Constraints on the mass-richness relation from the abundance and weak gravitational lensing of Sloan Digital Sky Survey (SDSS) clusters

Ryoma Murata[1,2], Takahiro Nishimichi[1,3], Masahiro Takada[1], Hironao Miyatake[4,1], Masato Shirasaki[5], Surhud More[1], Ryuichi Takahashi[6], and Ken Osato[2]

1. Kavli IPMU 2. Department of Physics, University of Tokyo 3. CREST, JST

4. Jet Propulsion Laboratory, California Institute of Technology 5. National Astronomical Observatory of Japan 6. Hirosaki University

Abstract

Clusters of galaxies (dark matter haloes) are the most massive self-gravitating systems and the physics inherent in their formation and evolution processes is governed mainly by **dark matter**. Hence the abundance and spatial clustering properties of galaxy clusters can be a powerful probe of cosmological parameters including **neutrino mass** and the nature of **dark energy**. The ongoing Subaru **Hyper Suprime-Cam (HSC) Survey**, which has been led by IPMU members, promises to advance our knowledge in cluster physics as well as the use of cluster observables for constraining cosmology. However, in order to attain the full potential cluster cosmology with the Subaru HSC Survey, we need to constrain **the relation between optical richness (the proxy of the number of member galaxies) and cluster masses, the mass-richness relation**, to connect the observation with simulation predictions as a function of cluster masses for a given cosmological model. Here we develop a method to constrain the mass-richness relation from a joint measurement of **the stacked weak lensing profiles and the abundance**. Here we apply this method to a sample of **8,312 clusters from the Sloan Digital Sky Survey (SDSS)**, as a proof of concept.

Weak Gravitational Lensing around Clusters

Weak gravitational lensing is a powerful means of constraining cluster masses. By measuring coherent distortion pattern in shapes of background galaxies due to gravitational lensing of clusters, **we can directly measure their projected mass density profile**. However, the signal is very noisy on individual cluster basis, thus the effect is measured in a statistical sense after stacking shapes around clusters in richness bins, called **stacked cluster-galaxy lensing**.

SDSS Cluster and Lensing Data

We used SDSS data for cluster of galaxies and background galaxies for the weak gravitational lensing analysis. This cluster catalog is constructed from redsquence technique which identifies the over-density of red galaxies as cluster (Rykoff et al. 2016). Each cluster has **optical richness (the number of member galaxies) estimate as cluster mass proxy**. The number of the clusters in the catalog is 8,312 after fiducial cut on redshift ($0.10 < z_{\rm cl} < 0.33$) and richness ($20 < \lambda < 100$). The cosmological analysis for this catalog is not done yet. The lensing background galaxies catalog has 39 million galaxies (Mandelbaum et al. 2013). The area is approximately 10,000 square degrees.

MCMC Analysis

To estimate the mass-richness relation parameter, we did **Markov Chain Monte Carlo (MCMC) analysis**. It solves the distribution of **Posterior~Likelihood x Prior**, where we used the **flat (non-informative) prior** on the parameters. The likelihood is given with the measurement, model prediction as a function of the mass-richness relation parameters, and the error covariance matrix, as $\mathcal{L} \propto \exp(-\chi^2/2)$ where $\chi^2 = \sum_{i,j} \left[\mathbf{D} - \mathbf{D}^{\rm model}\right]_i \left(\mathbf{C}^{-1}\right)_{ij} \left[\mathbf{D} - \mathbf{D}^{\rm model}\right]_j$.

