Galaxy Clusters from the DESI Legacy Imaging Surveys. I. Cluster Detection

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Abstract

Based on the photometric redshift catalog of Zou et al., we apply a fast clustering algorithm to identify 540,432 galaxy clusters at z < 1 in the DESI legacy imaging surveys, which cover a sky area of about 20,000 deg². Monte Carlo simulations indicate that the false-detection rate of our detecting method is about 3.1%. The total masses of galaxy clusters are derived using a calibrated richness–mass relation that is based on the observations of X-ray emission and the Sunyaev and Zel’dovich effect. The median redshift and mass of our detected clusters are about 0.53 and 1.23 × 10¹⁴ M⊙, respectively. Comparing with previous clusters identified using the data of the Sloan Digital Sky Survey, we can recognize most of them, especially those with high richness. Our catalog will be used for further statistical studies on galaxy clusters and environmental effects on galaxy evolution, etc.

Supporting material: FITS files

1. Introduction

Galaxy clusters are the most massive gravitationally bound systems in the universe. They are formed in the cosmic web, tracing the large-scale structure. Galaxy clusters are powerful probes for structure growth and provide important constraints on cosmological parameters (Kravtsov & Borgani 2012; Planck Collaboration et al. 2016a). Galaxy clusters are also excellent astrophysical laboratories for studying galaxy evolution, galaxy collision, gravitational lenses, dark matter, and extreme physics in dense environments (Dressler 1980; Butcher & Oemler 1984; Moore et al. 1996; Lin & Mohr 2004; Sand et al. 2004; Kneib & Natarajan 2011; Kravtsov & Borgani 2012; Ebeling et al. 2014).

Galaxy clusters are a collection of galaxies that are bonded by gravity. In addition to stars constituting the luminous matter of galaxies in a cluster, there are multiple observable compositions, including cold gas and dust in galaxies, hot ionized intracluster medium (ICM), and dark matter. The multicomponent nature of galaxy clusters makes them visible across the electromagnetic spectrum. The X-ray emission and Sunyaev and Zel’dovich (SZ) effect in the microwave band originating from the hot ICM (Sunyaev & Zeldovich 1972; Voit 2005; Bleem et al. 2015) can be used to detect redshift-independent samples of galaxy clusters (Piffaretti et al. 2011; Reichardt et al. 2013; Planck Collaboration et al. 2016b; Tarrio et al. 2019). These samples usually present relatively high purity and completeness but tend to be high-mass systems. The most effective detections of galaxy clusters are based on large-scale optical and near-infrared imaging data. A variety of cluster-finding techniques have been developed owing to ongoing and upcoming wide and deep large-scale photometric surveys. Generally, there are two kinds of cluster-finding methods: one is to find the overdensity of galaxies in three-dimensional space (Szabo et al. 2011; Wen et al. 2012; Gao et al. 2020; Yang et al. 2021) and the other is based on the red-sequence feature (Koester et al. 2007; Hao et al. 2010; Rykoff et al. 2014), which describes the narrow color distribution of red member galaxies in a cluster (also known as the E/S0 ridgeline). The red-sequence method utilizes intrinsic color properties of member galaxies, while the overdensity finding method can identify clusters not presenting the red-sequence feature, especially at high redshift.

In Gao et al. (2020), we introduced a new fast clustering algorithm, called Clustering by Fast Search and Find of Density Peaks (CFSFDP), to identify galaxy clusters from a photometric redshift (photo-z) catalog, which is based on the seven-band photometry of the South Galactic Cap U-band Sky Survey (SCUSS; Zhou et al. 2016; Zou et al. 2016), Sloan Digital Sky Survey (SDSS), and unWISE (Lang et al. 2016) surveys. A total of about 20,000 clusters were discovered over a sky area of 3700 deg² in the south Galactic cap. The latest data release of the DESI (Dark Energy Spectroscopic Instrument; DESI Collaboration et al. 2016) legacy imaging surveys provides five-band photometry over a sky area of about 20,000 deg² in both northern and southern Galactic caps (Dey et al. 2019). They are composed of three optical components in grz bands and one near-infrared component from the Wide-field Infrared Survey Explorer (WISE) satellite. We have obtained a catalog of accurate photo-zs and stellar masses for more than 0.3 billion morphologically classified galaxies with r < 23 mag and in the redshift range of z < 1 (Zou et al. 2019). Based on this catalog, we intend to identify a large sample of galaxy clusters by applying the CFSFDP algorithm. Combining existing and future spectroscopic data (e.g., SDSS/eBOSS and DESI), we will further statistically investigate the properties of clusters and their member galaxies, environment effect on galaxy evolution, gas inflow and outflow of ICM, and large-scale structures, etc.

