Multiwavelength study of X-ray luminous clusters in the Hyper Suprime-Cam Subaru Strategic Program S16A field†

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Abstract
We present a joint X-ray, optical, and weak-lensing analysis for X-ray luminous galaxy clusters selected from the MCXC (Meta-Catalog of X-Ray Detected Clusters of Galaxies) cluster catalog in the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP) survey field with S16A data. As a pilot study for a series of papers, we measure hydrostatic equilibrium (HE) masses using XMM-Newton data for four clusters in the current coverage area out of a sample of 22 MCXC clusters. We additionally analyze a non-MCXC cluster associated with one MCXC cluster. We show that HE masses for the MCXC clusters are correlated with cluster richness from the CAMIRA catalog, while that for the non-MCXC cluster deviates from the scaling relation. The mass normalization of the relationship between cluster richness and HE mass is compatible with one inferred by matching CAMIRA cluster abundance with a theoretical halo mass function. The mean gas mass fraction based on HE masses for the MCXC clusters is \( \langle f_{\text{gas}} \rangle = 0.125 \pm 0.012 \) at spherical overdensity \( \Delta = 500 \), which is \( \sim 80\% - 90\% \) of the cosmic mean baryon fraction, \( \Omega_b/\Omega_m \), measured by cosmic microwave background experiments. We find that the mean baryon fraction estimated from X-ray and HSC-SSP optical data is comparable to \( \Omega_b/\Omega_m \). A weak-lensing shear catalog of background galaxies, combined with photometric redshifts, is currently available only for three clusters in our sample. Hydrostatic equilibrium masses roughly agree with weak-lensing masses, albeit with large uncertainty. This study demonstrates that further multiwavelength study for a large sample of clusters using X-ray, HSC-SSP optical, and weak-lensing data will enable us to understand cluster physics and utilize cluster-based cosmology.

Key words: galaxies: clusters: intracluster medium — galaxies: stellar content — gravitational lensing: weak — X-rays: galaxies: clusters
1 Introduction

Galaxy clusters are the largest collapsed objects in the Universe, and the evolution of the dark halo mass is sensitive to the growth of matter density perturbations controlled by dark matter and dark energy. Thus, observations of the high-mass exponential tail of the mass function over wide redshift ranges can constrain cosmological parameters (e.g., Vikhlinin et al. 2009b; Mantz et al. 2016). The anticipated wealth of data from both ongoing and upcoming multiwavelength galaxy cluster surveys like the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP: Miyazaki et al. 2012, 2015; Aihara et al. 2018a, 2018b), the Canada–France–Hawaii Telescope Legacy Survey (CFHTLS: Shan et al. 2012), the Dark Energy Survey (DES: Dark Energy Survey Collaboration 2016), XXL (Pierre et al. 2016), the Extended Roentgen Survey with an Imaging Telescope Array (eROSITA: Cappelluti et al. 2011), Planck (Planck Collaboration 2015b), the South Pole Telescope (SPT: Bleem et al. 2015) and South Pole Telescope Polarimeter (SPTPol: Austermann et al. 2012), and the Atacama Cosmology Telescope (ACT: Hasselfield et al. 2013) and Atacama Cosmology Telescope Polarimeter (ACTPol: Louis et al. 2017) now launches us into a new era of cluster-based cosmology and cluster study. A persistent challenge that affects the ultimate scientific impact of all of these surveys is the need for accurate measurements of mass for individual clusters.

In the last two decades, X-ray observations (e.g., Vikhlinin et al. 2006; Zhang et al. 2008; Sun et al. 2009; Mahdavi et al. 2013; Martino et al. 2014; Donahue et al. 2014) of the intracluster medium (ICM) have been used to measure gas temperature and density distributions and estimate the total mass under the assumption of hydrostatic equilibrium (HE). However, it is known that clusters are not exactly in HE because of some non-thermal phenomena in clusters such as radiative cooling and feedback from supernovae and active galactic nuclei (AGNs) in cluster central regions (e.g., Kravtsov et al. 2005; Pratt et al. 2010; Planelles et al. 2013). Also, the efficiency of accretion-shock heating of the infalling gas (e.g., Kawaharada et al. 2010; Lapi et al. 2010; Walker et al. 2012; Fujita et al. 2013; Okabe et al. 2014b; Avestruz et al. 2016) is still not well understood. The deviation between the HE mass and the actual total mass depends on the hydrodynamical states of individual clusters. The mean deviation among a cluster sample is called “mass bias.” Indeed, the mass bias may be one of the main causes of the tension in cosmological parameters obtained by the Planck cluster number counts (Planck Collaboration 2015b) and the Planck cosmic microwave background (CMB) analysis (Planck Collaboration 2015a). Therefore, X-ray observations have posed a challenge to this fundamental assumption.

On the other hand, weak-lensing (WL) distortions of background galaxy images provide us with a unique opportunity to reconstruct the mass distribution in clusters without any assumptions of dynamical states (Bartelmann & Schneider 2001), making WL complementary to X-ray analysis. In the past decade, tremendous progress in WL analysis was made by prime focus cameras at large ground-based telescopes like Subaru/Suprime-Cam (e.g., Okabe & Umetsu 2008; Okabe et al. 2010, 2013, 2016; Oguri et al. 2010, 2012; Umetsu et al. 2011, 2016; Miyatake et al. 2013; Medezinski et al. 2016), or wide-field surveys (e.g., Mandelbaum et al. 2006; Melchior et al. 2017; Simet et al. 2017). Weak-lensing mass estimates are, however, sensitive to assumptions about the 3D shapes, halo orientations (e.g., Oguri et al. 2005), and substructures (e.g., Okabe et al. 2014a) in the cluster gravitational potential, as well as any other large-scale structure between the lensed sources and the observer (e.g., Hoekstra 2003). Numerical simulations (e.g., Meneghetti et al. 2010; Becker & Kravtsov 2011) have shown that WL mass estimates have scatter caused by a combination of the above effects.

In order to constrain the HE mass bias and to test the validity of the HE assumption, which are of fundamental importance for cosmological applications, previous studies (e.g., Zhang et al. 2010; von der Linden et al. 2014; Okabe et al. 2014b; Donahue et al. 2014; Hoekstra et al. 2015; Smith et al. 2016) compiled a large number of clusters having both HE masses and WL masses. They compared the two masses to indirectly constrain the non-thermal pressure component involved in turbulence and/or bulk motions and its radial dependence, assuming a random orientation of halo asphericity. As before, joint studies based on complementary X-ray, optical, and WL datasets are definitely important in the new era of cluster physics and cluster-based cosmology.

The Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP: Aihara et al. 2018a, 2018b) is an ongoing wide-field imaging survey using the HSC (Miyazaki et al. 2015), which is a new prime focus camera of the 8.2 m-aperture Subaru Telescope. The HSC-SSP survey is composed of three layers of different depths (Wide, Deep, and Ultra-Deep). The Wide layer is designed to obtain five-band (grizy) imaging over 1400 deg$^2$. The HSC-SSP survey has both excellent imaging quality ($\sim 0.7$ seeing in the $i$ band) and deep observations ($r \lesssim 26$ AB mag). The current status of the survey covers 456 deg$^2$ with non-full depth and 178 deg$^2$ with full depth and full color (Aihara et al. 2018b). The HSC-SSP survey enables optical detection of 2000 galaxy clusters (Oguri et al. 2018) in $\sim 232$ deg$^2$, and will
reconstruct the mass distribution of clusters up to $z \sim 1$ and beyond.

In this paper, we present HE mass measurements of galaxy clusters in the current HSC-SSP field using XMM-Newton X-ray data, and compare X-ray observables with optical and WL measurements. The HE mass measurement requires long integration times of an X-ray satellite and therefore we selected X-ray luminous galaxy clusters from an existing X-ray cluster catalog as a first study of the HSC-SSP survey.