Forward Modeling of Mass-Richness Relation

We use **"forward modeling approach" starting from $P(\ln\lambda|M)$, rather than** $P(\ln M|\lambda)$ as in previous works. In this work, we assume **a simple log-normal distribution for** $P(\ln\lambda|M)$ characterized by **mean and scatter relations with four free parameters,** $\{A, B, \sigma_0, q\}$:

Log-normal: $$P(\ln\lambda|M)\mathrm{d}\ln\lambda \equiv \frac{1}{\sqrt{2\pi}\sigma_{\ln\lambda|M}} \exp\left(-\frac{x(\lambda, M)^2}{2\sigma^2_{\ln\lambda|M}}\right)\mathrm{d}\ln\lambda$$

Mean: $$x(\lambda, M) \equiv \ln\lambda - \left[A + B\ln\left(\frac{M}{M_{\rm pivot}}\right)\right]$$

Scatter: $$\sigma_{\ln\lambda|M} = \sigma_0 + q\ln\left(\frac{M}{M_{\rm pivot}}\right)$$

In our modeling, we can calculate **the model prediction ($\mathbf{D}^{\rm model}$) of abundance and weak lensing profile** as:

Abundance: $$N_{\lambda_\alpha} = \Omega_{\rm tot}\int_{z_{\rm min}}^{z_{\rm max}} \mathrm{d}z \frac{\chi(z)^2}{H(z)} \int_{M_{\rm min}}^{M_{\rm max}} \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M} S(M|\lambda_{\alpha,{\rm min}}, \lambda_{\alpha,{\rm max}})$$

Mass selection function: $$S(M|\lambda_{\alpha,{\rm min}}, \lambda_{\alpha,{\rm max}}) \equiv \int_{\ln\lambda_{\alpha,{\rm min}}}^{\ln\lambda_{\alpha,{\rm max}}} \mathrm{d}\ln\lambda\, P(\ln\lambda|M) = \frac{1}{2}\left[\mathrm{erf}\left(\frac{x(\lambda_{\alpha,{\rm max}}, M)}{\sqrt{2}\sigma_{\ln\lambda|M}}\right) - \mathrm{erf}\left(\frac{x(\lambda_{\alpha,{\rm min}}, M)}{\sqrt{2}\sigma_{\ln\lambda|M}}\right)\right]$$

