Central Mass Profiles of the Nearby Cool-core Galaxy Clusters Hydra A and A478

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ABSTRACT
We perform a weak-lensing study of the nearby cool-core galaxy clusters, Hydra A ($z = 0.0538$) and A478 ($z = 0.0881$), of which brightest cluster galaxies (BCGs) host powerful activities of active galactic nuclei (AGNs). For each cluster, the observed tangential shear profile is well described either by a single Navarro–Frenk–White model or a two-component model including the BCG as an unresolved point mass. For A478, we determine the BCG and its host-halo masses from a joint fit to weak-lensing and stellar photometry measurements. We find that the choice of initial mass functions (IMFs) can introduce a factor of two uncertainty in the BCG mass, whereas the BCG host halo mass is well constrained by data. We perform a joint analysis of weak-lensing and stellar kinematics data available for the Hydra A cluster, which allows us to constrain the central mass profile without assuming specific IMFs. We find that the central mass profile ($r < 300$ kpc) determined from the joint analysis is in excellent agreement with those from independent measurements, including dynamical masses estimated from the cold gas disk component, X-ray hydrostatic total mass estimates, and the central stellar mass estimated based on the Salpeter IMF. The observed dark-matter fractions around the BCGs for the two clusters are found to be smaller than those predicted by adiabatic contraction models, suggesting the importance of other physical processes, such as the AGN feedback and/or dissipationless mergers.

Key words: galaxies: clusters: individual (Hydra A, A478) - gravitational lensing: weak

1 INTRODUCTION
The standard cold-dark-matter (CDM) paradigm excellently describes the statistical properties and growth
of cosmic structure from the early universe to the present day epoch, as observed from the cosmic microwave background radiation (e.g. Hinshaw et al. 2013; Planck Collaboration et al. 2013) and large scale clustering of galaxies (e.g. Percival et al. 2001; Anderson et al. 2014). Cosmological simulations of collisionless dark matter halos formed by collisionless gravitational dynamics is nearly universal and self-similar over wide mass ranges (Navarro, Frenk & White 1996, hereafter NFW). The spherically-averaged density profile exhibits a soft cusp ($\rho \propto r^{-1}$) in the center and has steeper slopes at larger halo radii ($\rho \propto r^{-3}$ in the outskirts). Recent observations of stacked weak gravitational lensing signals for massive galaxy clusters at $z \sim 0.2$ (Oguri et al. 2012; Okabe et al. 2013; Umetsu et al. 2011, 2014) revealed that the observed cluster lensing profiles are in excellent agreement with the NFW density profile predicted for collisionless dark halo. However, since the innermost cluster radius for weak lensing is typically limited to $r \sim 100 h^{-1}$ kpc due to the finite resolution of weak-lensing observations, it is practically difficult to directly constrain the innermost cluster mass distribution around bright cluster galaxies (BCGs).

The total mass density profiles of clusters in the central region have been subject of intense theoretical and observational studies. Numerical simulations of collisionless dark matter show that the central cusp slope of dark-matter halos is not strongly self similar (Gao et al. 2012). Baryonic effects cannot be ignored in the central region where the cooling time is shorter than the Hubble time and rich stellar populations within BCGs are abundant. Stars form from radiative gas cooling, and subsequently dark matter is pulled inward in response to the central condensation of baryons. A cuspy dark-matter density profile is formed through such energy exchange processes between dark matter and baryons, which is referred to as adiabatic contraction (e.g. Frenk, Cen & Navarro 1996; Blumenthal et al. 1986; Gao et al. 2003; Gnedin et al. 2004). On the other hand, if BCGs are formed by the accretion of dark matter to luminosity and stellar mass, whereas the stellar initial mass function (IMF) governs the normalization of the stellar mass to luminosity relation. Hence, the uncertainty of the stellar IMF can give rise to a systematic bias in stellar mass estimates. In order to break the degeneracy between the IMF uncertainty and the inner slope of the mass density profile, Oguri, Rusu & Falco (2014) proposed to use quasar microlensing observations.

We have two ideal clusters, Hydra A ($z = 0.0538$; Sato et al. 2012) and Abell 478 ($z = 0.0881$; Mochizuki et al. 2014), to study the mass distributions within both clusters and BCGs. The two clusters have been selected and observed as targets of joint Subaru weak-lensing and Suzaku X-ray studies (Okabe et al. 2014b). They are well-known cool-core clusters hosting central AGNs inside their BCGs. Recent X-ray and radio observations (e.g. McNamara et al. 2004; David et al. 2001; Wise et al. 2007; Sun et al. 2003; Sanders et al. 2003; Diehl et al. 2008) have shown that giant radio lobes triggered by prominent AGN jets are interacting with the surrounding intracluster medium (ICM). Isobaric cooling time scales in the central region are shorter than 1 Gyr. Hence, the clusters provide us with unique environments for studying the effects of baryons acting on the dark-matter distribution in the cluster center. Since these clusters are at very low redshifts, their large angular extents enable us to detect weak-lensing signals around the BCGs, in particular for Hydra A, and to measure the radial mass distribution, by using the unique combination of weak lensing and stellar kinematics or stellar photometry. For these very nearby clusters, strong-lensing information is not needed to resolve the central matter distribution.

This paper is organized as follows. In Section 2, we conduct shape measurements, examine the redshift dependence of the contamination level by member galaxies, and securely select background galaxies. We measure cluster masses in Section 3, perform joint analyses in Section 4, and discuss the results in Section 5. Section 6 is devoted to the summary. A comparison of weak-lensing masses and Suzaku X-ray observables is given in our previous paper (Okabe et al. 2014b). We use $\Omega_{m,0} = 0.27$, $\Omega_{\Lambda} = 0.73$ and $H_0 = 70 h_{70} \text{km s}^{-1} \text{Mpc}^{-1}$.