The paper is organized as follows. We briefly summarize our target selection in section 2. The X-ray, optical, and WL measurements are described in sections 3, 4, and 5, respectively. The main results and discussion are presented in section 6. All results use a flat $\Lambda$CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

## 2 Target selection

With the aim of measuring HE masses, we select our sample of X-ray luminous clusters in the HSC-SSP field using the MCXC (Meta-Catalog of X-Ray Detected Clusters of Galaxies) cluster catalog (Piffaretti et al. 2011), which is a homogeneously measured cluster catalog derived from several public catalogs based on the ROSAT all-sky survey (RASS). The cluster selection from the MCXC catalog satisfies the following criteria: $z < 0.4$, $L_X(<r_{500})E(z)^{-7/3} > 10^{44} \text{ erg s}^{-1}$, and $f_X > 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ in the HSC-SSP survey region, where $L_X$ is the X-ray luminosity in the 0.1–2.4 keV energy band, $f_X$ is the X-ray flux, and $E(z) = [\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}$. Adopting the mass–luminosity scaling relation (Piffaretti et al. 2011), the luminosity selection with the correction term $E(z)^{-7/3}$ is equivalent to the mass selection $M_{500} > 2 \times 10^{14} h^{-1}_{70} M_\odot$. Here, $M_{500}$ is the mass enclosed by the overdensity radius, $r_{500}$, inside of which the mean mass density is 500 times the critical mass density, $\rho_c$, at the redshift $z$. In the eventual full area of the HSC-SSP survey of $\sim 1400 \text{ deg}^2$, 22 clusters can be selected from the MCXC all-sky X-ray survey (figure 1). To date, four X-ray luminous clusters (table 1) are in an area suitable for investigating cluster physics with the HSC-SSP S16A data ($\sim 232 \text{ deg}^2$: Oguri et al. 2018). We obtained XMM-Newton data for the three clusters through our own program (table 2).

In the data analysis, we came across a companion cluster to the west of MCXC J1415.2–0030. As shown in table 1, its redshift is very close to that of MCXC J1415, and its richness, $N_{\text{corr}}$, is higher than the originally selected cluster (Oguri et al. 2018). We cannot rule out the possibility that the companion cluster is the dominant component of the system. We additionally carry out X-ray analysis for this

### Table 1. Cluster samples.

| Cluster name          | Alternative name | Redshift* | $(\alpha, \delta)_\text{XMM}$ | $(\alpha, \delta)_\text{BCG}$ | $(\alpha, \delta)_\text{CAMIRA}$ | $N_{\text{corr}}$ | WL |
|-----------------------|------------------|-----------|-------------------------------|-------------------------------|-------------------------------|-------------------|------|
| MCXC J0157.4–0550    | Abell 281        | 0.12890   | (29.294, -5.869)              | (29.279, -5.887)              | (29.301, -5.918)              | 41.3              | no  |
| MCXC J0231.7–0451    | Abell 362        | 0.18430   | (37.927, -4.882)              | (37.922, -4.882)              | (37.922, -4.883)              | 116.4             | yes |
| MCXC J0201.7–0212    | Abell 291        | 0.19600   | (30.429, -2.196)              | (30.430, -2.197)              | (30.445, -2.198)              | 76.2              | no  |
| MCXC J1415.2–0030    | Abell 1882A      | 0.14030   | (213.785, -0.491)             | (213.785, -0.494)             | (213.785, -0.493)             | 43.0              | yes |
| MCXC J1415.2–0030W   | Abell 1882B      | 0.14400** | (213.601, -0.377)             | (213.600, -0.379)             | (213.618, -0.330)             | 68.8              | yes |

*Cluster redshift from the MCXC catalog.
1X-ray centroid.
1BCG position.
1The center of the CAMIRA catalog.
1Cluster optical richness.
1Weak-lensing mass measurement satisfying the full-depth and full-color condition for the current HSC-SSP footprint.
**Data retrieved from the CAMIRA catalog (Oguri et al. 2018).
Table 2. X-ray data in the S16A field.

| Cluster name | Observational ID | Net exposure (ks)* |
|--------------|------------------|--------------------|
| MCXC J0157.4−0550 | 0781200101† | MOS1 27.8 MOS2 27.2 pn 16.1 |
| MCXC J0231.7−0451 | 0762870201† | MOS1 22.5 MOS2 22.3 pn 15.5 |
| MCXC J0201.7−0212 | 0655343801† | MOS1 22.4 MOS2 22.4 pn 14.9 |
| MCXC J1415.2−0030 | 0762870501† | MOS1 19.3 MOS2 19.0 pn 13.0 |
| MCXC J1415.2−0030W | 0145480101† | MOS1 11.0 MOS2 11.7 pn 7.0 |

*Net exposure time of each instrument after the data reduction.
†Data observed through our program.
†Archival data.

cluster, because it is important to precisely measure a gas density profile for MCXC1415 and the contamination of its companion cluster. The cluster is hereafter referred to as MCXC J1415.2−0030W. This paper compiles the analysis of the four MCXC clusters and the companion cluster in the S16A field. The details of the X-ray analysis for the full sample will appear in a future paper.

3 X-ray analysis

In order to measure the total cluster mass with X-rays from the ICM gas, which is assumed to be in HE with the cluster gravitational potential, we need the gas density and temperature profiles. The European Photo Imaging Camera (EPIC; Turner et al. 2001; Strüder et al. 2001) on board the XMM-Newton satellite offers an opportunity to perform extremely sensitive imaging/spectroscopic observations for clusters. EPIC data were analyzed with the ESAS (Extended Source Analysis Software) package (Snowden et al. 2008). The details of the data analysis are described in the following sections. In this work, we used SAS version 16.0.0 and HEASoft version 6.19 with the latest CALDB as of 2016 November.

3.1 Data reduction

The EPIC data were processed and screened in the standard way by using the ESAS pipeline. The data were filtered for intervals of high background due to soft proton flares, defined to be periods when the rates were outside the $2\sigma$ range of a rate distribution. Point sources are removed from three EPIC (MOS1, MOS2, and pn) images with simultaneous maximum likelihood point spread function (PSF) fitting. The radius to mask a point source is chosen so that the surface brightness of the point source is one quarter of the surrounding background. If the radius is less than half of the power diameter (HPD $\sim 15''$), we reset the radius to HPD. Table 2 summarizes the cluster data observed with XMM-Newton.

3.2 Spectral fit

In order to determine the gas temperature profile, a spectral fit is performed in the same way as in Snowden et al. (2008), where all spectra extracted from regions of interest are simultaneously fitted with a common model, including particle and cosmic background components that are assumed to be uniform across the detector except for instrumental lines. In this work, we used all three EPIC instruments of the MOS1, MOS2, and pn cameras. Three spectra, one from each instrument, are extracted from concentric annuli centered on an intensity-weighted centroid of the cluster (we first select an intensity peak and then iteratively determine intensity-weighted centroids within a radius of 500 $h^{-1}_{70}$ kpc of the centroid). At each iteration, we exclude regions the sizes of which are the same as those of the excluded point sources (subsection 3.1) at their axially symmetric positions with respect to the centroid computed by the previous iteration. This process is important in order to avoid central shifts by the excluded point sources. The calculation converges within several iterations. Each spectrum is binned in energy to have at least 35 counts per spectral bin, including background. Since the finite PSF effect cannot be ignored for spectral fits of cluster diffuse emission, we consider contaminations from surrounding annuli using crosstalk auxiliary response files (ARFs) in the spectral fitting. The crosstalk contribution to the spectrum in a given annulus from a surrounding annulus is handled as an additional model component.

The instrumental background spectrum, which is stable with time, is modeled with data acquired with the filter wheel closed, available in ESAS CALDB, and is subtracted from the observed spectrum. The other particle backgrounds consisting of a continuum produced by soft protons and instrumental lines are determined by adding a power-law spectrum and narrow Gaussian lines with fixed central energies to the fitting model, respectively. The power-law model representing the soft proton background is added only for MCXC J0157.4−0550, because for the other clusters the spectrum in the outermost region of interest is not affected by the contamination of the soft proton background and therefore the corresponding model is negligible.

The cosmic diffuse background consists of the cosmic X-ray background (CXB), Galactic diffuse emission, and solar wind charge exchange (SWCX) emission lines, all of which are added to the fitting model. The CXB component is modeled with a power-law spectrum with a fixed index of 1.46 according to Snowden et al. (2008). The Galactic diffuse emission is fitted with the sum of absorbed and non-absorbed thermal plasma emission models, with temperatures ranging from 0.25 to 0.7 keV and from 0.1 to 0.3 keV, respectively. The SWCX lines are two narrow Gaussian
models with fixed central energies of 0.56 and 0.65 keV, which correspond to O VII and O VIII lines, respectively. The CXB and Galactic diffuse emission are constrained by simultaneously fitting a spectrum extracted from the 1–2\textdegree annular region surrounding the cluster using the RASS data (Snowden et al. 1997).