This paper is the first of our series work and is organized as follows. Section 2 briefly describes the imaging data and photo-z catalog. Section 3 introduces our detection method for galaxy clusters. In this section, we apply Monte Carlo simulations to analyze the false-detection rate of our method. The cluster mass and richness are also estimated. Section 4 presents the cross-matching with the Abell and other cluster catalogs based on SDSS data. Section 5 gives a summary.
we assume a $\Lambda$CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. Imaging Data and Photo-z

The DESI is planned to conduct a large-scale spectroscopic survey with 5000-fiber robots installed on the focal plane of the 4 m Mayall telescope at Kitt Peak, Arizona (DESI Collaboration et al. 2016). It will measure the redshifts of about 35 million galaxies and quasars over a 5 yr period, aiming to explore the structure growth and expansion history of the universe. The DESI legacy imaging surveys are designed to provide spectroscopic targets for DESI. They are composed of three public optical surveys including the Beijing-Arizona Sky Survey (Zou et al. 2017), the Dark Energy Camera Legacy Survey (Blum et al. 2016), and the Mayall z-band legacy survey (Silva et al. 2016), which jointly image a sky area of $\sim 14,000 \text{ deg}^2$ in the $g$, $r$, and $z$ bands. The legacy surveys also integrate the latest WISE observations and provide deep force photometry when constructing the phot-z catalog. In order to make the redshift slice can be traced and clustered in the galaxy we have successfully applied some quality cuts to get clean galaxy samples to meet the following conditions:

$$
\text{MAG}_R < -20.5,
\text{PHOTO}_Z < 0.1,
$$

where $\text{MAG}_R$ is the $r$-band absolute magnitude and $\text{PHOTO}_Z$ is the photo-$z$ error. The cut of the photo-$z$ error is used to eliminate galaxies with a large photo-$z$ uncertainty. The cut of the absolute magnitude is set to keep more luminous galaxies and hence improve completeness. Finally, a total of 0.18 billion galaxies are left for identifying clusters in the rest of this paper.

3. Cluster Identification

3.1. Detecting Method

The CFSFDP approach was first proposed by Rodriguez & Laio (2014) and has been widely used for cluster analyses in a wide range of fields. In this approach, the cluster center is the point that has a higher density than its neighbors, while adequately far away from other points with higher densities. It was demonstrated that this approach can intuitively detect clusters and their members and automatically exclude the outliers. The CFSFDP is characterized by the algorithm’s simplicity and efficiency so that it is very suitable for identifying galaxy clusters in astronomical photometric surveys. We have successfully applied this approach to find clusters in the south Galactic cap with photo-$z$ based on the multiband data from SCUSS, SDSS, and unWISE (Gao et al. 2020). The photometric redshifts are used to project the galaxies onto the 2D sky plane and then the CFSFDP is used to identify the overdensity peaks. We adopt a similar method to that used in Gao et al. (2020). The details of the cluster-detecting process are described below.

1. Galaxies in our photo-$z$ catalog are divided into small equal-area sky patches (or pixels) in the Hierarchical Equal Area and isoLatitude Pixelisation (HEALPix) projection. We adopt the resolution parameter of $\text{nside} = 64$, giving each HEALPix pixel area of about 0.89 $\text{ deg}^2$. The above pixelation is to facilitate the parallelization of cluster detecting.

2. For each galaxy at a given redshift $z$ in a specified HEALPix pixel, we calculate the local density ($\Phi$) and background density ($\Phi_{\text{bkg}}$). These two quantities are computed from the galaxies in this pixel and its surrounding eight neighbor pixels, which have a total area of about 8 $\text{ deg}^2$. The area is large enough to estimate a proper local background. $\Phi$ is computed as the number of galaxies with distance $R < 0.5 \text{ Mpc}$ in a redshift slice of $z \pm 0.04 (1 + z)$. $\Phi_{\text{bkg}}$ is computed as the number of galaxies with $R > 1 \text{ Mpc}$ to avoid the possible cluster region) in the same redshift slice. The background density is scaled to the same area as used in the calculation of the local density. Another crucial parameter $D$ in megaparsecs is defined as the shortest distance of the specified galaxy to other galaxies with higher $\Phi$.

3. The cluster centers should be located on the overdensity peaks with a large-enough local density and adequately far away from other peaks. They are identified as the galaxies with $\Phi > 4\Phi_{\text{bkg}}$ and $D > 1$ (typical cluster radius is less than 1 Mpc). If there are multiple galaxies with the same local density, we assign the brightest galaxy in the $r$ band to be the cluster center. This cluster center is not always the brightest cluster galaxy (BCG) that is usually close to the densest region. We simply regard the $r$-band brightest galaxy within 0.5 Mpc around the density peak as the BCG. Because each galaxy is pointed to the nearest neighbor with a higher $\Phi$, the galaxies in the redshift slice can be traced and clustered in the cluster center. The clustered galaxies are roughly considered to be the member candidates. With these members, we can calculate the average position and redshift for each cluster.