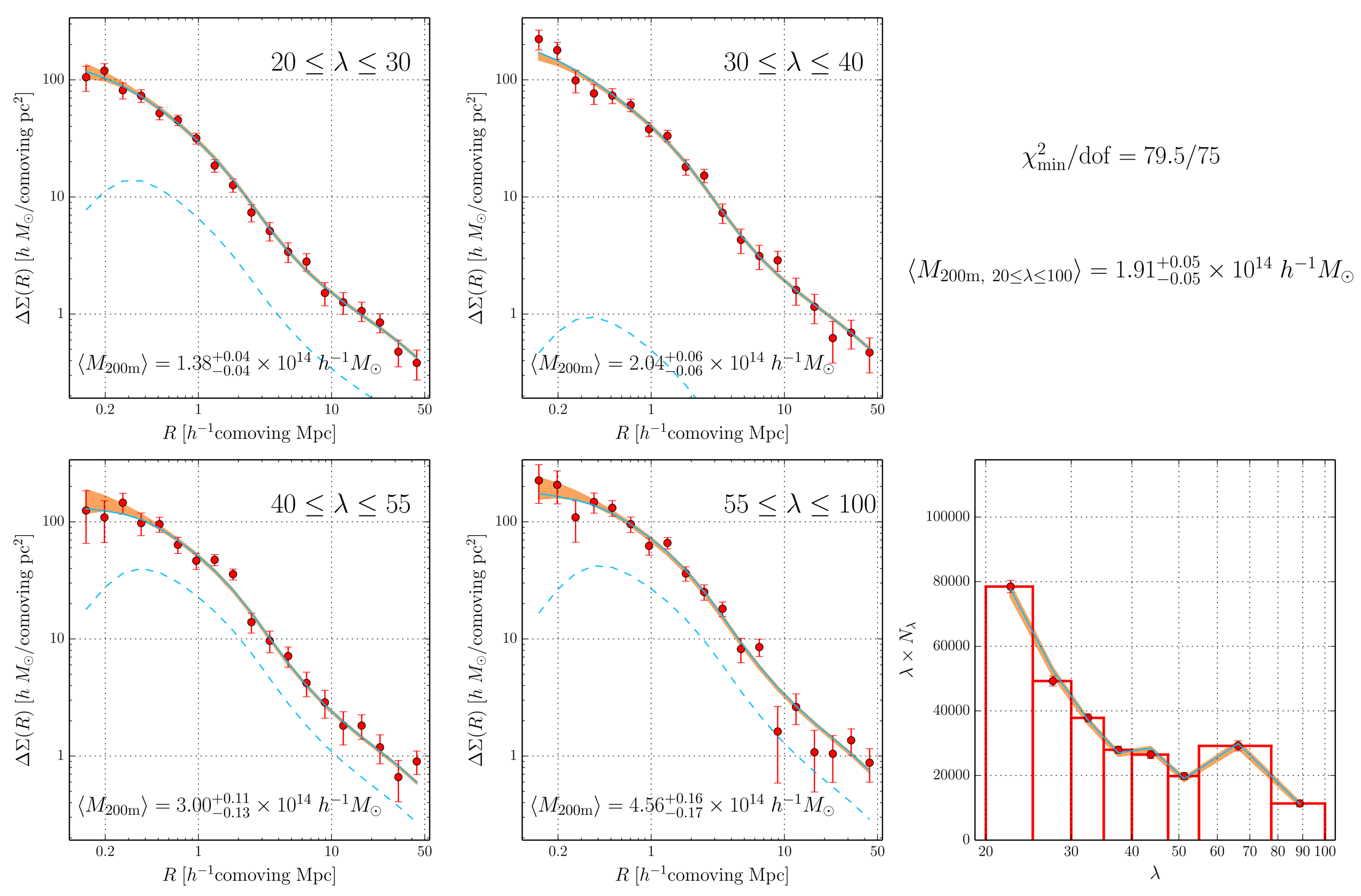
Lensing: $$\Delta\Sigma_{\lambda_\beta}(R) \equiv \frac{1}{N_{\Delta\Sigma}(\lambda_{\beta,{\rm min}}, \lambda_{\beta,{\rm max}})} \int_{z_{\rm min}}^{z_{\rm max}} \mathrm{d}z \int_{M_{\rm min}}^{M_{\rm max}} \mathrm{d}M \frac{\chi(z)^2}{H(z)} w_l(z; R) \frac{\mathrm{d}n}{\mathrm{d}M} S(M|\lambda_{\beta,{\rm min}}, \lambda_{\beta,{\rm max}}) \Delta\Sigma(R; M, z)$$

Simulation Prediction and Mock Catalogs

We used a **halo emulator** (Nishimichi et al. in prep) that outputs **the halo mass function and the stacked lensing profile as a function of halo mass, redshift** and cosmological parameters. This prediction is calibrated based on a suite of **high-resolution N-body simulations**. In this work, we fix the cosmological parameter to the Planck cosmology (Planck Collaboration et al. 2016). Additionally, we used **full-sky ray-tracing simulations** (Shirasaki et al. 2016, Takahashi et al. 2017) to model the error covariance matrix.