The ICM emission spectrum is fitted by a thermal plasma emission model, APEC (Smith et al. 2001), with the Galactic photoelectric absorption model phabs (Baliunaska-Church & McCammon 1992). In the identical annuli of the three EPIC detectors, each spectrum has common model parameters for ICM emission except for a normalization factor for cross-calibration. The metal abundance relative to solar from Anders and Grevesse (1989) in each annulus is co-varied among the three instruments. When the metallicity at large radii is not constrained, it is the same as the value determined in the adjacent inner annulus. The power-law indexes of the soft proton background are different free parameters in the MOS and pn, but are common in all annuli for each detector. The normalization for the soft proton background in individual annuli varies according to a scale factor computed from ESAS. Cluster redshift, the proton background in individual annuli varies according to annuli for each detector. The normalization for the soft proton background are different free determined in the adjacent inner annulus. The power-law at large radii is not constrained, it is the same as the value from Anders and Grevesse (1989) in each annulus.

3.3 Surface brightness profile

The X-ray surface brightness profiles over entire detector regions are derived from the 0.4–2.3 keV image, from which the instrumental background is already subtracted. We assume that the surface brightness profile follows a linear combination of β models (Cavaliere & Fusco-Femiano 1976; Jones & Forman 1984) to analytically describe multi-scale and/or multi-component X-ray emitting gas. The model profile is

\[ S_X^\text{tot}(R) = \sum_{i=1}^{n} S_{X,i}(R) + B, \]

where \( S_{X,i} \) is a single β model,

\[ S_X(R) = S_0 \left[ 1 + \left( R/r_{c,i} \right)^2 \right]^{-1/2-3\beta}, \]

and \( r_{c,i} \) is the three-dimensional distance from the center. We compute the emissivity in the given energy band from the best-fit parameters of spectral analysis and conversion factors between \( S_X \) and \( n_e \) considering detector sensitivities. The surface brightness is in general measured over larger radii than that for spectral analysis, and the conversion factor at large radii is extrapolated with a linear function of the radius. If we convert using the central emissivity only, the electron number density is underestimated by \( \sim 10\% \) at \( \sim r_{(0)} \).

To fairly model multiple components for an internal substructure in MCXC J0157.4–0550 (see...
figures 3 and 4 in subsection 6.1) and contamination from the close-pair cluster, MCXC J1415.2−0030 and MCXC J1415.2−0030W (subsection 6.4), we take into account X-ray emission from gas components offset from the main cluster when determining the surface brightness.

The off-centering effect in the surface brightness is calculated by

$$S_{X,\text{off}}(R) = \frac{1}{2\pi} \int_0^{2\pi} d\theta S_X\left(\sqrt{R^2 + d_{\text{off}}^2 - 2Rd_{\text{off}}\cos\theta}\right). \quad (4)$$

Here, $d_{\text{off}}$ is the off-centering distance on the sky. When we model without the off-centering effect, the outer slope $\beta$ is misestimated and the HE mass estimates are biased. As a sanity check, we compute the surface brightness profiles excluding the area within which the best-fit number density for the off-centered component is more than $10^{-2}$ of its central density and confirm that the best-fit results do not change.

### 3.4 Temperature profile

The temperature profile is modeled with a generalized universal profile (Martino et al. 2014; Okabe et al. 2014b),

$$T_{3D}(r) = T_0 \left(\frac{r}{r_t}\right)^{\alpha} \left[1 + \left(\frac{r}{r_t}\right)^2\right]^{-\frac{c}{2}}. \quad (5)$$

The temperature profile projected along the line of sight is estimated with a weight $w$,

$$T_{2D} = \frac{\int T_{3D} w dV}{\int w dV}. \quad (6)$$

in each annulus. We assume here a spectroscopic-like temperature (Mazzotta et al. 2004; Martino et al. 2014) with $w = n^2 T_{3D}^{-3/4}$. When the low photon statistics prevent us from constraining a temperature profile, we assume an inner slope of $\alpha = 0$ and/or an outer slope of $c = 1$, following a universal temperature profile out to $r_{200}$ based on joint Subaru WL and Suzaku X-ray analysis (Okabe et al. 2014b). We
also assume a constant profile for MCXC J1415.2−0030 W because the temperatures are measured only in two annuli. The measurement uncertainty for the number density is also propagated to the temperature fitting.

3.5 HE mass profile

Given the best-fit parameters, the three-dimensional spherical total mass is estimated with the HE assumption,

\[ M_{\text{HE}}(r) = -\frac{k_B T_3(r)}{n_e G} \left[ \frac{d}{d \ln r} \frac{d \ln \rho_\mu(r)}{d \ln r} + \frac{d}{d \ln r} \frac{d \ln T_3(r)}{d \ln r} \right], \]  

(7)

where \( \mu = 0.5964 \) is the mean molecular weight for the metallicity \( Z = 0.3 \) and \( \rho_\mu = 1.9257 \mu n_e m_p \) is the gas density profile. Here, \( n_e \) is the electron density and \( m_p \) is the proton mass. We then estimated the total mass, \( M_{500, \text{HE}} \), within \( r_{500} \) and the spherical gas mass, \( M_{\text{gas}}(r) \), calculated by integrating \( \rho_\mu \) out to the radius \( r_{500} \).

4 Optical catalog

We retrieved the cluster richness, \( N_{\text{tot}} \), and the stellar masses, \( M_\star \), from the CAMIRA cluster catalog (Oguri et al. 2018), which is constructed using the HSC-SSP Wide S16A data. The CAMIRA algorithm makes use of a stellar population synthesis model to predict colors of red-sequence galaxies at a given redshift for an arbitrary set of bandpass filters and a three-dimensional richness map with a compensated spatial filter. The details of the CAMIRA cluster algorithm are described in Oguri (2014) and Oguri et al. (2018). The smoothing scale for the compensated spatial filter is \( R_0 = 0.8 \, h^{-1} \, \text{Mpc} \) in physical units. The total stellar mass for red galaxies of each cluster is estimated by convolution with the spatial filter. Since blue galaxies are a subdominant component in stellar mass at low redshifts, we estimate the stellar mass only using red galaxies. We confirmed that the photometric redshifts provided by the CAMIRA cluster catalog agree well with the spectroscopic redshifts.

We use the stellar masses here rather than optical luminosities because the HSC-SSP multi-band datasets are capable of estimating the stellar masses (Oguri et al. 2018). Following Miyazaki et al. 2015, we convert the total stellar masses (\( M_\star^{\text{CAMIRA}} \)) of each CAMIRA cluster into one enclosed within a measurement radius [\( M_\star(<r_s) \)]. The conversion factor, \( A \equiv M_\star(<r_s)/M_\star^{\text{CAMIRA}} \), can be calculated as follows. We first assume that the stellar mass density profile is described by a universal mass density profile (Navarro et al. 1996, 1997, hereafter NFW) with the mass and concentration relation of Diemer and Kravtsov (2015) with the Planck cosmology (Planck Collaboration 2015a). Here, the NFW profile is expressed in the form

\[ \rho_{\text{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}, \]  

(8)

where \( \rho_s \) is the central density parameter and \( r_s \) is the scale radius. The halo concentration is defined by \( c_s = r_s/r_s \), where \( r_s \) is the overdensity radius. Given the mass and its assumed concentration, the conversion factor \( A \) is obtained as the ratio derived by integrating the projected NFW profile out to the measurement radius and to infinity, with a convolution of the spatial filter. When a measurement center is offset from the CAMIRA center, we calculate the azimuthally averaged, projected NFW density around the measurement center and then integrate it out to the measurement radius in a similar manner to equation (4). As mentioned in Miyazaki et al. (2015), this correction technique takes into account the three-dimensional deprojection. We measure stellar masses at \( \Delta = 300 \) derived by X-ray mass measurements and estimate gas and baryon fractions with the X-ray gas measurements (subsection 6.7). Some very luminous galaxies in clusters are missed by flags in the CAMIRA catalog because their luminosity cannot be accurately measured due to saturation. If an offset between the CAMIRA and X-ray centers is large, the number of missing luminous galaxies is relatively large. To include missing luminous galaxies, we add stellar masses of luminous member galaxies identified by SDSS spectroscopic observations. The stellar masses and gas fractions including the luminous galaxies are \( \sim 3\% \) to \( \sim 47\% \) and \( \lesssim 14\% \) higher, respectively.

5 Weak-lensing mass measurement

We carry out WL analysis using the WL shear data estimated by the re-Gaussianization method (Hirata & Seljak 2003) implemented in the HSC pipeline (see details in Mandelbaum et al. 2018). Both precise shape measurement and photometric redshift estimation are essential for WL-related studies, giving strict conditions on the depth of data and the availability of five-band photometry. For this reason, the WL shear catalog is restricted to the full-depth and full-color footprint. Three out of five clusters are located in the those regions, namely MCXC J0231.7−0451, MCXC J1415.2−0030, and MCXC J1415.2−0030 W, for which we measure WL masses (table 1).

