Independent Measurements of the Dynamical Masses of Six Galaxy Clusters in the Local Universe

Joung hun Lee
Astronomy Program, Department of Physics and Astronomy, Seoul National University, Seoul 08826, Korea; joung hun@astro.snu.ac.kr

Received 2017 February 17; revised 2017 March 19; accepted 2017 March 20; published 2017 April 11

Abstract

We present independent measurements of the masses of galaxy clusters in the local universe by employing the Dynamical Mass Estimator (DME) originally developed by Falco et al. In the catalog of the galaxy groups/clusters constructed by Tempel et al. from Sloan Digital Sky Survey Data Release 10, we search for galaxy clusters as the targets around which neighbor galaxies constitute thin straight filamentary structures in the configuration space spanned by the redshifts and the projected distances. Out of the 29 Sloan clusters that have 100 or more member galaxies, a total of six targets are found to have filamentary structures in their bound zones. For each of the six targets, we construct the profile of the recession velocities of the filament galaxies, which depend on the cluster mass and the angle of the filament relative to the line-of-sight direction. Fitting the constructed profile to the universal formula with constant amplitude and slope, we statistically determine the dynamical mass of each cluster and compare it with previous estimates made using the conventional method. The weak and strong points of the DME, as well as its prospects for measuring the dynamical masses of high-z clusters, are discussed.

Key words: cosmology: theory – large-scale structure of universe

1. Introduction

The accurate measurement of the masses of galaxy clusters is quite a narrow bottleneck in the success and completion of cluster cosmology. Although a plethora of methodologies have so far been developed to pass through this bottleneck, the required accuracy that would optimize the use of galaxy clusters as a cosmology probe has yet to be achieved (Allen et al. 2011). The conventional methodology obtains the masses of galaxy clusters by finding and modeling their correlations with other observables, such as the velocity dispersions of the member galaxies, the X-ray temperatures, the gravitational lensing signals, the Sunyaev–Zel’dovich (SZ) effect, the optical richness, and so on. The theoretical models for the correlations between the cluster masses and those observables, however, were often constructed by sacrificing the astrophysical complexities of real galaxy clusters, which include deviation from hydrostatic/thermal equilibrium, incomplete relaxation of their dynamical states, their non-spherical shapes, and existence of their substructures (for a comprehensive review, see Giodini et al. 2013).

In fact, it is not only the low accuracy but the inconsistency that has to be hurdled in the measurements of the cluster masses. Although the simplified assumptions about the correlations between the cluster masses and those observables yielded inaccurate measurements of the cluster masses, the variation of the degree of simplification yielded inconsistencies among the values of cluster masses estimated using different observables. It may also be responsible, at least partly, for the value of the linear power spectrum amplitude estimated from the abundance of the SZ clusters that is lower than the value of the cosmic microwave background radiation measured by the Planck experiment (Planck Collaboration et al. 2014a, 2014b).

Previous attempts to deal with the reality were either statistical or resorted to hydrodynamic simulations. The former approach statistically accounted for the intrinsic scatters of the correlations between the cluster masses and the observables, which ameliorated the accuracy but degraded the precision in the mass measurements of the galaxy clusters (e.g., Andreon & Hurn 2010 and references therein). The latter approach, based on hydrodynamic simulations, made it possible to incorporate astrophysical complexities into the models for the clusters but undermined the power of cluster cosmology since the detailed prescriptions of the baryon physics required to run hydrodynamic simulations are deeply cosmology dependent (e.g., Finoguenov et al. 2010; Stanek et al. 2010; Planelles et al. 2013; Wu et al. 2015; Truong et al. 2016, and references therein).

The algorithm recently developed by Falco et al. (2014) has cleared a path through the above generic difficulties toward an independent measurement of cluster masses. It estimates the dynamic mass of a galaxy cluster by using the mass dependence of the recession velocity profile of the neighbor galaxies located in its bound zone. Finding an empirical formula for the recession velocity profile from an N-body simulation and noting its universal behavior, Falco et al. (2014) suggested that their algorithm should be particularly useful for those dynamically young unrelaxed clusters in the middle of a merging process out of thermal equilibrium, which were difficult to deal with in previous approaches. Falco et al. (2014) tested their algorithm against the Coma cluster, finding a fairly good agreement of their estimate with the previous measurements. From here on, we call this algorithm the Dynamic Mass Estimator (DME).