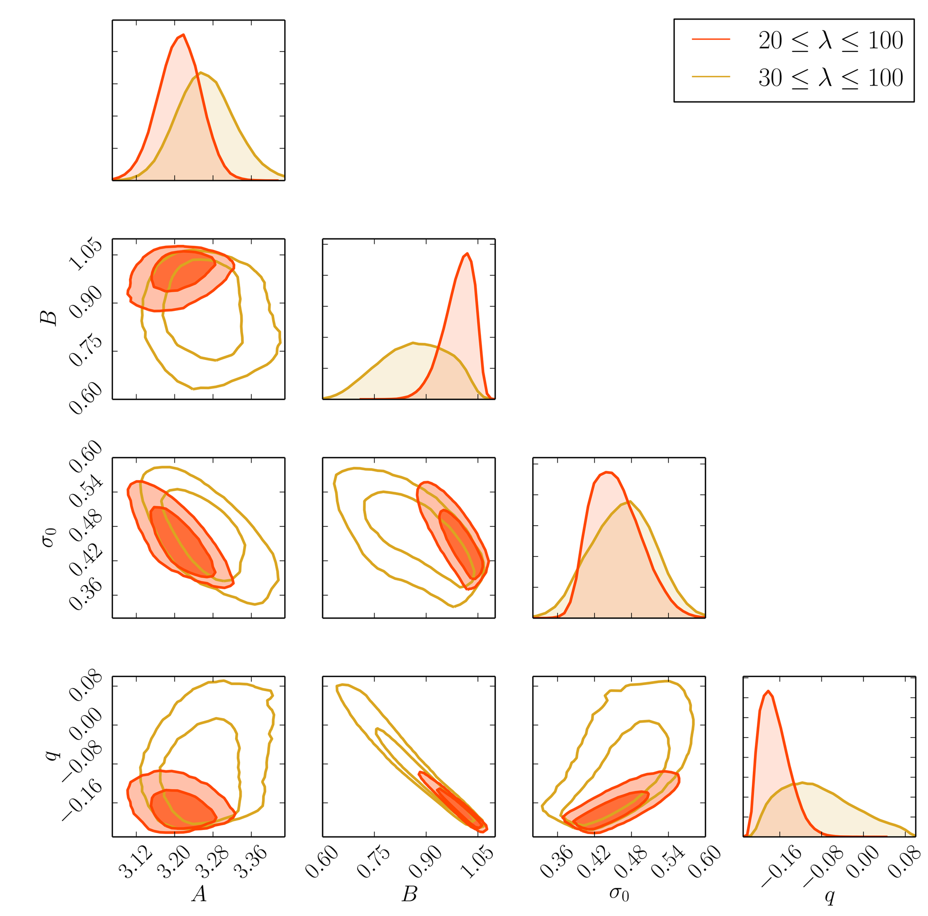
Main Results

Measurement of Weak Gravitational Lensing (left four panels) **and Abundance** (right lower panel), **and MCMC Fitting Results**



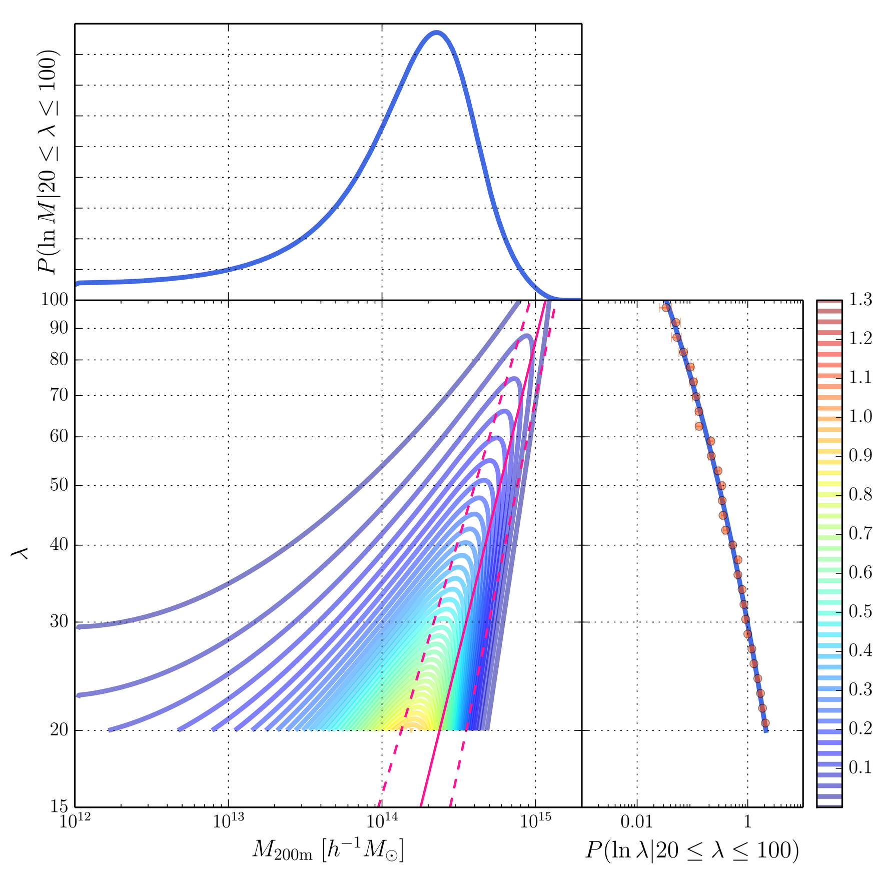
MCMC Parameter Constraints

We used flat (non-informative) priors, but the parameter constraint is strong.