In cluster lensing, contamination of unlensed member galaxies in the source catalog significantly underestimates lensing signals at small radii, because a fraction of member and background galaxies is increasing with a decreasing radius. This is known as the dilution effect (Broadhurst et al. 2005). Previous studies (e.g., Okabe...
et al. 2013, 2014b; Okabe & Smith 2016) have shown that if there is no background selection, lensing signals for massive clusters at \( z \sim 0.2 \) are underestimated by \( \sim 40\% \). Previous studies (Okabe et al. 2013; Medezinski et al. 2010, 2016; Okabe & Smith 2016; Umetsu et al. 2016) securely selected background galaxies using color information and succeeded in keeping the level of contamination below a few percent. We briefly summarize the method here. It is very difficult to discriminate between faint members and background galaxies by magnitude information because of large photometric uncertainty and the intrinsic scatter of color distribution. We select a color-space region in which member galaxies are negligible by monitoring consistency among three independent items of information on color, lensing signal, and available, external photometric redshift catalog (Ilbert et al. 2013). Since passively evolving member galaxies are localized in color space, the mean tangential distortion strength in the color space close to the red sequence is significantly underestimated because member galaxies are not lensed. However, the mean lensing signals, which are computed by the ensemble shear and the photometric redshift, outside of red-sequence color space are flattened due to a reduction in contamination by member galaxies. By modeling the color distribution of faint member galaxies, we have succeeded in keeping the contamination limit at less than a few percent. In this procedure, we considered both shape noises and errors of photometric redshifts.

Based on a similar philosophy, Medezinski et al. (2018) developed a new scheme to make a secure selection of background galaxies. We utilized lensing signals and four-band magnitudes (griz) of the HSC-SSP survey, internal photometric redshifts (Tanaka et al. 2018) computed by machine learning (MLZ: Carrasco Kind & Brunner 2014) calibrated with spectroscopic data. We have succeeded in selecting background galaxies in the \( rz \) and \( gi \) color plane as the best combination for the HSC-SSP survey. Based on Medezinski et al. (2018), we select background galaxies for WL mass measurements (see also H. Miyatake et al. in preparation). The number of background galaxies after the color cuts is \( \lesssim 11 \) arcmin\(^{-2} \).

Given the shape catalog of background galaxies, we measure the reduced tangential shear \( \langle \Delta \Sigma_i \rangle (r_i) \) computed by azimuthally averaging the measured galaxy ellipticity, \( \epsilon_i (\alpha = 1, 2) \), for the \( n \)th galaxy in the \( i \)th annulus \( (r_{\text{min}} < r_i < r_{\text{out}}) \), centering at the brightest cluster galaxies (BCGs),

\[
\langle \Delta \Sigma_i \rangle (r_i) = \frac{\sum_n \epsilon_{i, \alpha} w_n \left( \Sigma_{ct}^{-1} \right)^{-1}}{2K_i \left( 1 + K_i \right) \sum_n w_n}, \tag{9}
\]

where the tangential ellipticity is

\[
\epsilon_\alpha = - \left( e_1 \cos 2\varphi + e_2 \sin 2\varphi \right), \tag{10}
\]

and the inverse of the mean critical surface mass density \( \left( \Sigma_{ct}^{-1} \right) \), the weighting function \( w_n \), the shear responsivity \( R \), and the calibration factor \( K \) are defined below. The inverse of the mean critical surface mass density is computed by the probability function \( P(z) \) of the MLZ photometric redshift,

\[
\Sigma_{ct}^{-1} = \int_0^\infty \frac{\Sigma_{ct}^{-1}(z_i, z) P(z_i) dz_i}{\int_0^\infty P(z_i) dz_i}.
\tag{11}
\]

Here, \( z_i \) and \( z \) are the cluster and source redshift, respectively. The critical surface mass density for individual background galaxies is expressed by \( \Sigma_{ct} = c^2 D_l / 4\pi G D_s \), where \( D_l \), \( D_s \), and \( D_a \) are the angular diameter distances from the observer to the sources, from the observer to the lens, and from the lens to the sources, respectively. Since \( \Sigma_{ct} \) becomes zero for \( z_i < z \), the lower bound of the integration is truncated by \( z_i \). The weighting function \( w_n \) is given by

\[
w_n = \frac{1}{e_{\text{rms}}^2 + \sigma_e^2 \left( \Sigma_{ct,n}^{-1} \right)^2}, \tag{12}
\]

where \( e_{\text{rms}} \) and \( \sigma_e \) are the root mean square of intrinsic ellipticity and the measurement error per component (\( \alpha = 1 \) or 2), respectively. Here, the intrinsic ellipticity expresses the ellipticity of the intrinsic shape of galaxies. The shear responsivity is computed based on the ellipticity definitio:

\[
R_i = 1 - \frac{\sum_n \epsilon_{i, \alpha} w_n}{\sum_n w_n} \tag{13}
\]

(see also Mandelbaum et al. 2005; Reyes et al. 2012). We correct the measured values using the shear calibration factor \( (m, c) \) for individual objects (Mandelbaum et al. 2018), because of systematic errors in shape measurements. The measured ensemble shear, \( \langle \gamma \rangle \), can be expressed by \( (1 + m)\gamma_{\text{true}} + c \) with the input shear \( \gamma_{\text{true}} \), as defined by STEP (Shear TEsting Programme) simulations (Heymans et al. 2006; Massey et al. 2007). Here, a multiplicative calibration bias \( m \) and an additive residual shear offset \( c \) are estimated based on GREAT3-like simulations (R. Mandelbaum et al. in preparation; Mandelbaum et al. 2014, 2015) as a part of the GREAT (GRavitational Lensing Accuracy Testing) project. The calibration factor, \( K_i \), is computed by

\[
K_i = \frac{\sum_n w_n}{\sum_n w_n}, \tag{14}
\]

We also conservatively subtract

\[
\bar{c}_i = \frac{\sum_n \epsilon_{i, \alpha} w_n \left( \Sigma_{ct,n}^{-1} \right)^{-1}}{\left( 1 + K_i \right) \sum_n w_n} \tag{15}
\]

from \( \langle \Delta \Sigma_i \rangle (r_i) \) [equation (9)]. The additional offset term is negligible, \( \mathcal{O}(10^{-4}) \), compared to \( \langle \Delta \Sigma_i \rangle \sim \mathcal{O}(10^{-1}) \).
Following Okabe and Smith (2016), we employ a maximum-likelihood method to model the shear profiles, and express the log-likelihood as follows:

$$-2 \ln \mathcal{L} = \ln[\det(C_{ij})] + \sum_{i,j} \left[ \Delta \Sigma_{+i} - f_{\text{model}}(r_i) \right] C_{ij}^{-1} \left[ \Delta \Sigma_{+j} - f_{\text{model}}(r_j) \right]$$

where the subscripts $i$ and $j$ are for the $i$th and $j$th radial bins, respectively. We adopt that $r_i$ is the weighted harmonic mean radius of the background galaxies. Here, $f_{\text{model}}$ is the reduced shear prediction for a specific mass model,

$$f_{\text{model}}(r_i) = \frac{\Delta \tilde{\Sigma}_{\text{model}}(r_i)}{1 - [\mathcal{L}_{ij} \tilde{\Sigma}_{\text{model}}(r_i)]},$$

with $\Delta \tilde{\Sigma}_{\text{model}} = \gamma_+ (\Sigma_{+1})^{-1}$ and $\Sigma_{\text{model}} = \kappa (\Sigma_{1})^{-1}$. Here, $\gamma_+$ is the dimensionless tangential shear and $\kappa$ is the convergence, respectively. The covariance matrix, $C = C_g + C_s + C_{\text{LSS}}$, in equation (16) is composed of the shape noise, $C_g$, the uncertainty in source redshift, $C_s$, and the photometric redshift error computed by $P(z)$ and uncorrelated large-scale structure (LSS), $C_{\text{LSS}}$, along the line of sight (Schneider et al. 1998). The covariance matrix for shape noise is obtained as weighted variance,

$$C_{\text{G},ij} = \frac{1}{4R_i^2(1+K_i)^2 \sum w_n} \delta_{ij},$$

where $\delta_{ij}$ is the Kronecker delta function. The photometric error for individual galaxies is estimated by

$$\delta(\Sigma_{+i}) = \frac{\int_{-\infty}^{\infty} \left[ \Sigma_{+i}^{-1}(z_i, z_{s}) - (\Sigma_{+i}^{-1}) \right] \times P(z_i) dz_i}{\int_{0}^{\infty} P(z_{s}) dz_{s}},$$

and then we propagate it into the measurement as $C_s$. The covariance matrix $C_{\text{LSS}}$ is given by

$$C_{\text{LSS},ij} = (\Sigma_{+i}^{-1})^{-1} (\Sigma_{+j}^{-1})^{-1} \int \frac{dl}{2\pi} P_i(l) f_2(l_0) f_1(l_0),$$

where $P_i(l)$ is the weak-lensing power spectrum (e.g., Schneider et al. 1998; Hoekstra 2003) calculated by multipole $l$, the source redshift, and a given cosmology. We employ the Planck cosmology (Planck Collaboration 2015a) for $\Omega_{\text{m}}, \sigma_8$, and the spectral index $n_s$. Here, $f_2(l_0)$ is the Bessel function of the first kind and second order at the $i$th annulus (Hoekstra 2003).

