論文の内容の要旨

Cosmology and Cluster Astrophysics with Weak Gravitational Lensing and the Sunyaev–Zel'dovich Effect

（重力レンズとスニヤエフーゼルドビッチ効果を用いた銀河団宇宙論）

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In modern observational cosmology, the concordance model, which can remarkably explain the observational facts, has been established in the last decade. The foundation of the current understanding of the Universe is owed to various cosmological observations. The recent theoretical and observational developments in cosmology enable one to infer physical properties of the Universe, e.g., the age of the Universe, at sub-percent level.

One of major cosmological probes which have played a crucial role in observational cosmology is galaxy clusters. Galaxy clusters are the most massive and bound objects in the Universe, and it is regarded as ideal laboratories for energetic and violent dynamics. The abundance of galaxy clusters is sensitive to the underlying cosmological models, and the mass function can be predicted based on theoretical model. One of the ways to observe galaxy clusters is weak gravitational lensing (WL), which denotes the weak deformation of images of distant galaxies. Since galaxy clusters host abundant dark matter, they create strong gravitational field and it leads to coherent WL signal. Through WL, we can reconstruct the density distribution in galaxy clusters. In addition, we can probe into the large-scale structures in an unbiased way, and thus, WL is regarded as one of main science targets in imaging surveys. Another important probe into galaxy clusters is the thermal Sunyaev–Zel'dovich (tSZ) effect. The tSZ effect denotes the secondary temperature anisotropy of cosmic microwave background (CMB) induced by inverse Compton scattering between CMB photons and hot free electrons in galaxy clusters. The advantage of tSZ is that since Compton-y parameter, which is the observable of tSZ effect, is the projected pressure field, it directly connects the fundamental thermodynamic quantities, e.g., thermal pressure or number density, to the observed quantity. The distribution of the intra-cluster medium (ICM), which can be traced with tSZ, also reflects the large-scale structures.

In cluster cosmology, the mass function of galaxy clusters plays a key role. Thus, the mass of galaxy clusters is the most fundamental quantity which characterizes the galaxy clusters. WL can directly reconstruct mass of galaxy clusters, but the samples detected by WL are limited to very massive clusters. Therefore, X-ray or tSZ observations are employed to explore the larger samples of galaxy clusters. However, for these probes, the mass is not a direct observable, and we need to convert the observed flux to the mass. In many applications, galaxy clusters are assumed to be in hydrostatic equilibrium (HSE), where the thermal pressure balances the self-gravity of galaxy clusters. For several galaxy clusters which can be detected both through WL and X-ray or tSZ observations, the hydrostatic mass and true mass can be estimated, and this type of the measurements is called as mass calibration measurements. The deviation from unity of the ratio between the true mass and hydrostatic mass is defined as the hydrostatic bias $b_{\mathrm{HSE}} \equiv 1 - M_{\mathrm{HSE}}/M_{\mathrm{true}}$. The measured hydrostatic mass is 10–30% less than the true mass, which indicates the deviation from HSE, i.e., the existence of physical processes which support the self-gravity other than the thermal pressure. Such processes are called as non-thermal pressure. The amplitude of non-thermal pressure directly affects the mass estimate of galaxy clusters and may cause the bias in cosmological parameters from cluster counts. Thus, for accurate determination of cosmological parameters with cluster counts, the evaluation of non-thermal pressure contribution is essential. The origin of non-thermal pressure is still uncertain, but the dominant source is thought to be turbulent motion in galaxy clusters. From hydrodynamical simulations, the contribution due to the non-thermal pressure is estimated as around 20%, which is consistent with the mass calibration measurements. However, in the simulations and measurements, the samples are limited to massive clusters ($> 10^{14}\,\mathrm{M}_{\odot}$), and the contribution in low-mass galaxy clusters has not clearly been addressed yet. Interestingly, the analyses with tSZ auto-power spectrum or cluster counts of SZ detected sources suggest larger non-thermal contribution around 40%.

In this dissertation, we employ the cross-correlations of tSZ and WL. One of the advantages of the cross-correlations is that we can preferentially extract the information of ICM at the redshift $z \simeq 0.5$–1, where cluster formation and merger events actively occur, because WL probes the large-scale structures at this range. Although the tSZ observable is the projected quantity and has no redshift information, we can probe the redshift evolution with the help of WL. Furthermore, the cross-correlation is complementary to the tSZ auto-correlation, which is sensitive to the structures at higher redshifts ($z \gtrsim 1$). In addition, the cross-correlations measured based on maps contain the signals from low-mass halos, which are unresolved in the SZ survey due to the small signal.

