# 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 *normalization* and *scatter* between the X-ray observables and the true projected mass of galaxy clusters, 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 (Albrecht et al. 2006, Lima & Hu 2005), such as Planck, ACT (Kosowsky 2006) and SPT, and is a stringent test of cluster-physics models (*e.g.* Kravtsov et al. 2006, Stanek et al. 2006). This measurement requires an unbiased sample of clusters, with statistical errors in weak lensing (WL) masses of each cluster below the intrinsic scatter, and with systematic errors reduced to unprecedented levels. This project will be the first to achieve that goal for a sufficiently large cluster sample, containing objects in a variety of evolutionary/merger states. 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 one night to obtain single-band Subaru Suprime-cam images of the eight target clusters that are visible this semester and that do not already have lensing-quality public Subaru data (and will submit a similar proposal for the single remaining cluster in S08B). We will measure the shapes of $\sim 30$ background galaxies per arcmin$^2$ to map the cluster mass distribution via weak 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 $S/N$ 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 strongly-lensed features; and will have *multi-band optical photometry* from proposed Kitt Peak National Observatory (KPNO) imaging to yield photometric redshifts (in most cases supplemented by Spitzer IRAC data). Eleven of 20 targets have imaging of the required depth and resolution (FWHM$< 0.9''$) in the SMOKA archive; this proposal is to complete the sample. One night of new Subaru imaging will hence be leveraged into a large new survey database. The creation of this valuable, homogeneous dataset for supermassive clusters is not only necessary for determination of the $M(T_x)$ relation, but can be a resource for many investigations beyond this project.

**Cosmological constraints:** Mandelbaum & Seljak (2007) show that counts of clusters with $M > 5 \times 10^{14}h^{-1}M_{\odot}$ cannot constrain $\sigma_8$ to accuracy better than 0.10 without knowledge of the mass-observable scatter. 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 survey will determine the mass scatter to $\pm 5\%$, if the intrinsic scatter in $M(T_x)$ is 20% (Kravtsov et al. 2006, Stanek et al. 2006). We distinguish our project from others by (1) maximizing the WL $S/N$ by choosing the most massive clusters, and (2) minimizing the systematics by obtaining photometric redshifts of our source galaxies and using the best available WL pipeplines. Our project will be the first to produce WL masses with measurement error below the intrinsic scatter, for a sample large and complete enough to determine the scatter.

**Validating cluster models:** The mean and scatter in $M(T_x)$ are of intrinsic interest aside from their utility for cosmology. $N$-body+hydrodynamics models of galaxy clusters are quite advanced and make definitive, testable predictions for $M(T_x)$. Right now there are still $\sim$ 20% normalization discrepancies between scaling relations in simulations and observations (Nagai et al. 2007, Arnaud et al. 2007). This could be, for example, due to the fact that ICM in real clusters has non-thermal pressure support, neglected in hydrostatic estimates of the mass. Models predict that the X-ray "$Y_x$ parameter" (Kravtsov et al. 2006) has very low scatter w.r.t. mass even in unrelaxed clusters, but WL is the only path to accurate mass estimates for unrelaxed clusters. Hence there is substantial motivation for highest-quality data on a complete sample of clusters.

Our cluster survey will enable many new tests of models: first we will determine the $M-T$ and its scatter, but also joint distributions of other observables can be predicted and measured in our data—concentration parameters and multipole moments of the X-ray and dark-matter distributions, which are measurable at useful $S/N$ in these most massive clusters (without stacking).

An important subtlety is that most models refer to cluster 3d virial masses whereas WL measures a 2d projected mass distribution, which includes the cluster virial core, nonvirialized structure local to the cluster (e.g. Metzler et al. 2000), and distant large-scale structure randomly projected along the line of sight (e.g., Hoekstra 2003). The latter two sources of "projection noise" in the 2d WL masses depend, however, on less complicated physics, and can be constrained with $N$-body simulations at least as well as the baryonic processes producing the virial X-ray emission. Hence this subtlety does not degrade the power of our survey to validate cluster models. Nonetheless we have a new $1/h$ Gpc $N$-body simulation that can be used to determine the projection effects with much greater statistical power than before, so we can remove their contribution and estimate the intrinsic scatter in virial $M(T_x)$ to high precision.

**Weak gravitational lensing observations:** We 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 resolves $n_{\rm eff} \sim 20$ galaxies arcmin$^{-2}$ in typical seeing, even after 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 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 to of order 1% accuracy, as in the recent STEP2 results (Massey et al. 2007). Co-I's on this proposal have developed *three* of the best-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 5-band 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 existence of photo-$z$ data may also ameliorate the line-of-sight projection problem.

**Cluster mass 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 publicly available HST imaging of the strong-lensing regions. This survey will 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.

Non-parametric mass estimates will likely provide a more robust comparison to cluster models than parametric modeling. 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 $M(T_x)$; 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 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 insufficient 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 targeted 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 photo-$z$ 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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