論文の内容の要旨

Statistical analyses of optically selected galaxy clusters from Subaru Hyper Suprime-Cam
(すばるハイパーシュプリームカムの可視光観測により検出された銀河団の統計的研究)

氏名　村田　龍馬

Cosmological observations in the last twenty years have established the standard Λ-dominated Cold Dark Matter (ΛCDM) cosmological model based on General Relativity for the gravity theory thanks to the increasing amount of observational data. It is essential to validate the consistency of this model with other independent cosmological probes or to constrain extensions of the standard model such as self-interacting dark matter, time-evolving dark energy, and modified gravity with observational data.

Galaxy clusters are the most massive gravitationally bound structure in the Universe, which form in dark matter halos after interactions between gravitational dynamics and baryonic process related to galaxy formation. Observations of galaxy clusters in the literature have revealed and constrained the existence and nature of dark matter, dark energy, baryonic matter, and galaxy evolution and formation with other cosmological and observational probes.

Given the smaller number of such massive dark matter halos in which galaxy clusters reside, we require deep imaging data from wide field-of-view surveys to investigate the statistical properties of galaxy clusters over a wide redshift range. The recent development of wide-field optical imaging surveys such as the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP) makes an optical selection of galaxy clusters based on red member galaxies in such cluster regions particularly powerful, typically with a larger number of galaxy clusters than those selected by X-ray or radio wavelengths at present.

With the same imaging data, such wide-field optical imaging surveys also enable us to calibrate the relation of galaxy cluster mass (M) and the number of red member galaxies above some luminosity threshold for each cluster (N), called optical richness, through weak gravitational lensing effects around galaxy clusters by statistically averaging over a large number of weakly and systematically deformed shapes of distant galaxies to reveal their mass profiles with equal sensitivity to the dark and baryonic matter. Constraining this mass-richness relation via weak gravitational lensing is fundamentally important to connect theories or simulations with observations on galaxy clusters, since the halo mass determine the physical properties dominantly such as density profiles of dark matter halo and galaxy evolution and formation physics. Also, constraining the mass distribution function of dark matter halos at galaxy cluster mass scales leads to cosmological parameter estimations.

Among the physical properties of galaxy clusters, the splashback radius has been recently proposed as a physical boundary of dark matter halos at the outskirts from a suite of high-resolution N-body simulations, which separates orbiting from accreting materials (e.g., dark matter and galaxies) as a sharp density edge. At the splashback radius, the logarithmic derivative of density profiles is predicted to drop significantly over a narrow range of radius due to piling up of materials with small radial velocities at their first orbital apocenter after infall into halos. Importantly, recent observational constraints from different survey data in the literature on the splashback radius around optically selected galaxy clusters from an optical cluster-finding algorithm, called redMaPPer, have shown that the observed splashback radius is ~20% smaller than that predicted by N-body simulations under the ΛCDM model at a high significance (~4σ), with the help of the mass-richness relation from weak gravitational lensing effects. These observations with high signal-to-noise ratios are based on statistical measurements of projected photometric galaxy densities around galaxy clusters, since dynamics of galaxies are expected to follow dark matter distribution in the outskirts based on gravitational potentials dominantly determined by the larger amount of dark matter. The dependence of the splashback radius on new physics such as self-interacting dark matter, time-evolving dark energy, and modified gravity have been investigated in the literature over the last five years to try to explain the deviation in the observed splashback radius from the standard model. The features of the splashback radius have also been known as probes of galaxy formation and evolution with galaxy color or magnitude cuts.

In this thesis, we present observational and statistical studies of optically selected galaxy clusters on the mass-richness relation and the splashback radius with mock simulation analyses. We employ the data catalogs from the ongoing HSC-SSP with the Subaru telescope for optically selected galaxy clusters, weak lensing analyses, and photometric galaxies. We use ~2000 optically selected galaxy clusters from the independent cluster-finding algorithm, called CAMIRA, at a wide cluster redshift range of 0.1<zcl<1.0 thanks to deep and high-resolution HSC images, whereas previous observational works in the literature on the mass-richness relation and the splashback radius are limited to roughly zcl < 0.7.

First, we measure stacked weak lensing profiles around the HSC CAMIRA clusters over the wide redshift range. We detect lensing signals around high-redshift clusters at 0.7<zcl< 1.0 with a signal-to-noise ratio of 19. We constrain their richness-mass relations P(ln N | M,zcl) assuming a log-normal distribution without informative priors on model parameters, by jointly fitting to the lensing profiles and abundance measurements under two different sets of cosmological model parameters in the ΛCDM model based on the cosmic microwave background (CMB) measurements from the Planck and WMAP satellites. We show that constraints on the mean relation <M | N> with a precision of ~5% for each model are consistent between the Planck and WMAP models, whereas the scatter values sigma_{ln M | N} for the Planck model are systematically larger than those for the WMAP model, which is consistent with the literature. In addition, we show that the scatter values for the Planck model increase toward lower richness values when employing a flexible parametrization for the mass-richness relation, whereas those for the WMAP model are consistent with constant values as a function of richness. This result highlights the importance of the scatter in the mass-richness relation to constrain the cosmological parameters from galaxy clusters.

Second, we present analyses on the splashback radius of the HSC CAMIRA clusters with the results of the analysis for the mass-richness relation. We detect the splashback feature from the projected cross-correlation measurements between the clusters and photometric galaxies over the wide redshift range, including for high redshift clusters at $0.7<zcl<1.0$, thanks to deep HSC images. We investigate the dependence of splashback features on cluster redshift, richness, galaxy magnitude limits, and galaxy colors over the wide redshift range, which should also be informative to compare with hydrodynamic galaxy simulations when available for galaxy evolution and formation studies. We find that constraints from red galaxy populations only are more precise than those without any color cut, leading to 1σ precisions of ~15% for cluster samples at $0.4<zcl<0.7$ and $0.7<zcl<1.0$. We also find that these constraints at $0.4<zcl<0.7$ and $0.7<zcl<1.0$ are more consistent with the model predictions under the ΛCDM model with the help of our mass-richness relation (roughly $<1\sigma$) than their 20% smaller values as suggested by the previous studies based on redMaPPer clusters (~2σ for CAMIRA clusters). We also establish a methodology to investigate selection effects of an optical cluster-finding algorithm on the observed splashback features by creating a mock galaxy catalog from a halo occupation distribution model and, for the first time, closely resembling the procedure in data analyses and model prediction calculations with the real data. With this methodology, we find that such effects are insignificant for the CAMIRA cluster-finding algorithm compared to our statistical errors.

Hence, for the first time, we conclude that the observed splashback radii are consistent with the theoretical predictions based on the ΛCDM model and our mass-richness relation from weak lensing effects for the HSC CAMIRA clusters at our precisions over the wide redshift range (~15% for each bin of $0.1<zcl<0.4$, $0.4<zcl<0.7$, and $0.7<zcl<1.0$).

We can improve precisions on measurements of the mass-richness relation and the splashback radius by employing the upcoming full HSC survey data or other future survey data in various wavelengths, including X-ray and radio, in order to study cosmological and astrophysical aspects of galaxy clusters and the Universe itself in more detail. Our observational results with the CAMIRA clusters and our analysis frameworks and methodology for the observational data and mock observations are informative to conduct such analyses with properly accounting for the selection effects in the near future.