In subsequent works, the DME has been further improved and refined. Lee et al. (2015a), who attempted to estimate the dynamic mass of the Virgo cluster by using the DME algorithm, pointed out that the original DME identifies a bound-zone filament in a somewhat haphazard way and suggested that for the identification of a true bound-zone filament, it should first be examined if the recession velocities of the filament galaxies deviate from the Hubble flow.

Lee (2016) refined the analytic formula for the recession velocity profile of the filament galaxies by narrowing down the slopes and amplitudes that characterize the formula with the...
help of a higher resolution numerical simulation and showed that the universality of the formula for the recession velocity profile is valid only in the limited redshift range of $z \leq 0.2$. Although the refined DME algorithm was able to estimate the dynamical mass of the nearest Virgo cluster (Lee et al. 2015a), its power in competing with other conventional estimators has yet to be convincingly verified. It is essentially important to quantitatively explore with larger data sets how well it works in practice and what its success rate is, which we attempt to carry out in this paper.

The contents of the subsequent sections are summarized as follows. In Section 2, the DME algorithm is concisely reviewed. In Section 3.1, we present the physical analyses of the group/cluster catalog from a large galaxy survey to identify the bound-zone filaments and to construct the recession velocity profiles along the filaments. In Section 3.2, we present the dynamical mass estimates of the target clusters made by applying the DME to their bound-zone filaments and the comparison of our results with the conventional estimates. In Section 4, the summary of the final results and a discussion of the future prospects of the DME’s application to high-$z$ clusters are presented.

2. Review of the DME Algorithm

Consider a galaxy located in the bound zone around a massive cluster, where the separation distance between the galaxy and the cluster is large enough for the galaxy not to fall into the potential well of the cluster but is also small enough for it to develop a non-negligible peculiar velocity. The recession velocity of the bound-zone galaxy from the cluster should be lower than the Hubble speed but will gradually approach it with the increment of the separation distance. The more massive the cluster is, the less rapidly the recession velocity of the bound-zone galaxy will change with the separation distance. Hence,

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Recession velocities along the line-of-sight directions vs. the projected distances in the plane of the sky from the eight different wedges (W1–W8). In each panel, the filled blue circles correspond to the configurations of the member galaxies of one of the six target clusters (CL1) while the filled red circles represent those of the neighbor galaxies belonging to the candidate overdense pixels. The unfilled black circles represent the sloping straight line-like filaments that are steeper than the Hubble flow, which is denoted by the dashed green lines.}
\end{figure}
the profile of the recession velocity of the bound-zone galaxy should be a powerful indicator of the cluster mass.

Using an $N$-body experiment, Falco et al. (2014) showed that the following formula provides a good approximation for the profile of the mean recession velocity of the bound-zone galaxies around a cluster with a virial radius of $r_v$:

$$v_r(r) = H(z)r - A r^{-n}$$

where $v_r(r)$ is the radial component of the recession velocity of a bound-zone galaxy at a distance $r$ from the cluster center, $V_c$ is the circular velocity at $r_v$, and $H(z)$ is the Hubble parameter. This formula has two free parameters, $A$ and $n$, that represent the amplitude and the slope of the profile, respectively.

In the right-hand side (rhs) of Equation (1), the first term corresponds to the Hubble speed while the second term represents the peculiar velocity that depends on the cluster mass $M_c$ through $r_v$ as $M_c = 4\pi \Delta_c r_v^3 / 3$ where $\Delta_c \approx 100 \rho_c$ and $\rho_c$ is the critical density of the universe. The two parameters $A$ and $n$ were determined to be $A = 0.8 \pm 0.2$ and $n = 0.42 \pm 0.16$ and claimed by Falco et al. (2014) to be independent of the redshifts as well as of the key cosmological parameters.