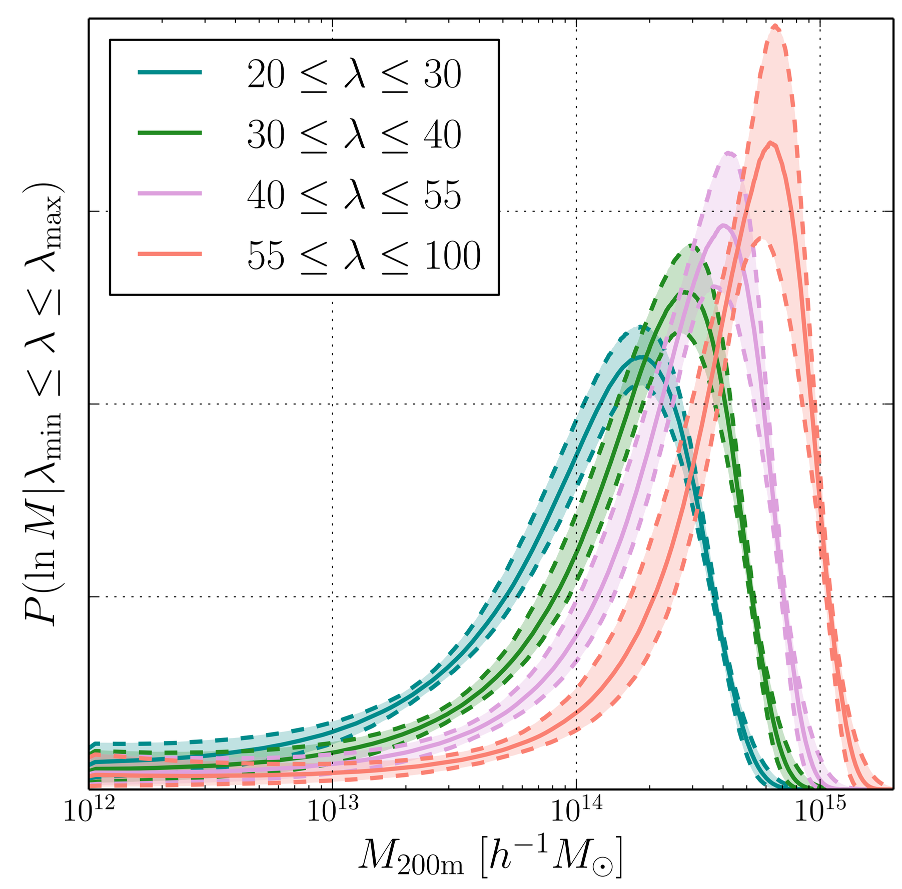
Joint Probability from the Best Fit Parameters