In Chapter 6, we carry out analysis with the recent measurement of cross-correlations with Red Cluster Sequence Lensing Survey (RCSLenS) and *Planck* to constrain the parameter α_0, which corresponds to the amplitude of the non-thermal pressure, and the cosmological parameter σ_8, which denotes the amplitude of the matter fluctuation at the scale of $8\,h^{-1}\,\mathrm{Mpc}$. Specifically, the parameter α_0 is the non-thermal pressure fraction at the halo radius R_{500}, and the best-fit value from hydrodynamical simulations with $\sigma_8 = 0.8$ is $\alpha_0 = 0.18$. The constraints on the parameters are shown in Figure 1. Only with tSZ auto-power spectrum, the analysis gives large $\sigma_8 \sim 0.85$ and high non-thermal pressure $\alpha_0 \sim 0.2$–0.3. In contrast, with tSZ-WL cross-correlations, smaller $\sigma_8 \sim 0.6$ and lower non-thermal pressure $\alpha_0 \sim 0.05$ are estimated. The difference arises from the different ranges of probed mass and redshift between the tSZ auto-power spectrum and the tSZ-WL cross-correlations, which have not been considered in previous studies. If we fix $\sigma_8 = 0.8$ in order to compare the previous studies with the tSZ auto-power spectrum, our tSZ auto-power spectrum analysis estimates the non-thermal pressure as $\alpha_0 \sim 0.25$, and the corresponding hydrostatic bias parameter is 0.4–0.5, which is consistent with previous studies. Hence, if σ_8 is taken as a free parameter, the inconsistency between the tSZ auto-power spectrum and the tSZ-WL cross-correlations arises, and it implies the redshift or mass evolution of the non-thermal pressure.

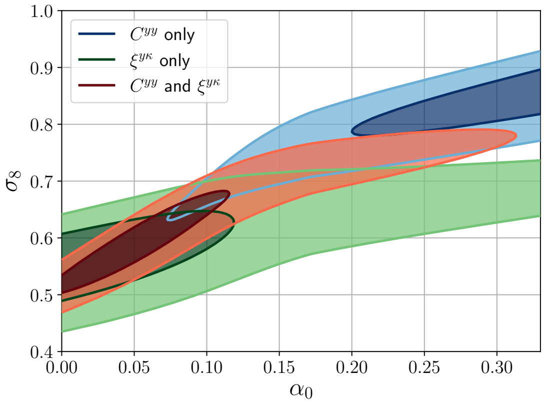

Figure 1: Constraints on α_0 and σ_8 with the tSZ auto-power spectrum and/or the tSZ-WL cross-correlation with RCSLenS and *Planck*.

From the study presented in Chapter 6, we build a hypothesis that the non-thermal pressure has mass and redshift dependence due to the evolution of galaxy clusters. In order to verify the hypothesis through the analysis with the different redshift distribution from RCSLenS (the median redshift is 0.608), we employ the Hyper Suprime-Cam (HSC) survey (the median redshift is 0.809). Since, in the study in Chapter 6, we adopt the specific model for radial distribution of non-thermal pressure and focus on constraints on the parameter α_0, it makes it difficult to directly compare the amplitude of non-thermal pressure with previous studies of mass calibration measurements or hydrodynamical simulations. Instead of assuming a specific model for the non-thermal pressure, we employ hydrostatic bias $b_{\rm HSE}$ to model non-thermal pressure, which is rather simplified but easier to compare with previous studies. In addition, we conduct a cosmological analysis to jointly constrain 5 standard cosmological parameters along with hydrostatic bias.

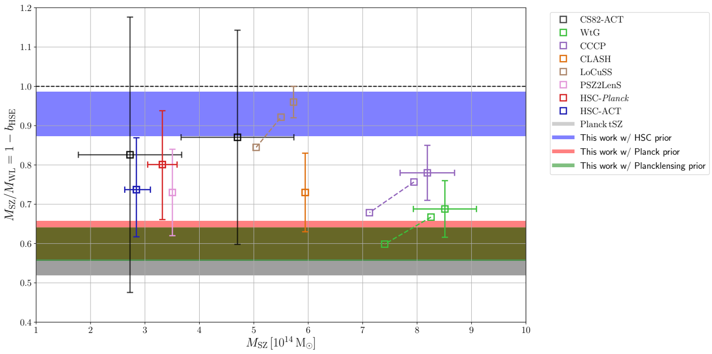

Figure 2: Constraints on hydrostatic bias $b_{\rm HSE}$ with the tSZ auto-power spectrum and the tSZ-WL cross-correlation with HSC and *Planck*. For comparison, the points with error bars show the results of mass calibration measurements.