The subsequent analysis of Lee (2016), based on the Millennium II simulations (Boylan-Kolchin et al. 2009), has confirmed that Falco et al.’s (2014) assumption is valid, but that the values of $A$ and $n$ are universal only in the limited range of $z \lesssim 0.2$. Lee et al. (2015b) demonstrated a weak dependence of $A$ and $n$ on the mass scales with the help of the MultiDark Planck simulations (Klypin et al. 2016) and determined their values with high precision to be $A = 0.88 \pm 0.02$ and $n = 0.43 \pm 0.01$ on the cluster mass scale of $10^{14} h^{-1} M_{\odot}$.

If $v_r(r)$ and $r$ were measurable from observations, then the mass of a galaxy cluster would be readily estimated by inserting the observed profile $v_r$ into Equation (1). This, however, cannot be put into practice since we are not capable of measuring the profiles $v_r(r)$ and $r$ directly from observations. Falco et al. (2014) put forth a clever idea to overcome this difficulty. Suppose that some of the bound-zone galaxies

Figure 2. Same as Figure 1 but for CL2.
around a cluster constitute a thin straight filament and that the filament is inclined at an angle of $\beta$ with the line-of-sight direction of the cluster. Their recession velocities, $v_r (r)$, and positions relative to the cluster center, $r$, can be expressed as $cz/\cos \beta$ and $r_{2d}/\sin \beta$, respectively, where $z$ denotes the relative redshift of the bound-zone galaxy from the cluster center and $r_{2d}$ is the projected value of $r$ onto the plane of the sky perpendicular to the line-of-sight direction to the cluster, both of which are all directly observable. Rewriting Equation (1) in terms of these readily measurable quantities, we have

$$cz (r_{2d}, \beta, M_v) = \left[ \frac{H_0 r_{2d}}{\sin \beta} - A V_c \left( \frac{r_{2d}}{\sin \beta r_c} \right)^{-p} \right].$$ (2)

The trade-off for expressing the profile in terms of the direct observables is having one more unknown quantity, $\beta$, in addition to $M_v$, which cannot help but degrade the precision in the measurements of $M_v$.

The application of the DME to the target clusters will proceed as follows. Detect a thin straight filamentary structure of the galaxies in the bound-zone regions around a target cluster. Calculate the redshift difference between the cluster and each filament galaxy, as well as the separation distance between them in the plane of the sky perpendicular to the line-of-sight direction toward the cluster, to construct the recession velocity profile along the filament. Fitting the observed profile to Equation (2), we find the best-fit values of the mass of the target cluster as well as the inclination angle of the bound-zone filament. In the following section, we will apply this DME to the galaxy clusters in the local universe.

3. Application of the DME to the Sloan Clusters

3.1. Detection of the Bound-zone Filaments around the SDSS Clusters

Tempel et al. (2014) identified the galaxy groups in a flux-limited spectroscopic data set of the galaxies from the Sloan Digital Sky Survey (Ahn et al. 2014; hereafter SDSS DR10)
with the help of the modified Friends-of-Friends (FoF) group finder and compiled a catalog that contains spectroscopic information on the member galaxies belonging to each group as well as on the field galaxies. Tempel et al. (2014) also provided information about the $M_{\text{nfw}}$ and $M_{\text{hern}}$ of each cluster in the catalog where $M_{\text{nfw}}$ and $M_{\text{hern}}$ denote two different dynamical masses, both of which were estimated from the radial velocity dispersions of the member galaxies. The difference between the two masses lies in the shape of the matter density profile of the cluster. The $M_{\text{nfw}}$ was estimated under the assumption that the density profile is well-approximated by the Navarro–Frenk–White (NFW) formula (Navarro et al. 1996, 1997), while for the $M_{\text{hern}}$, the Hernquist profile (Hernquist 1990) was used. For a detailed description of the modified FoF finder and the catalog of the galaxy groups, see Tempel et al. (2014).