2 DATA ANALYSIS

2.1 Data Analysis and Shape Measurement

We conducted observations of Hydra A and Abell 478 using the Subaru/Suprime-cam (Miyazaki et al. 2002), in $i'$ and $g'$ bands, on Jan 7th, 2013. The $i'$ imaging was taken to measure ellipticities of galaxies for the weak-lensing shape analysis. The two-band photometry in the $g'$ and $i'$ bands is to minimize contamination of the background source catalog by unlensed cluster member galaxies. The Hydra A and Abell 478 fields are covered by a mosaic of 8 and 9 pointings, respectively, as shown in Figure 1. We note that, for Hydra A, the middle-east pointing was not available as limited by A, the middle-east pointing was not available as limited by the number of allocated nights and bright stars in that region. The observing conditions are summarized in Table 1. The typical seeing is $\sim 0.7''$ in the $i'$ band for weak-lensing shape measurements. The exposure times for the $i'$ and $g'$ bands are $\sim 15$ and $\sim 12$ min, respectively. These are about...
Table 1. Summary of Subaru observations for Hydra A and Abell 478. Each pointing is shown in Figure 4. The seeing FWHM is for the i′-band used for shape measurements.

| Name       | i′ [arcsec] | g′ [arcsec] | Seeing [arcsec] |
|------------|-------------|-------------|-----------------|
| HYDRAA_00  | 15.0        | 11.7        | 0.75            |
| HYDRAA_02  | 15.0        | 10.0        | 0.71            |
| HYDRAA_10  | 15.0        | 11.7        | 0.73            |
| HYDRAA_11  | 15.0        | 11.2        | 0.71            |
| HYDRAA_12  | 15.0        | 10.0        | 0.63            |
| HYDRAA_20  | 15.0        | 11.7        | 0.67            |
| HYDRAA_21  | 15.0        | 11.2        | 0.71            |
| HYDRAA_22  | 15.0        | 10.0        | 0.65            |
| ABELL478_00| 15.0        | 11.7        | 0.67            |
| ABELL478_01| 15.0        | 11.7        | 0.79            |
| ABELL478_02| 15.0        | 11.7        | 0.73            |
| ABELL478_10| 15.0        | 11.7        | 0.65            |
| ABELL478_11| 15.0        | 11.7        | 0.79            |
| ABELL478_12| 15.0        | 11.7        | 0.71            |
| ABELL478_20| 15.0        | 14.0        | 0.69            |
| ABELL478_21| 15.0        | 11.7        | 0.69            |
| ABELL478_22| 15.0        | 11.7        | 0.71            |

Half of those typically used in our previous weak-lensing studies of intermediate-redshift clusters at $z \sim 0.2$ (e.g., Okabe & Umetsu 2008; Okabe et al. 2010, 2011, 2013). We used the standard Suprime-Cam reduction software SDFRED (Yagi et al. 2002; Ouchi et al. 2004) modified to accommodate new CCD chips, for flat-fielding, instrumental distortion correction, differential refraction, point-spread-function (PSF) matching, sky subtraction and stacking. An astrometric calibration was conducted with 2MASS point sources (Skrutskie et al. 2006). Typical residual astrometric offsets are no larger than the CCD pixel size.

We determine the mass distribution in nearby clusters using weak gravitational lensing. Weak lensing analysis is performed following Kaiser, Squires & Broadhurst (1993) with some modifications (Okabe et al. 2014). Technical details are described in Okabe et al. (2014a). The image ellipticity $e_\alpha$ of an object detected in the i′ band data is measured from weighted quadrupole moments of the surface brightness distribution. The PSF anisotropy is corrected for using second-order binomial functions of the stellar anisotropy kernel, which is expressed with KSB’s smear polarizability tensor and image ellipticity of unsaturated stars. To examine the validity of anisotropic PSF corrections, we have checked residual systematics in corrected ellipticities as described in Appendix of Okabe et al. (2014a). Two-point correlation functions between star and galaxy ellipticities after the correction are of the order of $10^{-8}$–$10^{-6}$, significantly improved from $10^{-5}$–$10^{-4}$ before the correction. This level of residual correlations is consistent with zero. The reduced shear signal is obtained by applying a correction for the isotropic smearing effect as $g_{\alpha\beta} = (P_{\alpha\beta})_{\delta=0} e_\alpha e_\beta$. Here, $e_\alpha$ is the image ellipticity after the anisotropic PSF correction and $P_{\alpha\beta}$ is the pre-seeing shear polarizability tensor. Since the measurement of $P_{\alpha\beta}$ is very noisy for faint individual galaxies, $P_{\alpha\beta}$ is calibrated using galaxies detected with high signal-to-noise ratio $\nu > 30$, following Okabe et al. (2014a). Similar calibration procedures are developed by Umetsu et al. (2010) and Oguri et al. (2012). Our shear calibration on $g_\alpha$ results in 2–3% accuracy (Okabe et al. 2014a).

We measure magnitudes of galaxies using SExtractor (Bertin & Arnouts 1996). The SExtractor configuration is optimized for shape measurements of faint galaxies. For each object, we compute a total Kron-like magnitude and an aperture magnitude for color measurements in the AB-magnitude system. To perform color measurements, the i′-band data are degraded to the PSF of g′-band data. For aperture photometry, the aperture diameter is set to 1.5 times the worst-seeing FWHM. Finally, we combine SExtractor-based photometry with weak-lensing shape measurements to create a weak-lensing-matched photometry catalog.

2.2 Background Selection

It is of prime importance for an accurate mass measurement to securely select background galaxies. Contamination of unlensed member and/or foreground galaxies in the shear catalog leads to a systematic underestimation of cluster lensing mass, referred to as a dilution effect (e.g., Broadhurst et al. 2003; Umetsu & Broadhurst 2003; Umetsu et al. 2010; Okabe et al. 2010, 2011, 2013). We used SExtractor-based photometry with weak-lensing shape measurements to create a weak-lensing-matched photometry catalog.
In order to clarify the dilution effect in noisy lensing signals, the mean distortion strength is cumulatively computed as a function of color offset from the red sequence, \( \Delta C \). We choose the central region of \( 100 - 500 h^{-1} \) kpc from brightest cluster galaxies (BCGs). We also compute the mean lensing depth \( \langle D_{ls}/D_s \rangle \). Since it is difficult to estimate photometric redshifts of individual objects using two bands, we used the COSMOS photometric redshift catalog \((\text{Ilbert et al. 2009})\) estimated by combining 30 bands. The mean photometric redshift is computed with a statistical weight of \( w_g \) by matching with the COSMOS photometric redshift in color-magnitude plane. If there were no contamination of unlensed member galaxies, it is expected that a “Dilution” estimator, which is defined by the ratio between the mean lensing signal and depth, \( D = (g+)/\langle D_{ls}/D_s \rangle (> \Delta C) \), is constant irrespective of the lower limit of the color offset, \( \Delta C \). Here, \( D_{ls} \) and \( D_s \) are the angular diameter distance between cluster (lens) and source redshifts and between observers and source redshifts, respectively. Therefore, \( D \) is a good estimator to investigate the color distribution of member galaxies.