In Chapter 7, we conduct the measurement of the tSZ-WL cross-correlations with HSC and *Planck*. Figure 2 shows the constraints on hydrostatic bias parameter from the tSZ auto-power spectrum and the tSZ-WL cross-correlations, and estimates for galaxy clusters in mass calibration measurements. Solely with the tSZ power spectrum and the tSZ-WL cross-correlations, the constraining power on cosmological parameters is weak, and thus we add priors on cosmological parameters from *Planck* CMB results or HSC cosmic shear analysis. Here, we focus on the results with *Planck* prior, which is widely adopted in the previous studies. The constraint on the hydrostatic bias with *Planck* prior is $b_{\rm HSE} = 0.394^{+0.046}_{-0.052}$, which is consistent with the tSZ auto-power spectrum analysis ($b_{\rm HSE} = 0.42 \pm 0.06$) and the result with RCSLenS (Chapter 6). This result implies no significant redshift evolution, which contradicts the naive expectation that non-thermal pressure evolves due to merger events or mass accretion. On the other hand, our results support the pseudo-evolution scenario, where the redshift evolution of non-thermal pressure can be absorbed by the evolution of background density. In order to verify that the appreciable fraction of the cross-correlation signal comes from low-mass halos ($\lesssim 10^{14}\,{\rm M}_\odot$), we measure the cross-correlations by masking the SZ-detected clusters by *Planck* in HSC footprints. After applying the additional mask, the signal is suppressed by at most 20% and we can conclude that most of the signal comes from low-mass halos, which information is not easily accessible by observables other than map-based tSZ analysis.

In this dissertation, we have addressed the contribution of the non-thermal pressure in galaxy clusters, especially at redshifts $z \simeq 0.5$–1.0, where clusters are undergoing mergers and mass accretion. The existence of the non-thermal pressure directly affects the mass estimate of galaxy clusters, and thus, the accurate determination of the contribution is essential for cluster cosmology. In Chapter 6, we adopt the specific ICM model and constrain the parameter α_0, which controls the amplitude of the non-thermal pressure, along with the cosmological parameter σ_8 from the measurement of the tSZ-WL cross-correlation with RCSLenS and *Planck*. The best-fit values of α_0 and σ_8 are $\alpha_0 \sim 0.05$ and $\sigma_8 \sim 0.6$, both of which are lower than previous studies. However, by fixing $\sigma_8 = 0.8$ to be consistent with previous studies, we obtain $\alpha_0 \sim 0.2$, which corresponds to the hydrostatic bias $b_{\rm HSE} \sim 0.4$–0.5. This result is consistent with the previous analysis of tSZ power spectrum ($b_{\rm HSE} = 0.42 \pm 0.06$) but contradicts the result with mass calibration measurements ($b_{\rm HSE} \sim 0.2$). This inconsistency can be due to the difference of probed mass and redshift scales between the tSZ auto-power spectrum and the tSZ-WL cross-correlations. In order to investigate the non-thermal pressure at the different redshifts, we employ the data of the

HSC survey, which provides deeper data than RCSLenS. With the prior on cosmological parameters from *Planck* CMB measurements, which is widely adopted in previous studies, we constrain hydrostatic bias and 5 standard cosmological parameters. The estimated hydrostatic bias is $b_{\rm HSE} = 0.394^{+0.046}_{-0.052}$, which is consistent with the tSZ-WL cross-correlations from RCSLenS and *Planck* and the tSZ auto-power spectrum analysis, though the tSZ auto-power spectrum and the tSZ-WL cross-correlations with RCSLenS or HSC are sensitive to galaxy clusters at different redshifts. Accordingly, our results indicate no significant redshift evolution of non-thermal pressure. In contrast, mass calibration measurements suggest lower non-thermal pressure for massive galaxy clusters of $b_{\rm HSE} \sim 0.2$. This difference can be explained by the fact that the tSZ auto-power spectrum and the tSZ-WL cross-correlations can be sourced by low-mass halos ($\lesssim 10^{14}\,{\rm M}_{\odot}$). In summary, our results imply that non-thermal pressure is more predominant for low-mass halos than massive halos. Thus, the cross-correlations are promising probes for such low-mass halos, which contributions are hard to estimate otherwise.

Finally, we remark on future prospects. The current constraints are limited by the small coverage of the HSC survey ($\sim 100\,{\rm deg}^2$). However, the survey is still ongoing, and more data will be released in short timescale. For the full sky coverage ($\sim 1000\,{\rm deg}^2$), the statistical errors become small, and thus, tighter constraints can be obtained. Furthermore, the high source galaxy number density in the HSC survey enable one to carry out the tomographic measurement of the cross-correlations. With this technique, we can closely address the redshift evolution of the hydrostatic bias. For the tSZ side, we are planning to employ the data with Atacama Cosmology Telescope (ACT), which angular resolutions is $1\,{\rm arcmin}$. In the current analysis, we are restricted to constraints on simplified model parameters α_0 and $b_{\rm HSE}$ due to the large beam size $10\,{\rm arcmin}$ in *Planck*. The high resolution of ACT enables one to probe the fine structure of ICM, e.g., radial profile of non-thermal pressure. By refining the model of ICM, we can improve the constraints on cosmological parameters and investigate the mass and redshift evolution of the non-thermal pressure.