From the group catalog of Tempel et al. (2014), we selected 29 massive groups as the target clusters using the criterion that the number of member galaxies should be equal to or exceed 100, expecting that the gravitational influence of those massive clusters should be strong enough to be readily detectable in their bound zones. Those groups with fewer than 100 member galaxies are excluded to reduce the statistical noise in the mass measurement with the DME. The more massive a cluster is, the longer the filament it tends to have in its bound zone. The longer bound-zone filament composed of a larger number of neighbor galaxies suffers less from statistical noise.

We also select 533,256 galaxies as the sample galaxies from the spectroscopic data set of the SDSS DR10 using the criterion that the galaxies are either field galaxies or members of low-mass groups with 10 or fewer members. The reason for excluding galaxies belonging to groups with more than 10 members is as follows. In Equation (2), it is implicitly assumed that the most dominant gravitational influence on a galaxy with recession velocity $v_r(r)$ is the cluster with mass $M_v$. If a galaxy in the neighbor region around a target cluster is a member of a group with more than 10 members, then the gravitational effect of the other members belonging to the same host group on the galaxy may be comparable to that of the cluster, and thus its peculiar velocity would no longer be well-approximated by the second term in the rhs of Equation (2).

Now, to identify a bound-zone filament from the spatial distribution of the sample galaxies around each target cluster,
we follow the prescriptions of Falco et al. (2014). First, we determine the relative redshifts, $z$, and the projected distances, $r_{2d}$, of the sample galaxies from the center of each target cluster. The former is obtained by taking the difference between the redshifts of the target cluster and its sample galaxies, while the latter is measured in the plane of the sky perpendicular to the line-of-sight direction to the cluster, based on information on their equatorial coordinates. Around each of the six target clusters, the sample galaxies that satisfy the conditions of $r_{2d} \leq 20$ $h^{-1}$ Mpc and $|cz/H| \leq 40$ $h^{-1}$ Mpc are selected as the neighbor galaxies, where $c$ is the speed of light. Dividing the ranges of $r_{2d}$ and $l_z \equiv (cz)/H$ into 4 and 20 bins, respectively, we pixelate the configuration space spanned by $r_{2d}$ and $l_z$ around each target cluster into 80 squares, each of which has an area of $d r_{2d} dl_z = 16$.

To compute the number density of the neighbor galaxies at each pixel, we also split the plane of the sky around each cluster into eight wedges according to the polar angles $\theta$ defined as $\theta = \tan^{-1}(x/y)$ in the range of $(0, 2\pi)$. Here, $(x, y)$ is the Cartesian coordinates of the two-dimensional position vector of the pixel center in the plane of the sky from a target cluster, satisfying the condition $r_{2d} = \sqrt{x^2 + y^2}$. The $k$th wedge corresponds to the $\theta$ interval of $[(k - 1)\pi/4, k\pi/4)$, where the integer $k$ varies from 1 to 8. Grouping the pixels in the $r_{2d}-l_z$ plane by the polar angles of the position vectors of the centers of the pixels, we end up with eight different realizations, from the eight wedges, for the number density of the neighbor galaxies at each pixel.

Let $n^k_i$ be the number density of the neighbor galaxies belonging to the $i$th pixel (i.e., the $i$th bin of $r_{2d}$ and the $j$th bin of $l_z$) from the $k$th wedge. The dimensionless density contrast, $\delta^k_i$, can be calculated as $\delta^k_i \equiv (n^k_i - \bar{n}^k_i)/\bar{n}^k_i$. Here, we evaluate the mean number density $\bar{n}^k_i$ by taking the ensemble average over the number densities at the same $i$th pixel but from the five different wedges, excluding the realizations from the $k$th wedge and its two adjacent wedges. Then, we select only those pixels that meet the condition of $\delta^k_i \geq 3$ as the candidate overdense sites where the bound-zone filaments may be found, as done in Falco et al. (2014).
The eight panels of Figure 1 depict the distributions of the neighbor galaxies belonging to the candidate overdense pixels with \( \delta_y^k \geq 3 \) (red dots) from the eight wedges (W1–W8) in the \( r_{2d} - l_z \) configuration space around one of the 29 target clusters. In each panel, the blue dots represent the configurations of the member galaxies of the target cluster (dubbed CL1). In the original procedure described by Falco et al. (2014), a bound-zone filament was identified in the distribution of the overdense pixels as a sloping straight line that exhibits a monotonic increment of \( |l_z| \) with \( r_{2d} \). As mentioned in Section 2, Lee et al. (2015a) suggested that a bound-zone filament should be identified not just as a sloping straight line but as satisfying an additional condition that is in fact essential to the success of the DME. If the neighbor galaxies belonging to a bound-zone filament is under the dominant gravitational influence of a target cluster, then their recession velocities should be lower than the Hubble speed at small distances but should gradually approach it as the distance increases (see Kim et al. 2016). In other words, a bound-zone filament should appear as a sloping straight line steeper than the straight line of \( |l_z| = r_{2d} \), which is plotted as the green dotted line in each panel of Figure 1.