The resultant \( D \) is shown in the top panel of Figure 2. The red diamonds and blue circles denote \( D \) for A478 and Hydra A, respectively. Although the error is large, \( D \) for A478 is constant at \( \Delta C \sim 0 \), increases with \( \Delta C \) at \( \Delta C \sim 0.1 \), and becomes flat at \( \Delta C > 0.3 \). The small \( D \) at \( \Delta C \sim 0 \) indicates a presence of member galaxies. On the other hand, \( D \) of Hydra-A shows a random distribution for \( \Delta C \), suggesting no significant feature of the contamination. We model a color distribution of \( D \), given by \( A + B \tanh(\Delta C - \Delta C_0)/\sigma \). Here, \( A \) is the normalization at \( \Delta C = 0 \), \( A + B \) is a mean lensing strength of pure background galaxies, and the second term represents a constant \( D \) at \( \Delta C \sim 0 \) and \( \Delta C > 0.3 \). As shown in Figure 2, the best-fit model (red solid line) of A478 well describes the data. As for Hydra A, the best-fit model is consistent with no contamination. We derive a color distribution of contamination level of unlensed galaxies in background shear catalog (the bottom panel of Figure 2). The maximum contamination level is at most 17% at \( \Delta C = 0 \). In order to investigate a cluster-redshift dependence of the dilution effect, we compute the mean \( D \) within the same physical radius for 50 clusters at \( z \sim 0.2 \) from the Local Cluster Substructure Survey (LoCuSS). Here, \( \Delta C \) is the color offset from the red sequence in the \( i'-V \) band. The calculation and model for stacked 50 clusters are described in \((\text{Okabe et al. 2013})\). The maximum contamination level for 50 clusters (green dashed line in the bottom panel) is \( \sim 40\% \) at \( \Delta C = 0 \). The virial mass of A478 is even massive than the average of 50 clusters (Section 3 and our data is shallower than those of 50 clusters, but nonetheless the contamination is less than half of those of clusters \( z \sim 0.2 \).

There are two reasons for low contamination of the very nearby cluster (\( z \sim 0.09 \)). First, since the colors of red-sequence galaxies become more blue as the redshift decreases, the number of red background galaxies increases. Second, the ratio of member to background galaxies for very nearby clusters becomes lower because an apparent covering area becomes larger. Therefore, the dilution effect for clusters at lower redshifts becomes drastically less significant. It is consistent with the feature of the very nearby cluster of Hydra-A (\( z \sim 0.05 \)).

In order to securely select background galaxies, we employ 1% contamination level following \((\text{Okabe et al. 2013})\) and define background galaxies with \( \Delta C > 0.17 \) for A478. As for Hydra A, we do not apply the color cut because of the tiny contamination level, because \( D \) is almost constant in the wide color range of \( -1 < \Delta C < 1 \). In order to assess our background selection for Hydra A, we make another background catalog selected with the same color cut of A478.
LoCuSS: 50 clusters simulations of dark matter particles. They found that the icoanly well-motivated mass model according to numerical 5 + 28 bin with the statistical weight of w. The other distortion component, g_x, which is the 45 degree rotated component, is also estimated. Hereafter, we refer to \( g_{+,(\times),i} \) as \( g_{+,(\times),i} \).

In order to interpret the lensing signals, we introduce mass models as the cluster mass density profile. The NFW model (Navarro, Frenk & White 1996, 1997) is a theoretically well-motivated mass model according to numerical simulations of dark matter particles. They found that the matter density profile of CDM halos is well described by an analytic function

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

where \( \rho_s \) is the central density parameter and \( r_s \) is the scale radius. The asymptotic mass density slopes are \( \rho \propto r^{-1} \) and \( r^{-3} \) for \( r \ll r_s \) and \( r \gg r_s \), respectively. The NFW profile is specified by two parameters of \( M_\Delta \) which is a mass enclosed within a sphere of radius \( r_\Delta \) and the halo concentration \( c_\Delta = r_\Delta/r_s \). Here, \( r_\Delta \) is the radius inside of which the mean density is \( \Delta \) times the critical mass density, \( \rho_{cr}(z) \), at the redshift, \( z \). For a comparison, we model a singular isothermal sphere (SIS) profile for the main halo, given by

\[
\rho_{\text{SIS}}(r) = \frac{\sigma_v^2}{2\pi G r^2},
\]

where \( \sigma_v^2 \) is a one-dimensional velocity dispersion. We also consider the BCG mass model to estimate the lensing signals for the BCGs. Since the innermost radii for the profiles are outside the BCGs, we apply the point mass, \( M_{\text{pt}} \), to estimate the BCG mass, in terms of \( g_+(r) \propto M_{\text{pt}}/(\pi r^2) \).

Given specific mass models, we perform \( \chi^2 \) fit to the tangential shear profile, \( g_+ \). The \( \chi^2 \) is defined as follows:

\[
\chi^2 = \frac{\sum_{i,j} (g_{+,(\times),i} - g_{+,(\times),i}^{\text{model}}) C_{ij}^{-1} (g_{+,(\times),j} - g_{+,(\times),j}^{\text{model}})}{\sum_{ij} 2 \delta_{ij}},
\]

where

\[
C_{ij} = C_{\text{stat},ij} + C_{\text{LSS},ij}.
\]

The first term of \( C \) is the statistical noise relevant to the intrinsic ellipticity of background galaxies. The statistical noise for the shear is given by \( C_{\text{stat},ij} = \sigma^2_{g_i,j} \delta_{ij}/2 \), where \( \sigma_{g_i,j} \) is the statistical uncertainty of the two components in the \( i \)-th radial bin and \( \delta_{ij} \) is Kronecker’s delta. The second term, \( C_{\text{LSS},ij} \), is the error covariance matrix of uncorrelated large-scale structure (LSS) along the line-of-sight, (e.g. Schneider et al. 1998, Hoekstra 2003, Umetsu et al. 2011, 2014, Oguri et al. 2014, Oguri & Takada 2011, Okabe et al. 2014, 2014a), estimated from the weak-lensing power spectrum with WMAP7 cosmology (Komatsu et al. 2011). The cosmic shear correlation function leads to non-zero off-diagonal elements for \( C_{\text{LSS},ij} \).