The source redshift at each radial bin is calculated from a lensing-efficiency weighted value, as follows:

$$\mathcal{L}_{ij} = \sum_n \frac{(\Sigma_{+i}^{-1}) w_n}{\sum_n w_n}.$$

Following numerical simulations (Navarro et al. 1996) and previous observational results (e.g., Oguri et al. 2012; Okabe et al. 2013, 2016; Umeda et al. 2016), we adopt the NFW profile (Navarro et al. 1996) as the mass model. Similar to the X-ray analysis, we define the three-dimensional spherical mass, $M_{500}$, enclosed by the radius, $r_{500}$. We basically fit for two parameters: the mass and the halo concentration. The resulting masses are shown in Table 3.

### 6 Results and discussion

We carried out X-ray analysis and joint X-ray and optical analysis for the four MCXC clusters and the non-MCXC cluster (Table 1) in the current coverage region for the HSC-SPP survey. As mentioned in section 5, the sample for WL mass measurement is only the three clusters (Table 1) due to the full-color and full-depth condition. Thus, we shall use the WL mass estimates only for X-ray and WL mass comparisons.

Since this paper is a sort of pilot study to directly compare multiwavelength datasets, we shall first discuss results for individual clusters based on both X-ray and optical datasets. We then perform studies of a correlation between HE masses and richness, a mass comparison, and baryon fraction for the current sample of clusters.

#### 6.1 MCXC J0157.4—0550

MCXC J0157.4—0550 is an ongoing cluster merger at $z = 0.1289$, as shown in Figure 3. The system is composed of the western main gas halo and the northeast subhalo. Optically luminous galaxies are concentrated in the western region, where the X-ray morphology is highly elongated along the west–east direction. The CAMIRA center is slightly offset from both the X-ray and BCG centers, because some luminous galaxies are missing in the HSC CAMIRA catalog. A comma-shaped feature in the X-ray emission is discovered at $\sim 1.6 r_{500} \sim r_{200}$ based on HE mass estimation (subsection 3.5), which suggests ram-pressure stripping of the subcluster. An optically luminous galaxy is located at the subcluster X-ray peak. The redshift retrieved from the SDSS, 0.1286, is very close to the cluster redshift, suggesting that the substructure is infalling in the

| Name         | HE mass | WL mass |
|--------------|---------|---------|
| MCXC J0157.4—0550 | $1.37^{+0.09}_{-0.08}$ | — |
| MCXC J0231.7—0451  | $3.43^{+0.77}_{-0.65}$ | $7.96^{+2.58}_{-2.89}$ |
| MCXC J0201.7—0212  | $3.21^{+0.51}_{-0.44}$ | — |
| MCXC J1415.2—0030  | $1.54^{+0.34}_{-0.23}$ | $2.09^{+1.43}_{-0.90}$ |
| MCXC J1415.2—0030W | $0.44^{+0.07}_{-0.07}$ | $0.80^{+0.87}_{-0.58}$ |
plane of the sky. This is consistent with the fact that a prominent tail is observed. The comma-shaped feature also implies that the infalling gas observed in the X-ray has large angular momentum. If we improperly treat the substructure in the X-ray surface brightness (\(S_r\)) modeling, it may change the outer density slope [equation (2)] of the main halo and eventually affect the HE mass estimation. Furthermore, we cannot rule out the possibility that the slopes in the disturbed (east) and undisturbed (west) sectors are different. Since our analysis assumes spherical symmetry to measure spherical HE masses, it is not good to divide into azimuthally dependent subsectors. To solve these problems, we implement the subtraction using the off-centering effect [equation (4)] in a model of the azimuthally averaged surface brightness profile centering on the western gas halo. As a first approximation, we assume the \(\beta\) model for the western main gas halo and the northeast subhalo. The resulting profile describes well the observed surface brightness (figure 4).

The HE mass is estimated only for the main cluster. The total gas mass within \(r_{200}\) computed for both the main gas and the gas substructure is \(\sim 8\%\) higher than that estimated by the main cluster component, while the gas mass within \(r_{500}\) does not change.

Unfortunately, this cluster is located outside of the full-depth and full-color region of the HSC-SSP S16A data, and thus the WL shape data are not available. A mass comparison for this cluster will be carried out in a future study.

### 6.2 MCXC J0231.7−0451

We present new observations of the cluster (\(z = 0.1843\)) located in the XXL survey region with XMM-Newton. An X-ray luminous point source at \(\sim 3.5\) east of the X-ray center is found. Faint X-ray emission from another CAMIRA cluster at \(z = 0.2760\) is also detected around the edge of the X-ray detectors (figure 5). These X-ray sources are excluded in our analysis.

The cluster is referred to as XXL091 in the XXL survey (Eckert et al. 2016), and has \(M_{\text{gas}} = 5.00^{+0.80}_{-0.83} \times 10^{13} h^{-1} M_{\odot}\) within \(r_{500}^{\text{XXL}} = 1149 \pm 161 h^{-1} \text{Mpc}\) derived from a scaling relation between WL mass and X-ray temperature (Lieu et al. 2016). We find that our measurement \(M_{\text{gas}} = 5.10^{+0.85}_{-0.84} \times 10^{13} h^{-1} M_{\odot}\) is within the same radius is in good agreement with Eckert et al. (2016).

The mass estimation of the Planck SZ observation (Planck Collaboration 2015b) gives \(M_{\text{SZ}} = 3.96^{+0.46}_{-0.45} \times 10^{14} M_{\odot}\), which agrees with our HE mass estimate \(M^\text{HE} = 3.43^{+0.77}_{-0.66} \times 10^{14} M_{\odot}\).

Our WL mass measurement gives \(M^\text{WL}_{500} = 7.96^{+2.58}_{-1.85} \times 10^{14} h^{-1} M_{\odot}\), which agrees within errors with the CFHT WL mass measurement \(M^\text{WL}_{500} = 6.2^{+2.1}_{-1.8} \times 10^{14} h^{-1} M_{\odot}\) (Lieu et al. 2016).

### 6.3 MCXC J0201.7−0212

This cluster is known as Abell 291, and has a cool core (Okabe et al. 2010, 2016; Martino et al. 2014). Since the HSC-SSP S16A data of the cluster do not satisfy the full-depth and full-color condition for WL mass measurement, we carry out X-ray and optical analysis.

We analyzed the same X-ray data used in Martino et al. (2014). The gas density profile is described well by a double \(\beta\) model. The CAMIRA center is slightly offset from the X-ray centroid and the BCG (figure 6), because a few bright galaxies are missing in the CAMIRA catalog. Our HE mass estimate, \(M^\text{HE}_{500} = 3.21^{+0.51}_{-0.44} \times 10^{14} M_{\odot}\), agrees with a previous X-ray study: \(M_{500} = 2.92 \pm 0.56 \times 10^{14} h^{-1} M_{\odot}\) (Martino et al. 2014). They are slightly lower than the WL mass, \(M^\text{WL}_{500} = 4.46^{+1.00}_{-0.94} \times 10^{14} h^{-1} M_{\odot}\) (Okabe & Smith 2016), but the difference is not statistically significant. A mass comparison using the HSC-SSP data is left for future work.