A shrewd reader might think that this condition is too stringent since \( r_{2d} \) is not a real three-dimensional distance, \( r \), between a target cluster and its neighbor galaxies but only a two-dimensional distance projected onto the plane of the sky.

| Group ID | Redshift | R.A. (°) | Decl. (°) | \( N_m \) | \( N_r \) |
|----------|----------|----------|-----------|--------|--------|
| CL1      | 175      | 0.02     | 181.1     | 20.4   | 139    | 36    |
| CL2      | 1701     | 0.05     | 169.1     | 29.3   | 113    | 18    |
| CL3      | 2111     | 0.07     | 190.3     | 18.6   | 120    | 27    |
| CL4      | 3070     | 0.09     | 239.5     | 27.3   | 212    | 22    |
| CL5      | 5278     | 0.08     | 184.4     | 3.7    | 106    | 23    |
| CL6      | 7045     | 0.07     | 230.7     | 27.8   | 161    | 41    |

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A shrewd reader might think that this condition is too stringent since \( r_{2d} \) is not a real three-dimensional distance, \( r \), between a target cluster and its neighbor galaxies but only a two-dimensional distance projected onto the plane of the sky.
However, without having any information on \( r \), it is the most conservative and secure condition required to guarantee the validity of the DME. We look for such a sloping straight line that is steeper than the green solid line in the distributions of the red dots. We identify one in the seventh wedge (W7), which is shown by the unfilled black circles overlapping with the filled red circles in the bottom-left panel of Figure 1.

We followed the same procedures to find the bound-zone filaments of the 29 target clusters and found that only six targets have such thin straight filamentary structures in their bound zones. Figures 2–6 display the same information as Figure 1 but for the other five clusters (CL2–CL6). Table 1 lists the identification number, Group ID, spectroscopic redshift, equatorial coordinates, the number of member galaxies (\( N_m \)), and the number of neighbor galaxies belonging to the bound-zone filaments (\( N_c \)), of the six target clusters. Regarding the other 23 target clusters, we fail to find bound-zone filaments from the configurations of the neighbor galaxies in the \( r_{2d} \)-\( l_z \) space. Figure 7 shows one example of a target cluster in the bound zone for which no thin straight filamentary structure is found in any of the eight wedges.

### 3.2. Estimates of the Dynamic Masses of Six Clusters with DME

For each of the six clusters in the bound zone for which a thin straight filamentary structure is detected in Section 3.1, we fit the observational results to Equation (2) to simultaneously find the best-fit values of \( m_* \equiv \log M_*/(h^{-1} M_\odot) \) and \( \beta \) that maximize the likelihood distribution of \( p\{-\chi^2(m_*, \beta)/2\}. \)

\[
\chi^2(m_*, \beta) = \sum_{i=1}^{N_c} \left\{ \frac{l_{z,i}}{\cos \beta} - \left[ \frac{r_{2d,i}}{\sin \beta} - A \frac{V_0}{H} \left( \frac{r_{2d,i}}{\sin \beta r_e} \right)^{-n} \right] \right\} \frac{1}{\sigma_i^2} \tag{3}
\]

where \( l_{z,i} \) and \( r_{2d,i} \) denote the observed values of \( l_z \) and \( r_{2d} \) of the \( i \)th galaxy belonging to the bound-zone filament. As done in Lee et al. (2015a), the one standard deviation errors \( \sigma_i \) are all set to unity, given that the uncertainties associated with the
measurements of $l_z$, including the ones associated with the identification of the bound-zone filaments by eye, are unknown.