The signal-to-noise ratio (S/N) for the tangential shear profile is computed by

\[
\left( \frac{S}{N} \right)^2 = \sum_{ij} g_{+,(\times),i} C_{ij}^{-1} g_{+,(\times),j},
\]

3 MASS MEASUREMENTS

Tangential distortion signals contain full information on the lensing signals of clusters. Since clusters can be considered as gravitationally bound spherical objects at zeroth order, a measurement of tangential shear profile is a powerful way to measure cluster masses. The tangential shear is measurable by averaging over sufficient background galaxies, in order to suppress shape noise attributable to random intrinsic ellipticities of background galaxies. We measure a mean tangential shear \( g_{+,(\times),i} \) as an average of the tangential shear component of background galaxies residing in the \( i \)-th radial bin with the statistical weight of \( w_g \). The other distortion component, \( g_x \), which is the 45 degree rotated component, is also estimated. Hereafter, we refer to \( g_{+,(\times),i} \) as \( g_{+,(\times),i} \).

In order to interpret the lensing signals, we conduct a weak lensing mass measurement (Section 3) and confirm the result does not change. The background number densities for A478 and Hydra A are \( n_{\text{bkg}} = 6.2 \text{[arcmin}^{-2}] \) and 28.9 [arcmin\(^{-2}\)], respectively. The mean source redshifts for A478 and Hydra A are \( \langle z_s \rangle \approx 0.643 \) and \( \langle z_s \rangle \approx 0.591 \), respectively.

3.1 A478

The tangential reduced-shear profile for A478 is shown in Figure 3 in a range of 100kpc \( \lesssim r \lesssim 5.5 \text{Mpc} \). The innermost radius is determined by requiring a sufficient number of background galaxies. The S/N of the tangential shear profile is 8.1. The tangential shear profile exhibits a clear curvature. On the other hand, the B-mode, \( g_x \), shows both negative and positive values, which is consistent with null signal. We plot \( \theta \cdot g_x(\theta) \) in the bottom panel of Figure 4 so that the scatter is independent of radius for logarithmically spaced binning (Miyatake et al. 2013).

We fit a single NFW model or two components of the central mass profiles of Hydra A and A478.
For instance, an innermost radius of a stacked lensing study of very nearby clusters, because cluster central regions at higher redshifts are randomly distributed across the full signal. In order to estimate the validity of the additional point source, we calculated F test probability. 0.7, indicating that there is no strong reason to add the point source to describe the current data. The best-fit SIS profile (σr = 958 ± 76 ± 111 km s⁻¹) is highly deviated from the data, albeit still acceptable (χ²/ν (d.o.f) = 9.13(8)).

3.2 Hydra A

A large apparent size of Hydra A allows us to estimate the tangential shear profile in a wide radial range of 30 kpc < r < 3 Mpc, as shown in Figure 4. In particular, lensing signals at r < 50 kpc is detected solely by weak-lensing analysis. It is an advantage of weak-lensing study of very nearby clusters, because cluster central regions at higher redshifts are in the strong-lensing regime. For instance, an innermost radius of a stacked lensing profile for 50 clusters z ∼ 0.2 [Okabe et al. 2013] is 70h⁻² kpc. The tangential profile is highly detected at S/N = 7.0. The profile shows two characteristic features: a sharp decrease in the central region (r < 100 kpc) and a clear curvature in the range of 100 kpc < r < 3 Mpc. The B-mode values, gB, are randomly distributed across the null signal.

First, we fit the profile with the NFW model and obtain a high concentration parameter cvir = 9.37 ± 2.99 with virial mass Mvir = 2.74 ± 1.21 × 10¹⁴ M₀. The best-fit mass profile shows a clear curvature (Figure 4). However, we found that the best-fit model is lower than the observed lensing signals at r < 50 kpc and r < 2 Mpc. It suggests that the virial mass is underestimated because the mass estimate is sensitive to lensing signals in the outskirts. A similar deviation is found in the best-fit SIS model (σr = 631 ± 21 ± 33 km s⁻¹). On the other hand, when we fit the NFW model to the lensing profile beyond 150 kpc, the best-fit concentration becomes lower cvir = 4.52 ± 1.75 (Table 2). The best-fit profile well describes the data at r > 300 kpc, but significantly underestimates the signals at r > 100 kpc.

It indicates that the inner slope of the tangential profile becomes steeper than expected from the outskirts. The steep inner slope suggests one possibility that an extra component exists inside the innermost radius. In particular, the slope for the lensing profile at a few inner bins is proportional to ∼ −2. We thus consider two components of the NFW model and the point mass (NFW+point). The best-fit parameters are shown in Table 2. The χ²/ν (d.o.f) is improved from 8.62(18) to 4.02(17). The best-fit profile well describes the data in the full radial range (Figures 4). In order to estimate the validity of the additional point source, we conducted F test and found that the probability 4 × 10⁻² is significantly small. It is thus reasonable to add the extra component to the smooth mass component for describing the observed lensing signals. In other words, the two-components model better describes the tangential profile.
4 JOINT ANALYSES

4.1 Joint Weak-lensing and Stellar Photometry Study of A478

We study the mass distribution of A478 using weak-lensing and BCG (PGC014685) photometry measurements.

The tangential shear profile (Section 3.1) for A478 is well described by a single NFW model or a two-component mass model including the BCG as an unresolved point mass. Complementary information at small scales is useful to directly determine the BCG mass profile as well as to better constrain the total mass profile in combination with lensing data.

For this purpose, we use stellar mass estimates of the BCG from a photometry. We estimate the stellar mass for the BCG using K-band photometry using the K-correction and galactic extinction from 2MASS extended source catalog (Skrutskie et al. 2000). Since the K-band luminosity is sensitive to the light of old stars and less sensitive to recent star-formation activities, it serves as a reasonable proxy for stellar mass. The difference in K-band transmission between the 2MASS and traditional Johnson K filters is not important for our purpose (Carpenter 2001). We employ both empirical (Arnouts et al. 2007) and theoretical (Lombrini & Saracco 2000) scaling relations between the stellar mass and K-band luminosity. We consider the Salpeter (Salpeter 1955), Chabrier (Chabrier 2003) and Kroupa (Kroupa 2001) IMFs. The mass uncertainty is estimated by taking into account the photometric errors, 15% intrinsic scatter for the empirical scaling relation (Arnouts et al. 2007), and systematic uncertainties from different scaling relations.