### 6.4 MCXC J1415.2−0030 and MCXC J1415.2−0030W

The system is mainly composed of the originally identified MCXC cluster MCXC J1415.2−0030 at the east and its companion cluster at \(\sim 2\) Mpc northwest of the MCXC cluster. We refer to the western cluster as MCXC J1415.2−0030W for convenience. The X-ray emission shows no evidence of disturbance due to merger activity. Besides the two clusters, two faint, diffuse X-ray emissions are found in the field (figure 7). The northern
Fig. 6. MCXC J0201.7–0212. The colors and contours are the same as those in figure 3. (Color online)

Fig. 7. MCXCJ1415.2–0030 field, overlaid with X-ray contours in red color. Four diffuse X-ray sources are found in this field, MCXC J1415.2–0030 and MCXC J1415.2–0030W are at the middle left and middle right of the panel, respectively. The other two diffuse X-ray emissions surrounding the system are found at (α, δ) = (213.740, −0.350) and (α, δ) = (213.541, −0.272). The green circles have a 1.2 radius and are centered on the CAMIRA clusters. Two high-z CAMIRA clusters (z > 0.9 and N_{gal} ≥ 15) are found in the field, marked by light-blue circles with 0.6 radii. The contours are the same as figure 3. (Color online)

emission (α, δ) = (213.740, −0.350) and the north-western emission (α, δ) = (213.541, −0.272) are associated with galaxies at z = 0.1389 and z = 0.1398, respectively. These components of radii ∼ 0.7–0.8 are excluded in the following X-ray analysis. In the CAMIRA catalog, these galaxies are identified as a part of MCXC J1415.2–0030W, giving a large richness. The X-ray emission from the eastern MCXC cluster coincides with the CAMIRA center, while the western emission is ∼3′ offset from the CAMIRA center. This is because the western CAMIRA cluster includes the northern and north-western groups. We find no evidence that the BCGs of the eastern and western clusters are significantly offset from the X-ray centroids. The X-ray luminosity of the eastern MCXC cluster is brighter than that of the western cluster, while the richness for the western cluster is higher. Owers et al. (2013, figure 4) have shown based on spectroscopic data that member galaxies of the eastern and western clusters are spread over ∼4 Mpc and ∼1 Mpc, respectively.

We analyzed X-ray data for these two clusters in order to measure gas temperatures and surface brightness profiles. To carefully estimate density outer slopes, we computed two surface brightness profiles centering on each of the two clusters and simultaneously fitted them with the two surface brightness models with the off-centering effect. We found that the observed profiles are described well by the sum of X-ray emission of the two clusters, requiring no extra component such as a filamentary gas component bridge between the two clusters. In the surface brightness profile centered on MCXCJ1415.2–0030, the flux of the cluster, the other cluster, and the background at R ∼ 1 Mpc account for ∼1%, ∼13%, and ∼86%, respectively. In the temperature measurements for each cluster, we selected the background-dominated region for the annulus. Again, if we ignore the flux contamination from the other cluster in the surface brightness modeling, we overestimate the background component and eventually misestimate the outer slopes.

Based on the HE assumption, we estimate $\Sigma_{\text{off}} = 54.0^{+14.3}_{-14.3} \times 10^{14} h_{70}^{-1} M_{\odot}$ for MCXC J1415.2–0030 and $\Sigma_{\text{off}} = 44.0^{+17.0}_{-17.0} \times 10^{14} h_{70}^{-1} M_{\odot}$ for MCXC J1415.2–0030W (table 3), respectively. This suggests that the originally identified MCXC cluster is the main cluster.

We also carry out WL mass measurements for the two clusters. We adopt a maximum radius for each tangential shear profile centered on each BCG of ∼1.3 $h_{70}^{-1}$ Mpc. Since the maximum radius is much less than the projected distance between the two clusters, the off-centering effect of the lensing signal is negligible, ∼0(10^{-5}) × (\Sigma_{\text{off}})^{-1} (Yang et al. 2006), in contrast to X-ray analysis. This is caused by the fact that $\Delta \Sigma_{\text{off}} / \Sigma_{\text{off}} = \Sigma_{\text{off}} - \Sigma_{\text{net}}$, where the the surface mass density for the off-centering component at the measured radius, $\Sigma_{\text{off}}(R)$, is comparable to the mean surface mass density within the radius, $\Sigma_{\text{net}}(< R)$. The WL masses are $M_{\text{WL}} = 2.09^{+1.14}_{-1.09} \times 10^{14} h_{70}^{-1} M_{\odot}$ for MCXCJ1415.2–0030 and $M_{\text{WL}} = 0.80^{+0.87}_{-0.68} \times 10^{14} h_{70}^{-1} M_{\odot}$ for MCXCJ1415.2–0030W (table 3). Since the signal-to-noise ratio of the tangential shear profile for
MCXC J1415.2−0030W is small, we used one parameter, $M_{500}$, assuming the halo concentration based on the median value of the mass versus concentration relation (Diemer & Kravtsov 2015). A sum of best-fit virial radii $\sim 2.6$ Mpc is comparable to the projected separation $\sim 2$ Mpc and non-disturbed gas distribution, suggesting that the two clusters are at an early phase of cluster merger. The HE mass for the western companion cluster is comparable to the WL mass.

Virial mass estimation (Owers et al. 2013) using spectroscopic data has shown that $M_{500}^{\text{vir}} = 1.5 \pm 0.3 \times 10^{14} h^{-1} M_\odot$ for the main cluster (A1882A) and $M_{500}^{\text{vir}} = 1.0 \pm 0.5 \times 10^{14} h^{-1} M_\odot$ for the companion cluster (A1882B), respectively. Dynamical mass estimates are in good agreement with our WL masses. Owers et al. (2013) also concluded, based on joint X-ray and kinematics analysis, that the system is likely to be before cluster merger. Our results agree with their conclusions.

6.5 Richness vs. $M_{\text{HE}}$

We compare the HE masses for the MCXC clusters with the CAMIRA cluster richness. Since the cluster richness is generally proportional to the number of member galaxies, it is expected to be a good mass proxy. Indeed, Oguri et al. (2018) have compared public X-ray temperature and luminosity in the XXL and XMM-LSS fields with the CAMIRA cluster richness, and found good correlations. The slope in a richness and temperature scaling relation is found to be shallower than that predicted by a self-similar solution. The temperatures are measured within a fixed radius, 300 kpc, and thus are potentially and partially affected by baryonic physics. We study here a correlation between the HE masses and cluster richness.

Figure 8 compares the richness with the HE mass. The HE masses for the original sample of the MCXC clusters are $M_{500} \gtrsim 1.5 \times 10^{14} h^{-1} M_\odot$, which is consistent with our selection function $M_{500} \gtrsim 2 \times 10^{14} h^{-1} M_\odot$ (section 2). A small discrepancy is acceptable when we consider intrinsic scatter in the scaling relation (Piffaretti et al. 2011). We fit the relation with a single power-law model:

$$\log \left( \frac{M_{\text{HE}}^{\text{vir}}}{10^{14} h^{-1} M_\odot} \right) = a \log N_{\text{cor}} + b.$$  \hspace{1cm} (22)

With the selection function of the MCXC clusters, we consider here the four MCXC clusters and obtain $a = 0.84 \pm 0.15$ and $b = -2.73 \pm 0.61$. The best-fit slope agrees with the $\sim 1$ predicted by $N_{\text{cor}} \propto M$ (Lin et al. 2004). The best-fit normalization suggests that $M_{500}^{\text{vir}} \sim 6 \times 10^{14} h^{-1} M_\odot$ at $N_{\text{cor}} = 15$. When we fix $a = 1$, we obtain $b = -3.41 \pm 0.50$ and $M_{500}^{\text{HE}} \sim 5 \times 10^{13} (N_{\text{cor}}/15) h^{-1} M_\odot$.

Oguri et al. (2018) have shown that $N_{\text{cor}} = 15$ roughly corresponds to $M_{200m} \sim 10^{14} h^{-1} M_\odot$, if the number of discovered clusters agrees with the prediction of a cluster mass function computed by Tinker et al. 2010 with $\sigma_8 = 0.82$. Here, 200 m means that the mean density is 200 times the mean matter density of the Universe. Assuming the median halo concentration $c_{200m} = 6$ (Diemer & Kravtsov 2015), $M_{200m} \sim 10^{14} h^{-1} M_\odot$ gives $M_{500} \sim 7 \times 10^{13} h^{-1} M_\odot$. Our HE mass estimation roughly agrees with the expectations of Oguri et al. (2018). More precise comparison using a large number of clusters will be carried out in future work.

Interestingly, the HE mass for the non-MCXC cluster, MCXC J1415.2−0030W, is significantly lower than the best-fit baseline. The deviation might be explained by two possibilities or their combination. First, at the early stage of cluster merger, the ICM would strongly deviate from HE, consistent with our finding that the WL mass is higher (subsection 6.4). Second, the richness would be overestimated because the CAMIRA member galaxies of MCXC J1415.2−0030W include the other group components. We also fit the mass–richness scaling relation for the five clusters with $a = 1$ fixed, and confirm that the normalization, $b = -3.74 \pm 0.45$, does not significantly change.