Each panel of Figure 8 displays the 68%, 95%, and 99% contours of the likelihood in the $m_v$–$\beta$ plane as the solid, dashed, and dotted-dashed lines, respectively, for each of the six clusters. As can be seen, for all six clusters, the 68% contours are well-localized. Marginalizing $p(-\chi^2(m_v, \beta)/2)$ over $m_v$ as $p(\beta) = \int_{-\infty}^{\infty} p(m_v, \beta) dm_v$, we obtain the one-point probability density function $p(\beta)$ for the six clusters, the results of which are shown in Figure 9. As can be seen, for the case of CL3, which has the thinnest bound-zone filament among the six, the probability density function $p(\beta)$ has the narrowest shape. For the cases of CL2 and CL6, however, whose bound-zone filaments appear relatively thick in the $r_2r$–$l_z$ plane, the widely spread shape of $p(\beta)$ is noted.

Marginalizing $p(-\chi^2(m_v, \beta)/2)$ over $\beta$ yields the one-point probability density function $p(m_v)$, the results of which are shown in Figure 10. As can be seen, the probability density distributions deviate from the Gaussian shape, and is asymmetric around the best-fit value where $p(m_v)$ reaches it maximum. For the case of CL6 whose bound-zone filaments have the largest number of neighbor galaxies, $N_g$, the shape of $p(m_v)$ is the closest to a Gaussian distribution, which indicates that the asymmetric shape of $p(m_v)$ is likely due to the small number statistics. The red and blue dotted lines in each panel of Figure 10 correspond to the two mass estimates for each of the six clusters made by Tempel et al. (2014) with the conventional method based on the radial velocity dispersions of the cluster galaxies:

**Figure 8.** 68%, 95%, and 99% contours of the likelihood distributions in the plane spanned by the logarithmic mass $M_v$ and the inclination angle $\beta$ for the six clusters around which bound-zone filaments are detected.

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**Figure 9.** Probability density functions $p(\beta)$ for the six clusters.

**Figure 10.** Probability density functions $p(m_v)$ for the six clusters.
As can be seen, although our best-fit values for $m_v$ do not show a significant difference from $m_{nfw}$ and $m_{hern}$, the amount and trend of the difference change from cluster to cluster. For the case of CL1, our best-fit value for $m_v$ exceeds both $m_{nfw}$ and $m_{hern}$. For the case of CL2, our result agrees well with $m_{nfw}$. For the cases of CL3 and CL4, our estimates coincide with $m_{hern}$. For the other two cases of CL5 and CL6, our best-fit values for $m_v$ lie between $m_{nfw}$ and $m_{hern}$.

4. Discussion and Conclusion

The DME algorithm developed by Falco et al. (2014) estimates the mass of a galaxy cluster from the profile of the recession velocities of the neighbor galaxies that constitute a thin straight filament in its bound zone. Therefore, the application of the DME is inherently limited to the galaxy clusters in the bound zones where thin straight line-like filaments exist. In the current analysis, only 6 out of the 29 clusters composed of 100 or more member galaxies in the SDSS group catalog are found to have such thin straight filaments in their bound zones, which implies that the success rate of DME should be around 20%.

The other downside of the DME is the somewhat casual way in which thin straight filaments are identified in the bound zones. From the distributions of the neighbor galaxies in the configuration space spanned by their redshifts and projected distances, the sloping straight line-like structures that are steeper than the Hubble flow had to be determined by eye as the bound-zone filaments (Falco et al. 2014). It would be quite desirable to construct a more formal, deliberate routine to detect a bound-zone filament from the spatial distributions of the neighbor galaxies.