We assume a pseudo isothermal mass distribution (PIEMD) model (Eliaflottir et al. 2007; Limousin et al. 2004; Natarajan et al. 2006) to describe the stellar mass distribution of the BCG. The PIEMD model is specified with three parameters, namely, the core radius (a), the scale radius (s), and the normalization (p0), in the following form:

\[ \rho = \frac{p_0}{(1 + r^2/a^2)(1 + r^2/s^2)} \quad (s > a). \]  

(6)

The core and scale radii are determined from the light distribution of the BCG. We find the best-fit solution by minimizing the combined \( \chi^2 \) function, \( \chi^2 = \chi^2_0 + \chi^2_\delta \), with \( \chi^2_\delta \) defined by

\[ \chi^2_\delta = \frac{(M_\delta - M_{\text{PIEMD}}(s))^2}{\delta^2_{M_\delta}}. \]  

(7)

Here, \( M_\delta \) and \( \delta_{M_\delta} \) are the stellar mass and its uncertainty in the measurement radius 17 kpc, respectively. We determine the normalization of the PIEMD model and the NFW parameters from a joint fit.

Figure 5 shows the best-fit model for the tangential shear profile and BCG stellar mass profile (inset) for A478. The red-solid line represents the best-fit solution for the total lensing signal with the NFW (blue-dotted line) plus BCG (Salpeter IMF) model. The green-dotted and magenta-dashed lines show the best-fit lensing profiles and BCG stellar mass profiles, obtained with the Salpeter and Chabrier IMFs, respectively.

![Figure 5](image)

| Table 2. Mass estimates for Hydra A and A478. The NFW mass \( M_{\text{NFW}} \) and the point mass \( M_{\text{pt}} \) are in units of \( 10^{14} h^{-1} M_\odot \) and \( 10^{12} h^{-1} M_\odot \), respectively. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Cluster         | model & method  | \( M_{\text{NFW}}^{\text{vir}} \) | \( M_{\text{NFW}}^{200} \) | \( M_{\text{NFW}}^{500} \) | \( M_{\text{NFW}}^{1000} \) | \( M_{\text{NFW}}^{2500} \) | \( M_{\text{pt}} \) |
| A478            | NFW            | 16.38^{+5.70}_{-4.41} | 12.93^{+3.96}_{-3.22} | 8.67^{+1.24}_{-1.98} | 5.95^{+1.28}_{-1.17} | 3.17^{+0.72}_{-0.67} | -- |
| A478            | NFW+point      | 16.72^{+6.30}_{-4.65} | 13.05^{+4.12}_{-3.36} | 8.56^{+1.19}_{-1.97} | 5.74^{+1.55}_{-1.23} | 2.93^{+1.28}_{-1.22} | < 25.90 |
| Hydra A         | NFW \( (r > 150 h_70^{-1}\text{kpc}) \) | 4.66^{+2.27}_{-1.31} | 3.62^{+1.85}_{-1.31} | 2.40^{+0.95}_{-0.76} | 1.63^{+0.55}_{-0.46} | 0.85^{+0.29}_{-0.26} | -- |
| Hydra A         | NFW+point (full radial range) | 4.88^{+3.29}_{-2.04} | 3.66^{+1.41}_{-1.41} | 2.27^{+0.98}_{-0.77} | 1.43^{+0.55}_{-0.46} | 0.64^{+0.32}_{-0.31} | 6.10^{+2.47}_{-2.50} |
4.2 Joint Weak-lensing and Stellar Kinematics

**Study of Hydra A**

The tangential shear profile for the Hydra A cluster is well described by the two-component mass model of the BCG’s point mass and the smooth NFW profile. The smooth mass component is determined by fitting lensing signals at outer cluster radii, whereas the point mass measurement is sensitive to lensing signals at innermost bins because the BCG lensing signal is embedded in the lensing signals of the main cluster. Recently, Newman et al. (2009, 2011, 2013) performed a joint analysis of weak/strong-lensing and stellar kinematics data to break the IMF uncertainty and measure the mass profile from the BCG to the cluster main halo. They demonstrated that the BCG stellar kinematics is powerful for determining the BCG mass profile and the cluster inner mass profile under two assumptions of dynamic equilibrium and mass tracing light. Following their pioneering studies, we here conduct a joint weak-lensing and stellar-kinematics analysis of Hydra A. We note that there are no publicly available data of stellar kinematics for A478. Since the Hydra A cluster is at a very low redshift, strong-lensing information is not required for our joint analysis.

We here summarize the dynamical properties of the BCG (3C218). It is well known that the AGN in the BCG ejects a pair of jets, showing interaction between the jets and surrounding ICM (McNamara et al. 2000). Fujita et al. (2013) have discovered a dusty lane in the central region of the BCG (4 kpc × 0.8 kpc). The major axis is along the east-west direction, nearly perpendicular to the jet axis. Hamer et al. (2014) found that the dusty lane is a rotating disk by measuring several line emissions. The maximum rotating velocity reaches ~400 km s⁻¹.

Melnick, Gopal-Krishna & Terlevich (1997) also found a fast rotating disk using the Hα line. Ekers & Simkin (1983) measured stellar velocities and pointed out that the BCG is composed of a rotating disk of stars embedded in non-rotating stellar components. The rotational velocity inside 4" (~4 kpc) is found to be ~50 km s⁻¹ (Loubser et al. 2005). The stellar velocity dispersion is ~200–300 km s⁻¹ (Heckman et al. 1983; Loubser et al. 2005). Therefore, the central part of the BCG (~4") comprises cold rotating disk, rotating stellar, and non-rotating stellar components, exhibiting complex dynamics. On the other hand, the non-rotating stellar components dominate outside the rotating disk (~4").

