intrinsic scatter in these parameters of $\sim 30\%$ and 20% (Stanek et al. 2006). The intrinsic scatter itself can be determined to 7% and 4% (i.e., 1 part in 5 of the expected value). This unprecedented precision is primarily achievable because the measurement error is smaller than the theoretical intrinsic scatter.

Non-parametric mass estimates will likely provide a more robust comparison to cluster models than parametric modeling. Our results can be compared against theoretical predictions by computing projected aperture masses in simulations. For our lower mass limit of $10^{15}h^{-1}M_{\odot}$, we expect a S/N on the WL signal of 22 *per cluster*. Our high S/N non-parametric mass reconstruction will be an important test of the theory prediction that non-relaxed clusters are expected to deviate from the NFW density profile. Recent studies (Okabe & Umetsu 2007; Umetsu et al. 2007) have demonstrated that meaningful model constraints can be placed by comparison of Subaru WL data with X-ray data; the key improvement of this proposal is to extend the sample of clusters for which Subaru WL data is available so that it is large enough to constrain scatter on M and α; so that it includes all clusters above a temperature threshold for $0.15 < z < 0.3$ regardless of cluster morphology; and so that it has reliable, homogeneous photo-z data (from pending KPNO proposal).

Target selection: The X-ray temperature is more highly correlated with the cluster mass than the X-ray luminosity; we require $T_x > 6.5$ keV to obtain virial masses $> 10^{15}h^{-1}M_{\odot}$ (Dahle et al. 2002, Smith et al. 2005). A large, relatively unbiased catalog of clusters with temperatures from ASCA (Horner 2001) is the basis for our selection, with corrections for point-source contamination and cooling cores derived from high-resolution Chandra data (Cavagnolo & Donahue 2007). We choose the redshift range $0.15 < z < 0.3$: at lower redshift, the lensing efficiency is low, and for higher redshift clusters, the X-ray measurements would have insufficiently high flux for detailed comparisons of the temperature map against the shear map. In short, due to the high mass and the redshift range, we have the ideal sample for studying the relationship between X-ray observables and mass. We also require dec $> -20°$ and r-band extinction < 0.3 mag to facilitate ground-based observations and photoz determination. Our selection criteria lead to an unbiased sample of supermassive clusters, because we do not eliminate complex or merging systems.

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