6.6 Mass comparison

We compare WL masses with HE masses at $\Delta = 500$ as a first attempt for our further studies. The full-depth and full-color condition allows us to compare the two masses
When we exchange $M_{\text{HE}}$ for $M_{\text{WL}}$, in the equation, the second term of this quantity becomes the inverse in contrast to an estimation with $\sum_i(M_{\text{HE}}/M_{\text{WL}})_i/n$. If the HE mass is statistically consistent with the WL mass, the bias parameter $b_m$ is equal to zero. We obtain $b_m = 0.44^{+0.31}_{-0.45}$ for the three clusters at $\Delta = 500$ (figure 9). We also obtain $b_m = 0.34^{+0.16}_{-0.19}$ for the two MCXC clusters. Since the measurement errors for WL masses of the two MCXC clusters are relatively small, the error in $b_m$ becomes smaller. This indicates that the HE mass at $\Delta = 500$ is consistent with the WL mass in the current sample at the $2\sigma$ level.

When we use the same radii determined by weak-lensing masses, we obtain $b_m = 0.40^{+0.19}_{-0.45}$ for the three clusters and $b_m = 0.34^{+0.28}_{-0.41}$ for the two clusters, respectively. Here we consider the error propagation of measurement uncertainties of the WL radii. The result does not significantly change. When we measure WL masses with X-ray centers, the best-fit WL masses are changed only by a few percent because the offset distances between X-ray centroids and BCG positions are very small.

Although our results are statistically poor because of a small sample of clusters, we compare them with the literature. Direct comparisons between weak-lensing masses and X-ray masses are not trivial, because previous studies applied their own methods: boost factor correction (e.g., von der Linden et al. 2014; Hoekstra et al. 2015) or no correction (e.g., Okabe et al. 2016; Umetsu et al. 2016) in WL analyses and emission-weighted temperatures (e.g., Zhang et al. 2008; Mahdavi et al. 2013) or spectroscopic-like temperature (e.g., Mazzotta et al. 2004; Martino et al. 2014) in X-ray analyses. Smith et al. 2016 obtained the average bias $b_m = 0.05 \pm 0.05$ for 50 clusters at $z \sim 0.2$, and Mahdavi et al. (2013) computed $b_m = 0.12 \pm 0.05$ with their WL radii. Using the same sample between the two papers, the major difference ($\sim 10\%)$ would come from X-ray mass measurements (Smith et al. 2016). We assume here that the difference is mainly caused by temperature definitions and discuss this possibility. Mazzotta et al. (2004) discovered using realistic simulations that the HE mass estimations with emission-weighted temperatures would be underestimated by $\sim 10\%$, and those with spectroscopic-like temperature would recover the input mass. When we estimate the HE masses with emission-weighted temperatures, the masses are indeed lower by $\sim 10\%$ than our results. Therefore, the possibility does not conflict with a difference between the two papers (Mahdavi et al. 2013; Smith et al. 2016). However, the current uncertainty in the averaged bias is too large to discuss the details. When we compile the full sample of 22 clusters, we expect that the uncertainty for the average bias will be comparable to those for previous studies for 50 clusters (Hoekstra et al. 2015; Smith et al. 2016). We will therefore compare WL and HE masses for the full sample, and investigate the redshift dependence and radial dependence of the mass bias.

6.7 Baryon fraction

The ratio of baryonic to total mass in massive clusters is expected to closely match the cosmic mean baryon fraction, $\Omega_b/\Omega_m$, measured from CMB experiments if baryons are trapped in potential wells (e.g., Evrard 1997; Kravtsov et al. 2005). However, the baryon budget in galaxy clusters is sensitive to non-gravitational processes; stars are formed...
from gas through radiative cooling, and AGN feedback may push the gas outside the potential well. Thus, measurements of the cluster baryon fraction are important to understand baryonic physics and the interplay between baryons and dark matter. Furthermore, assuming that the gas mass fraction is constant across redshifts, gas mass fraction measurements potentially provide a cosmological probe (e.g., Allen et al. 2008).

This paper focuses on the baryon fraction at Δ = 500 based on the HE mass, because the result based on the WL mass is statistically poor. We define gas and baryon fractions as follows:

\[
\begin{align*}
    f_{\text{gas}}(<r) &= \frac{M_{\text{gas}}(<r)}{M_{\text{HE}}(<r)}, \\
    f_b(<r) &= \frac{M_{\text{gas}}(<r) + M_*(<r)}{M_{\text{HE}}(<r)}.
\end{align*}
\]

Here, \(M_{\text{gas}}\), \(M_*\), and \(M_{\text{HE}}\) are gas, stellar, and HE masses, respectively. Gas mass is measured from X-ray analysis. Stellar masses are delivered from the deprojection estimation of the CAMIRA cluster catalog using the HSC-SSP five-band photometry (section 4). Measurement uncertainty of the total mass propagates through the over-density radius into gas and stellar masses. Figure 10 shows the gas and baryon fractions based on HE masses.

We also investigate how much the stellar mass estimation is changed if blue galaxies are included. We select blue galaxies whose colors are bluer by 1–3 σ than those of the red-sequence galaxies within \(r_{500}\), and estimate their stellar mass in a cylinder volume subtracted by (2–3)\(r_{500}\) as the background region. The total stellar masses change only by sub-percent. Even if we neither subtract the background components nor change the background region, the result does not significantly change. This is not surprising because the faint and blue galaxies are not dominant in cluster central regions, in contrast to the bright and red galaxies. We note that the stellar mass estimation for blue galaxies is in the cylinder volume because the characteristic spatial distribution for the blue galaxies makes us to carry out the deprojection method. We stress that we estimated the total stellar mass using red galaxies in a spherical volume using the deprojection method (section 4).

In contrast to previous observational studies (e.g., Lin et al. 2003; Vikhlinin et al. 2009b) showing that gas mass fraction increases and stellar mass fraction decreases with increasing total mass, we find no significant evidence of a halo mass dependence of \(f_{\text{gas}}\) and \(f_b\) in the current sample. The relation might be difficult to measure given the intrinsic scatter and the small sample size. We therefore focus on a comparison between the averages for \(f_{\text{gas}}\) and \(f_b\) for the current sample and the literature. Based on the defined selection function of the MCXC clusters, we compute unweighted averages of gas and baryon fractions for the four MCXC clusters.

To investigate the mass dependence of \(f_{\text{gas}}\) using the literature, we plot the averaged fraction enclosed within \(r_{500}\) and mass plane (left panel of figure 11). The average value is \(f_{\text{gas}} = 0.125 ± 0.012\), which is in agreement with previous studies based on HE mass or Sunyaev–Zel’dovich effect (SZE) mass (e.g., Vikhlinin et al. 2009a; Sun et al. 2009; Martino et al. 2014; Chiu et al. 2016) and based on WL masses (e.g., Zhang et al. 2010; Mahdavi et al. 2013; Okabe et al. 2014b). All points are unweighted averages from tables in the literature. Differences for those gas fractions at \(M_{500} \sim 2.4 \times 10^{14} h_{70}^{-1} M_\odot\) and \(\sim 7 \times 10^{14} h_{70}^{-1} M_\odot\) are ∼8% and ∼6%, respectively. However, the gas fraction of the XXL survey (Eckert et al. 2016) is systematically lower than in other studies in a wide mass range. The deviation is at the ∼5.3 σ level, where we use the 8% scatter. In our sample of the four MCXC clusters, the gas mass fraction is ∼0.8 ± 0.1 of the cosmic mean baryon fraction \(\Omega_b/\Omega_m\) for WMAP (Hinshaw et al. 2013) and ∼0.9 ± 0.1 for Planck (Planck Collaboration 2015a), though the two experiments have reported slightly discrepant results. The values are slightly higher than \(f_{\text{gas}}\Omega_m/\Omega_b \sim 0.6\) from numerical simulations (e.g., Kravtsov et al. 2005; Planelles et al. 2013; Battaglia et al. 2013).
Fig. 11. Comparison with the literature: gas fraction (left) and baryon fraction (right). Left: The red diamond is the average for \( f_{\text{gas}} \) for the four MCXC clusters. The blue circle, green square, and magenta cross are \( \langle f_{\text{gas}} \rangle \) from Martino et al. (2014), Mahdavi et al. (2013), and Okabe et al. (2014b), respectively. The blue, green, magenta, and red solid lines are scaling functions between gas fraction and mass from Vikhlinin et al. (2009a), Sun et al. (2009), Chiu et al. (2016), and Eckert et al. (2016), respectively. The dotted lines are 1σ uncertainties of the scaling functions. For simplicity, we plot \( \Omega_{b}/\Omega_{m} \) for WMAP (Hinshaw et al. 2013). Upper superscripts denote methods of total mass estimation. Right: The white diamond is the average for \( f_{b} \) for the four MCXC clusters, derived by this study. The blue, green, cyan, and magenta solid lines are scaling functions between baryon fraction and mass from Lin, Mohr, and Stanford (2003), Lagané et al. (2011), Giodini et al. (2009), and Chiu et al. (2016) respectively. (Color online)