$$P(M, \lambda | 20 < \lambda < 100) \propto P(\lambda|M)P(M)$$



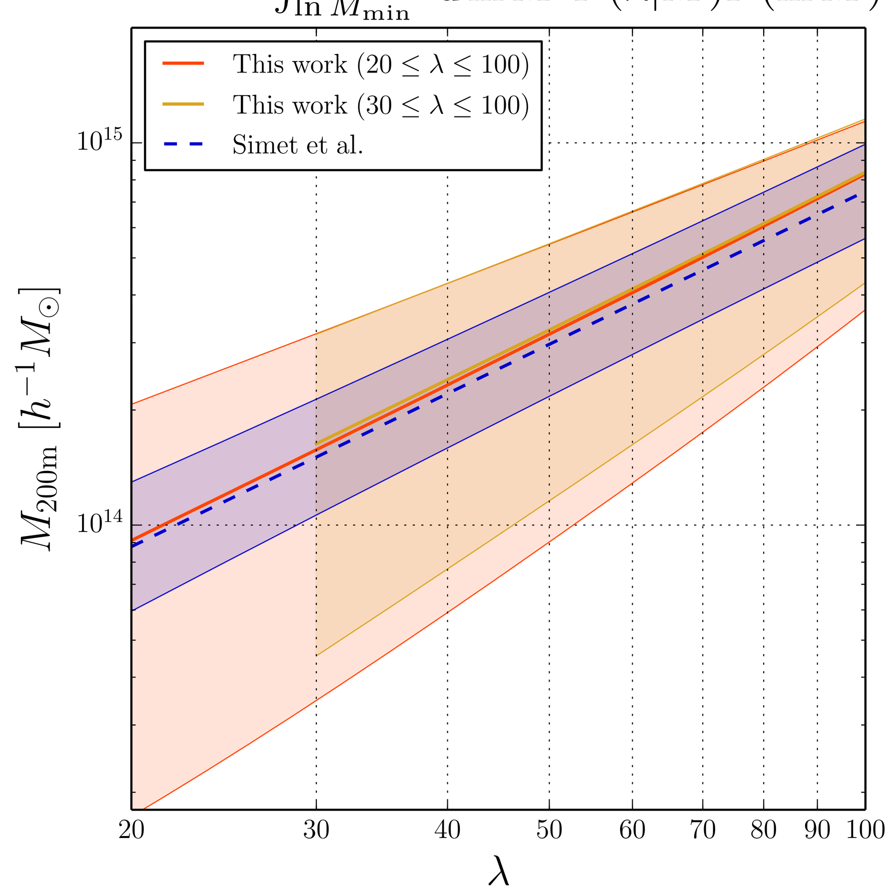
Mass Distribution Constraints in Richness Bins

$$P(\ln M | \lambda_{{\rm min},i} < \lambda < \lambda_{{\rm max},i}) = \int_{\lambda_{{\rm min},i}}^{\lambda_{{\rm max},i}} \mathrm{d}\lambda\, P(\ln M, \lambda)$$



Comparison with a previous work (Simet et al. 2016), which uses a different modeling approach. Their scatter constraint is from a strong prior, not from data.

$$P(\ln M|\lambda) = \frac{P(\lambda|M)P(\ln M)}{\int_{\ln M_{\rm min}}^{\ln M_{\rm max}} \mathrm{d}\ln M\, P(\lambda|M)P(\ln M)}$$



Discussion and Conclusion

We have constrained **the mass-richness relation for the SDSS clusters** by comparing **the joint measurements of abundance and stacked lensing profiles** with the model predictions that are built from a suite of **high-resolution N-body simulations** for the Planck cosmology. We found that the log-normal distribution model for $P(\ln\lambda|M)$ with four free parameters **remarkably well reproduce the abundance and lensing measurements simultaneously**. Since we used the abundance in addition to lensing, we are able to constrain **the scatters around the mean mass-richness relation**. Our results indicate that low-mass halos with $M_{\rm halo} \lesssim 10^{13} h^{-1} M_\odot$ needs to be included in the cluster sample, by about 10% fraction, in order to have the nice agreement. This might be a residual systematics in low richness bin, e.g. projection effect where multiple less-massive systems along the line-of-sight direction are recognized as a single cluster.

Our method allows various applications. By combining the SDSS and Subaru HSC data, we can explore the evolution of massive clusters over $z_{\rm cl} \lesssim 1$, about 10G years that cover both the decelerating and accelerating expansion phases. Firstly, we are working on applying this method to the cluster catalog constructed from the Subaru HSC data. Secondly, we are planning to combine the auto-correlation functions of clusters with the abundance and the stacked lensing profiles in order to constrain cosmological parameters from the forward model fitting. Thirdly, we will in detail study the projection effect using mock catalogs of clusters in the light-cone simulations, in order to **understand the systematics of projection effects to robustly conduct the cluster cosmological analysis.**