We use the PIEMD model (Equation 3), assuming spherically symmetry, isotropic orbits, and mass tracing light. We determine the core and scale radii by fitting the light distribution and then estimate the normalization of the PIEMD and the NFW parameters by a joint fit to weak-lensing and stellar velocity dispersion measurements. The combined χ² function is defined by χ² = χ²Δ + χ²dyn, where

\[
\chi^2_{\text{dyn}} = \sum_{i} \frac{(\sigma_{v,i} - \sigma_{v,i,0})^2}{\delta^{2}_{\sigma_{v,i}}}
\]

(see also eq 9 of Newman et al. 2013), where \(\sigma_v\) presents the velocity anisotropy, and \(\nu_v\) and \(\Sigma_v\) are the spherical and surface density profiles of the stellar components, respectively; here we use the best-fit light distribution of the PIEMD model to describe \(\nu_v\) and \(\Sigma_v\). The kernel \(F(r)\) is \((r^2 - R^2)^{1/2}\) for the isotropic-orbit case, \(\beta = 0\) (see Cappellari 2008). Lemze et al. (2012) studied the radial dependence of \(\beta(r)\) for simulated cluster-sized dark-matter halos, finding \(\beta \sim 0 - 0.2\) at \(\sim 0.05\) \(\text{r}_{\text{vir}}\). Since the line-of-sight integral is weighted by the stellar density and thus dominated by the innermost region, the results are insensitive to \(\beta(r)\) around the BCG. Hence, we can reasonably assume a constant \(\beta\). We fix \(\beta = 0\) throughout the paper. We also checked that these results are not sensitive to the choice of \(\beta\) and do not change significantly when fitting with \(\beta = 0.2\).

We use the stellar velocity dispersion at \(r > 4''\) where the contribution from the non-rotating component is negligible. The best-fit radial profiles of weak-lensing and projected velocity dispersion are shown in the left panel of Figure 4. The best-fit profile for the total lensing signal at \(r < 100\) kpc is systematically lower than the measurements, although consistent within errors.

The spherical mass profiles \(M(< r)\) in the central region (\(r < 300\) kpc) are shown in the right panel of Figure 4. The stellar mass component (green dotted line) dominates over the NFW halo component (blue dotted line) at \(r < 20\) kpc. The NFW mass component from the joint fit is consistent with the best-fit NFW profile from the \(g_0\) fitting using the data at \(r > 150\) kpc (yellow region). The total mass profile (black solid line) agrees with the weak-lensing-only results using the full-range data (\(r > 30\) kpc; cyan region) because these best-fit tangential profiles are similar at \(r \gtrsim 100\) kpc (Figures 4 and 6). The NFW+point total mass profile from tangential-shear fitting (magenta region) is in good agreement at \(r \gtrsim 150\) kpc with that from the joint analysis, but overestimates the joint results at \(r \lesssim 50\) kpc. We shall discuss this point in the last paragraph of this section as well as in Section 4.3. We note that the best-fit BCG mass profile is extrapolated beyond the maximum radius for the light-profile measurements (~30 kpc) assuming a constant mass-to-light ratio. If the mass profile for the BCG is sharply truncated at this radius, the BCG mass is \(M_{\text{BCG}} = 1.0^{+0.4}_{-0.3} \times 10^{12} M_\odot\).

For comparison, we overplot the dynamical masses estimated from the cold gas disk component (blue diamonds; Hamer et al. 2014) and hydrostatic masses from X-ray observations (David et al. 2001, red circles). A detailed comparison of weak-lensing and X-ray mass measurements at mass overdensities \(\Delta < 2500\) are presented in Okabe et al. 2013. Hamer et al. (2014) assumed a rotating exponential disk for the central cold disk and obtained dynamical mass estimates within 3.2 kpc and 2.2 kpc using the Hα and Paα lines, respectively. David et al. (2001) derived hydrostatic mass estimates using Chandra data.

Overall, our results agree well with independent measurements from dynamical masses estimated from the cold gas disk and X-ray hydrostatic mass estimates, over a wide
range of radii from a few kpc to 300 kpc, irrespective of different physical conditions and nature of cold gas particles, hot diffuse plasmas, and stars used as mass tracers. Although the effects of non-thermal pressure (e.g., sound waves, subsonic gas motions, and cosmic rays) are expected to be significant as triggered by AGN activities, the X-ray and weak-lensing mass measurements in the central region are in excellent agreement. Since turbulent and/or rotational gas motions in the ICM can be directly proved by the SXS onboard Astro-H, a complementary combination of kinetic information about the ICM, cold gas, and stars and weak-lensing data will be able to provide an improved understanding of the physical state of the cluster center.

We also estimate the stellar mass of the BCG using K-band luminosities as described in Section 4.1. An empirical scaling relation (Arnouts et al. 2007) gives $M_{\text{BCG},*} \sim 5^{+3}_{-1} \times 10^{11} M_\odot$, within a photometric aperture radius of 17 kpc. The errors represent a 15% scatter in the stellar mass-to-light ratio (Arnouts et al. 2007). The inferred stellar mass is in remarkable agreement with the BCG mass determined by our joint analysis (Figure 6). Using the theoretically-predicted scaling relation (Longhetti & Saracco 2009, Table 2), we find $M_{\text{BCG},*} \sim 4 - 6 \times 10^{11} M_\odot$ for the Salpeter IMF. On the other hand, the Chabrier (Chabrier 2003) and Kroupa (Kroupa 2001) IMFs give a stellar mass of $\sim 3 \times 10^{11} M_\odot$, which is slightly lower than our best-fit estimate.

The best-fit tangential shear profile at $r \lesssim 100$ kpc is somewhat discrepant with the data. Newman et al. (2009, 2013) took into account a calibration factor, $m_{\text{WL}} = g_{\text{+},\text{obs}} / g_{\text{+},\text{true}}$, for their lensing model (i.e., $g_{\text{+},\text{model}} \rightarrow m_{\text{WL}} \times g_{\text{+},\text{model}}$), possibly caused by systematic shear calibration and/or redshift errors, to solve the discrepancy between their lensing and dynamical data. Newman et al. (2009) found $m_{\text{WL}} = 0.80$, and Newman et al. (2013) used a prior $m_{\text{WL}} = 0.89 \pm 0.05$, meaning that their shear measurements are underestimated by $\sim 10\% - 20\%$, relative to their dynamical measurements.