The average baryon fraction for the four MCXC clusters, \( (f_{b}) = 0.146 \pm 0.012 \), is comparable to \( \Omega_{b}/\Omega_{m} \) (right panel of figure 11). Our result is also comparable to previous observational studies (Lin et al. 2003, 2012; Giodini et al. 2009; Lagané et al. 2011; Chiu et al. 2016). The difference between those baryon fractions at \( M_{500} \sim 2.4 \times 10^{14} h^{-1} M_{\odot} \) is only \( \sim 7\% \). There are some discrepancies in \( f_{b} \) even between different numerical simulations. Kravtsov, Nagai, and Vikhlinin (2005) have shown that the total baryon fraction agrees with \( \Omega_{b}/\Omega_{m} \), while Planelles et al. (2013) have pointed out that it accounts for \( \sim 85\% \) because some fraction of gas is displaced outside potential wells by AGN activities.

We also note that if there were HE mass bias then the gas and baryon fractions would be overestimated. Observations of baryon budget in galaxy clusters are still open questions. Since small clusters and groups are sensitive to baryonic physics (e.g., Kravtsov et al. 2005; Planelles et al. 2013; Battaglia et al. 2013), future progress of the HSC-SSP survey and future studies based on WL masses will play a key role in this subject.

7 Summary

We selected X-ray luminous clusters from the MCXC cluster catalog (Piffaretti et al. 2011) to measure HE masses for galaxy clusters in the HSC-SSP survey region. Based on the XMM-Newton and HSC-SSP datasets, we carried out a multiwavelength study of four MCXC clusters in the S16A field and a non-MCXC cluster associated with one MCXC cluster.

We found a correlation between cluster richness and HE mass for the MCXC clusters. The mass normalization agrees with expectations by comparing the CAMIRA cluster abundance with a theoretical prediction of cluster mass function with \( \sigma_{8} = 0.82 \) (Oguri et al. 2018). However, an infalling cluster to one MCXC cluster is highly deviant from the scaling relation, which could be caused by mass underestimation and/or richness overestimation. The average cluster gas mass fraction based on HE masses, \( (f_{b}) = 0.146 \pm 0.012 \), accounts for \( \sim 80\%\sim 90\% \) of the cosmic mean baryon fraction. In comparison with gas and baryon fractions from the literature based on various mass measurements (Vikhlinin et al. 2009a; Sun et al. 2009; Giodini et al. 2009; Mahdavi et al. 2013; Martino et al. 2014; Okabe et al. 2014b; Eckert et al. 2016; Chiu et al. 2016), our measurements are somewhat higher than previous studies but agree overall. Differences of gas and baryon fractions between these studies are \( \sim 8\% \) and \( \sim 7\% \) at \( M_{500} \sim 2.4 \times 10^{14} h^{-1} M_{\odot} \), respectively. We also note the possibility that the average gas and baryon fraction is somehow overestimated if there were an HE mass bias. Therefore, future studies using WL masses for a large number of clusters/groups will be important to understand the baryon budgets and improve the current quality level.
The full-depth and full-color condition of the HSC-SSP survey allows us to compare HE mass with WL mass for the three clusters. The estimated mass bias, $b_m = 0.44^{+0.31}_{-0.45}$, allows for the possibility that the HE masses agree with the WL ones. In order to quantify the validity of the HE assumption, we need to carry out WL analysis for the full sample of clusters.

Further joint studies using a large number of clusters are vitally important to improve statistical uncertainty. Pointed X-ray observations with XMM-Newton and Chandra with sufficient integration times are essential to fairly compare X-ray observables with WL and optical measurements. The approach is complementary to the forthcoming X-ray survey from eROSITA, whose typical exposure in the HSC-SSP survey region is too shallow to estimate HE masses. A collaboration with the ongoing XXL survey is powerful for understanding cluster physics and carrying out cluster-based cosmology. In similar ways, joint studies with the ACTPol SZE observations (H. Miyatake et al. in preparation) provide us with a unique route for cluster studies. Future studies based on survey-type datasets will also reveal how much cluster properties are changed by cluster selection methods, like X-ray, SZE, optical, and WL techniques. The paper has demonstrated the power and impact of the HSC-SSP survey on other wavelengths and shown the first result of a series of multiwavelength studies.

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Appendix 1. Results of spectral fit

We summarize the results of the simultaneous fit for the spectrum in table 4. The technical details are described in section 3.
| Cluster name         | Annulus* | counts±error† | Temperature‡ | Abundance‡ |
|---------------------|----------|---------------|--------------|------------|
|                     | (″)      | MOS1 MOS2 PN  | (keV)        | (Z⊙)      |
| MCXC J0157.4−0550   | 0–60     | 834 829 1400  | 3.51±0.32−0.26 | 0.26       |
|                     | 60–100   | 1038 1163 1975| 3.02±0.27−0.22 | 0.18       |
|                     | 100–140  | 1196 1267 1955| 3.28±0.33−0.25 | 0.18       |
|                     | 140–180  | 1228 1303 2085| 2.84±0.30−0.23 | 0.20       |
|                     | 180–270  | 2867 2732 4647| 2.73±0.28−0.13 | 0.16       |
|                     | 270–360  | 2920 2640 5306| 2.54±0.31−0.10 | 0.10       |
|                     | 360–600  | 7778 8959 17871| —           | —          |
|                     | 600–900  | 3117 5036 13795| —           | —          |
| MCXC J0231.7−0451   | 0–40     | 1411 1355 3084| 5.64±0.40 0.52 | 0.12       |
|                     | 40–60    | 1381 1353 2739| 5.03±0.37−0.37 | 0.12       |
|                     | 60–80    | 1339 1229 2492| 4.33±0.26 0.27 | 0.46       |
|                     | 80–100   | 1182 1198 2455| 5.03±0.47 0.47 | 0.33       |
|                     | 100–140  | 1936 1882 3737| 4.09±0.32−0.22 | 0.20       |
|                     | 140–180  | 1155 1174 2052| 4.50±0.44 0.44 | 0.20       |
|                     | 180–270  | 1665 1591 3373| 3.10±0.38 0.38 | 0.20       |
|                     | 270–400  | 1633 1798 4002| —           | —          |
|                     | 270–360  | —           | —           | —          |
| MCXC J0201.7−0212   | 0–40     | 7690 7369 16494| 3.30±0.05−0.05 | 0.41       |
|                     | 40–60    | 2617 2379 4139| 4.23±0.36−0.36 | 0.28       |
|                     | 60–80    | 1649 1686 3218| 4.26±0.48−0.36 | 0.14       |
|                     | 80–100   | 1157 1151 2440| 4.47±0.58−0.69 | 0.14       |
|                     | 100–140  | 1667 1710 3198| 3.38±0.41−0.40 | 0.17       |
|                     | 140–180  | 1044 1034 1750| 4.28±0.67−0.49 | 0.17       |
|                     | 180–270  | 1596 1719 2486| 2.43±0.27−0.28 | 0.17       |
|                     | 270–400  | 1324 1502 2463| —           | —          |
|                     | 270–360  | —           | —           | —          |
| MCXC J1415.2−0030   | 0–50     | 509 519 889  | 3.13±0.25−0.23 | 0.22       |
|                     | 50–90    | 690 683 1102  | 3.99±0.46−0.41 | 0.29       |
|                     | 90–140   | 761 736 1522  | 3.00±0.31−0.34 | 0.47       |
|                     | 140–180  | 481 444 890  | 2.03±0.34−0.38 | 0.21       |
|                     | 180–270  | 969 953 1984  | 1.71±0.12−0.13 | 0.12       |
|                     | 270–360  | 1302 1225 2653| —           | —          |
| MCXC J1415.2−0030W  | 0–80     | 191 229 417  | 2.06±0.29−0.22 | 0.34       |
|                     | 80–140   | 198 246 430  | 1.80±0.34−0.28 | 0.33       |
|                     | 140–270  | 772 803 1473 | —           | —          |

*Cluster-centric annulus.
†Counts in the energy band of 0.3–11 keV of each instrument.
‡Best-fit temperature and abundance.
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