Figure 9. Probability density functions of the inclination angles of the bound-zone filaments around the six clusters, marginalized over the logarithmic masses.
Nevertheless, the above downsides of the DME do not overshadow its distinct advantage over the other conventional mass estimators. Since the DME requires no simplified assumptions about the dynamical and/or thermal states nor about the shapes and profiles of the clusters, it can be applied even to those clusters that are in the middle of a merging process, which have very disturbed shapes with very low X-ray/SZ emissions. The dynamic masses of the six Sloan clusters estimated by the DME in the current analysis are found to not be substantially different from the previous estimates made using conventional methods, which are based on the radial velocity dispersions of the cluster galaxies assuming that the galaxy clusters are quite relaxed with spherically symmetric shapes. Finding that the difference between our estimate and previous ones changes from cluster to cluster, we suggest that the DME should also be useful to examine the deviation of the dynamical/thermal states of the clusters from equilibrium and the asymmetry of their true density profiles as well.

The usefulness of the DME confirmed in the current analysis leads us to expect that the DME may be an optimal algorithm for measuring the dynamic masses of high-redshift clusters. Gravitational lensing and/or SZ effects have almost exclusively been employed to estimate the masses of high-redshift clusters. This is not only because the velocity dispersions of the cluster galaxies at high redshifts are difficult to determine with high accuracy, but also because the high-redshift clusters are often dynamically young because of merger events with abundant substructures; in these cases the previous methods are likely to fail. Moreover, modified gravity models generically predict the dynamical masses of galaxy clusters to be higher than the masses estimated using gravitational lensing effects (e.g., Schmidt 2010). Measuring the dynamic masses of the high-redshift galaxy clusters with the DME and comparing them with the

Figure 10. Probability density functions of the dynamical masses of the clusters marginalized over the inclination angles of the bound-zone filaments.
lensing counterparts would allow us to efficiently test the gravity, which is the direction of our future work.

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2016R1D1A1A09918491). It was also partially supported by a research grant from the NRF to the Center for Galaxy Evolution Research (No. 2010-0027910).

References

Ahn, C. P., Alexandroff, R., Allende Prieto, C., et al. 2014, ApJS, 211, 17
Allen, S. W., Evrard, A. E., & Mantz, A. B. 2011, ARA&A, 49, 409
Andreon, S., & Hurn, M. A. 2010, MNRAS, 404, 1922
Boylan-Kolchin, M., Springel, V., White, S. D. M., Jenkins, A., & Lemson, G. 2009, MNRAS, 398, 1150
Falco, M., Hansen, S. H., Wojtak, R., et al. 2014, MNRAS, 442, 1887
Finoguenov, A., Sanderson, A. J. R., Mohr, J. J., Bialek, J. J., & Evrard, A. 2010, A&A, 509, A85
Giodini, S., Lovisari, L., Pointecouteau, E., et al. 2013, SSRv, 177, 247
Hernquist, L. 1990, ApJ, 356, 359
Kim, S., Rey, S.-C., Bureau, M., et al. 2016, ApJ, 833, 207
Klypin, A., Yepes, G., Gottlöber, S., Prada, F., & Heß, S. 2016, MNRAS, 457, 4340
Lee, J. 2016, ApJ, 832, 123
Lee, J., Kim, S., & Rey, S.-C. 2015a, ApJ, 807, 122
Lee, J., Kim, S., & Rey, S.-C. 2015b, ApJ, 815, 43
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2014a, A&A, 571, A16
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2014b, A&A, 571, A20
Planelles, S., Borgani, S., Dolag, K., et al. 2013, MNRAS, 431, 1487
Schmidt, F. 2010, PhRvD, 81, 103002
Stanek, R., Rasia, E., Evrard, A. E., Pearce, F., & Gazzola, L. 2010, ApJ, 715, 1508
Tempel, E., Tamm, A., Gramann, M., et al. 2014, A&A, 566, A1
Truong, N., Rasia, E., Mazzotta, P., et al. 2016, arXiv:1607.00019
Wu, H.-Y., Evrard, A. E., Hahn, O., et al. 2015, MNRAS, 452, 1982