We repeated fitting including an additional correction factor $m_{\text{WL}}$ as a free parameter and obtained $m_{\text{WL}} = 3.42 \pm 1.24$, which is extremely higher than our shear calibration uncertainty ($2 - 3\%$, Okabe et al. 2013b, 2014a). It is therefore unlikely that the discrepancy is primarily caused by shear calibration errors, suggesting alternative possibilities, such as the choice of mass models. We estimate lensing signals from member galaxies located in the gap between the BCG-kinematics and weak-lensing data regions (8 kpc $\lesssim r \lesssim$ 30 kpc), assuming a stellar mass-to-light ratio based on the Salpeter IMF. Including their contributions, the best-fit lensing profile is enhanced by $\sim 20\%$, which however is insufficient to account for the discrepancy. In the joint analysis, we assumed that the BCG stellar mass traces the light distribution, and did not explicitly include BCG’s dark-matter contribution relative to the NFW form. If there is a significant and extended dark-matter contribution associated with the BCG, the apparent discrepancy may be explained. We shall examine this hypothesis in the next subsection.

4.3 Flat Dark-Matter Profile around the BCG in Hydra A

For the Hydra A cluster, the total mass profile around the BCG has been tightly constrained by the joint analysis of weak-lensing and dynamical data. We find that the inferred stellar mass contribution is not sufficient to fully explain the observed lensing signal $g_{\text{+}} \propto r^{-2}$ at $r \sim 100$ kpc. This may imply that there is an additional dark-matter component associated with the BCG. Here, we adopt as a working hypothesis that the central dark-matter distribution $\rho_{\text{DM}}(r)$ is shallower than that of the stellar component $\rho_{\star}(r)$, namely $\rho_{\text{DM}}(r) < \rho_{\star}(r)$ at $r \rightarrow 0$ and $\rho_{\text{DM}}(r) > \rho_{\star}(r)$ at larger radii. We have first attempted to fit with the generalized NFW model $\rho \propto (r/r_s)^{-3}(1 + r/r_s)^{-3+\gamma}$ and the core NFW model $\rho \propto (1 + r/r_s)^{-3}(1 + r/r_s)^{-2}$, both described by three parameters, to account for the hypothetical dark-matter contribution. We find both models fall short of the central tangential shear signal and fail to explain the discrepancy.

Now we employ the PIEMD model to describe the additional mass component around the BCG. We express the total mass in Equation (9) as $M(r) = M_{\text{PIEMD},\star}(r) + M_{\text{PIEMD,DM}}(r) + M_{\text{NW}}(r)$, where $M_{\text{PIEMD,DM}}(r)$ is specified by three parameters, namely the normalisation, core and scale radii. In order to satisfy the requirement of the shallow dark-matter distribution, we assume the minimum core radius to be 0.4’. Figure 7 shows the resulting best-fit tangential shear profile $g_{\text{+}}(\theta)$ (left) and the spherical mass profile $M(< r)$ (right). We find that adding the extended central dark-matter component can fully account for the dynamical and lensing data. The change on the total mass profile due to the additional dark-matter component is small (right panel of Figure 7). The resulting total mass profile agrees better with those from independent measurements. In Figure 8 we show the spherical mass density profiles for the total, dark-matter, and BCG stellar components in the central region. The dark-matter density profile in the center is shallower than the stellar density profile, as imposed by the prior. The minimized $\chi^2_{\text{min}}(\text{d.o.f.}) = 6.1 (20)$ has been improved from 9.0 (23) relative to the NFW model. The $F$ test gives a probability of $5 \times 10^{-2}$, thus supporting the addition of the flat dark-matter component.

Lensing systematics, such as the effects of halo/BCG triaxiality (e.g., Corless & King 2007; Oguri & Blandford 2009, Meneghetti et al. 2010; Umetsu et al. 2014), cannot also be ignored as one of the possible causes of the discrepancy between the stellar kinematics and weak-lensing data. Further systematic studies of very nearby clusters are of vital importance for understanding of the mass distribution around BCGs.

4.4 Dark-Matter Fraction around the BCGs

Isobaric cooling time scales for the two clusters are less than 1 Gyr within the central 30 kpc (David et al. 2000, Sun et al. 2008). Gas cooling thus causes condensation of baryons, leading to formation of stars and contraction of dark matter in the central cluster region. One of the most plausible scenarios for the dark-matter response to the cooling of baryons is adiabatic contraction (e.g., Gnedin et al. 2004). A joint analysis of stellar kinematics, stellar photometry, and
Figure 6. Left: tangential reduced-shear for the Hydra A cluster and projected velocity dispersion for the central BCG (inset). The red-solid lines represent the best-fit models for the total lensing signal and the projected velocity dispersion. The dotted-green and blue-dot-dashed lines show the lensing signals for the BCG and NFW mass components, respectively. Right: spherical mass profile within 300 kpc. The back-solid and dashed-lines represent the total mass profile and its 1σ uncertainty, respectively. The green-dotted and blue-dot-dashed lines represent the BCG stellar and NFW halo components, respectively. The magenta, cyan, and yellow shaded areas (from the top to the bottom) show the 1σ error regions for the NFW+point, NFW (r > 30 kpc), and NFW (r > 150 kpc) models from the weak-lensing-only fits, respectively. The top arrows indicate the radial ranges for the dynamical data and weak-lensing data.

Figure 7. Left: results for Hydra A including an additional extended dark-matter component associated with the BCG. The red-solid lines show the best-fit models for the total lensing signal and the projected velocity dispersion. The green-dotted, magenta-dashed, and blue-dot-dashed lines are the lensing signals for the stellar component, the dark-matter component associated with the BCG, and the NFW halo component, respectively. Right: spherical mass profile within 300 kpc. The back-solid, green-dotted, and blue-dotted-dashed lines show the results for the total mass, stellar mass, and total dark-matter distributions, respectively. For comparison, the total mass profile in Figure 6 is shown by the magenta-dashed line. The blue diamonds, red circles, and green squares are the same as those in Figure 6.
weak lensing data allows us to test the validity of adiabatic contraction models.

Here we estimate dark-matter mass fractions around the BCGs, given by $f_{DM} = M_{DM}/(M_{DM} + M_\star + M_{gas})$, where $M_{DM}$ is the dark-matter mass, $M_\star$ is the stellar mass, and $M_{gas}$ is the gas mass (Sanderson, Finoguenov & Mohr 2003; David et al. 2001). We employ the NFW (Sections 4.1 and 4.2) and composite dark-matter (NFW+PIEMD; Section 4.3) models to calculate $M_{DM}(< r)$. The stellar mass is composed of the BCG and cluster elliptical galaxies. The BCG stellar mass profiles are calculated using the best-fit parameters given in Sections 4.1 and 4.2. The stellar masses for elliptical member galaxies are estimated by their K-band luminosities. Here, we assume the Salpeter IMF for Hydra A (Section 4.2) because the stellar mass estimated by the Salpeter IMF agrees with that estimated by the stellar mass profiles in the central region, as imposed by the prior and favored by the data.

Figure 9 shows the resulting dark-matter fraction profiles for the two clusters. The cumulative dark-matter fractions progressively increase with the increasing cluster radius. The slope is slightly steeper beyond effective radii of BCGs, $r_e \sim 20$ kpc, and flattened at $r \sim 100$ kpc. Similar results have been reported by earlier work (e.g. Nagino & Matsushita 2009; Oguri, Rusu & Falco 2014). Nagino & Matsushita (2009) found that the integrated mass-to-light ratio profiles for early-type galaxies based on the X-ray and photometry analysis increases beyond effective radii of galaxies. Oguri, Rusu & Falco (2014) conducted a joint analysis of strong lensing and stellar photometry for a large ensemble of elliptical galaxies, finding that the slope of the dark-matter fraction becomes steeper at $r > r_e$.

Now we examine the dark-matter fractions using models with and without adiabatic contraction (Gnedin et al. 2004). We use the Jaffe model (Jaffe 1983) as a stellar mass distribution, where the density profile follows $\rho(r) \propto r^{-2}(r + a)^{-2}$. In the limit of $r \gg a$ for the PIEMD model (Equation 13), the PIEMD density profile resembles the Jaffe profile. For the dark-matter component, we only consider the NFW model. The dark-matter fractions (dashed lines) predicted by adiabatic contraction models (Gnedin et al. 2004) underestimate our measurements irrespective of the chosen stellar IMFs and of the methods of joint analysis. On the other hand, models without contraction agree better with the observed dark-matter fractions, consistent with the results of Newman et al. (2013) and Oguri, Rusu & Falco (2014). This suggests that other physical processes are critically important to suppress the modification of dark-matter profiles.

5 DISCUSSION

We find that the dark-matter fraction profiles (Section 4.3) agree better with models without adiabatic contraction than those with contraction (Gnedin et al. 2004). One of possible scenarios is that the gas outflows driven by AGN activities suppress condensation of the dark-matter distribution in the central region (e.g. Tevssier et al. 2011; Martizzi et al. 2012; Ragone-Figueroa, Granato & Abadi 2012). In fact,
on-going jet activities of central AGNs have been reported in two clusters (David et al. 2001, Sun et al. 2003, Diehl et al. 2008, e.g.). The projected distances between the BCG and X-ray bubbles triggered by the observed activities are $r \sim 25$ kpc for Hydra A and $r \sim 9$ kpc for A478, respectively (e.g. David et al. 2001, Sun et al. 2003, Wise et al. 2005, Diehl et al. 2008). Characteristic scale radii obtained by equating the interior stellar and NFW masses are $r_{eq} \sim 25$ kpc for Hydra A; $r_{eq} \sim 22$ kpc and $\sim 15$ kpc for A478, assuming the Salpeter and Chabrier IMFs, respectively. This suggests that the current AGN jet activities can directly affect the baryons over the region where stellar mass dominates. The results here hold even if there is a sizable uncertainty in the bubble orientation of $\sim 40^\circ$ from the plane of the sky. Another alternative scenario assumes minor, dry (dissipationless) mergers of clumpy structures (e.g. El-Zant, Shlosman & Hoffman 2001, Lackner & Ostriker 2010), which can flatten the central dark-matter density profile (Section 4.3) and be closely correlated with the BCG growth.

Further systematic studies of central dark-matter mass fractions and density slopes, using a large sample of AGN and non-AGN clusters, are required to distinguish between the effects of gas outflows and dissipationless mergers, for deep understanding of physical processes governing the BCG growth. Systematic joint studies combining weak lensing and stellar kinematics data will also be useful to examine correlations between stellar population properties and IMF constraints inferred from joint analyses (McDermid et al. 2014).

6 SUMMARY

We have presented a weak-lensing study of the nearby cool-core clusters Hydra A and A478. To minimize dilution of the lensing signal due to contamination by cluster members, we carefully select populations of background source galaxies in the color-magnitude plane. Compared to weak-lensing studies of clusters at intermediate redshifts $z \sim 0.2$ (Okabe et al. 2013), the level of background contamination by cluster members is significantly reduced. This enables us to obtain a larger number of background galaxies for weak-lensing measurements while achieving a low level of contamination. This is one of the advantages of weak-lensing analysis of very nearby clusters.

The S/N ratios for detection of the tangential shear signals are 7.0 and 8.1 for Hydra A and A478, respectively, after accounting for the contribution from projected uncorrelated LSS. The resulting S/N ratios are comparable to those of clusters at $z \sim 0.2$, thanks to the increased number of background galaxies behind the clusters.

We find that, for each cluster, the tangential shear profile is well fitted with a single NFW model. For Hydra A, the tangential shear signal in the central region is well described by a two-component model including the central BCG as an unresolved point mass.

We find that the choice of IMFs can introduce a large uncertainty (factor of $\sim 2$) in the BCG stellar mass estimates, which makes it difficult to decompose the observed total projected mass profile into the stellar and dark-matter components (Section 4.2). On the other hand, as demonstrated by Newman et al. (2009, 2011, 2013), the internal stellar kinematics of BCGs enables us to precisely measure the mass profiles of two components independent of the IMF uncertainty (Section 4.2). For Hydra A, we find that the central mass profile ($\leq 300$ kpc) determined from weak lensing is in excellent agreement with those from independent measurements, including dynamical masses estimated from the cold gas disk component, X-ray hydrostatic total mass estimates, and central stellar mass estimates. For the BCG, the data prefer the Salpeter IMF to the Chabrier and Kroupa IMFs. An additional flat dark-matter component around the BCG accounts simultaneously for the weak-lensing and stellar-kinematics data for Hydra A.

Dark-matter fractions around the BCGs for the two clusters are found to be smaller than those predicted by adiabatic contraction models, and to agree well with model predictions without contraction. This implies that other baryonic processes, such as the AGN feedback, dissipationless mergers, or the combination of the two, could play important roles in shaping the central cluster mass profile. A precise joint measurement of the central cluster mass profile provides us with complementary information about the dynamics of hot intrachannel gas, which will be directly probed by Astro-H.

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