4. The number of member galaxies within 1 Mpc around the cluster center are calculated, which is subtracted from the local background and denoted by $N_1$. Thus, $N_1$ is regarded as the first-order approximation of the cluster richness. We require that clusters should have $N_1 > 10$. The total $r$-band luminosity of member galaxies around the cluster center ($L_1$) is calculated in units of $L^\prime$, where $L^\prime$ is the characteristic luminosity. $L_1$ will be used as a proxy of the cluster mass and richness later. When calculating $L_1$, we also subtract the background luminosity that is estimated.
in the same way as $\Phi_{\text{bkg}}$. Note that the richness and luminosity in this paper are not corrected for the variation of the imaging depth. Such corrections are quite complicated due to the mixed nature of our data from three different optical surveys plus the WISE infrared survey and the selection of the photo-$z$ sample. Actually, more than 90% of the area has a 5σ $r$-band magnitude limit larger than 23.4 mag. As presented in Zou et al. (2019), the completeness of galaxies at $r < 23$, which is the magnitude cut for the photo-$z$ catalog used in this paper, is higher than 90%. As a preliminary estimate, the correction for the richness or luminosity would be less than 10%.

The above process is performed over the photo-$z$ catalog. Finally, we obtain a catalog of 540,432 galaxy clusters at $z \lesssim 1$. The catalog content is described in Appendix A. Figure 1 presents four examples of our detected clusters at different redshifts. As can be seen from this figure, the prominent overdensity features of galaxies make them easily identified from our imaging data by using the above cluster-finding method.

3.2. Reliability Analysis

The cluster-detecting process is executed in relatively large redshift slices due to the photo-$z$ uncertainty. The projection
effect will inevitably be introduced and hence cause false cluster detections. In addition, the local background fluctuation will contaminate the low-richness clusters. We perform a Monte Carlo simulation to evaluate the detecting approach and estimate the false-detection rate following a method similar to Wen & Han (2011). The simulation is based on the actual photometric data, and the specific steps are described as follows. (1) An arbitrary region with an area of 400 deg$^2$ is selected in our photo-$z$ catalog. (2) Galaxies in this region are redistributed on the sky with random walks from original locations in the range of 1–2.5 Mpc, and then their redshifts are shuffled. This step can generate new random galaxy backgrounds and meanwhile retain the projection effect to some degree. (3) The same clustering detection process used in this paper is applied to these mock galaxies and to finding fictitious clusters.

We make a total of 10 simulations and identify the false detections in these simulations. The false rate is defined as the ratio of the number of false clusters identified in the simulation to the number of detected clusters in the original catalog. Figure 2 presents the average false rate of the above 10 simulations as functions of redshift and $N_{1\text{Mpc}}$. From this figure, we can see that the false rate generally increases with redshift and decreases with $N_{1\text{Mpc}}$. In other words, the contamination of our detections is more serious for distant or low-richness clusters. The overall false rate is about 3.1%, and it can go up to about 7%–8% at high redshift and the lowest richness.

It should be noted that the above simulations can estimate the false detections induced by chance associations and part of the false detections caused by the projection effect of uncorrelated structures, because we generate random galaxy backgrounds with limited position changes. Nevertheless, the projection effects include the impacts from both correlated and uncorrelated large-scale structures. It is very important to estimate their effect on basic cluster properties (e.g., richness and halo mass), especially when the cluster catalog is used to constrain the cosmological parameters. For example, Costanzi et al. (2019) combined both real data and numerical simulations to characterize the impact of projection effects on the redMaPPer cluster catalog, and they found that the projection effect obviously biases the cosmological parameter measurements. Principally, we can use the mock catalogs from N-body simulations to assess the reliability of our cluster finder. However, the synthetic data are model dependent and are probably biased compared to realistic observations, such as the halo occupation distribution of cluster galaxies, galaxy color distributions, photometric uncertainty, and corresponding photo-$z$ uncertainty. Considering the complexity of the projection effects, we expect an investigation of their impact on the reliability of our detecting method and on the following mass estimation in future work.

3.3. Mass and Richness Estimation

The X-ray and SZ surveys provide large samples of galaxy clusters at different redshifts, which have reasonable estimates of the cluster mass with a relatively small intrinsic scatter. The observables, such as luminosity and temperature in X-ray and the integrated Comptonization parameter (or SZ parameter), are tightly linking to the cluster mass via scaling relations. Wen & Han (2015) collected a sample of 1192 clusters from the literature and scaled the cluster masses derived by different authors to a unified calibration. These samples are limited to match the galaxy clusters identified from SDSS, with the maximum redshift of 0.75. The clusters at high redshift are insufficient, so we supplement the sample of Wen & Han (2015) with other clusters from X-ray and SZ observations (Piffaretti et al. 2011; Takey et al. 2013, 2014; Wen & Han 2015; Planck Collaboration et al. 2016b; Takey et al. 2016). The cluster masses in different catalogs were estimated using different mass proxies and scaling relations, so it is necessary to recalibrate the masses. So, we use the rescaling relations derived by Wen & Han (2015) to calibrate the cluster mass for these additional data. All of the cluster masses are rescaled to the standard of Vikhlinin et al. (2009). We should note that the published Planck catalog has not applied the Eddington bias correction, which can systematically bias the SZ masses (Battaglia et al. 2016; Medezinski et al. 2018). The above recalibration process can reduce this kind of systematic effect. Here, the cluster mass is denoted as $M_{500}$, which is the
mass within a characteristic radius \(R_{500}\). \(R_{500}\) is defined as the radius within which the mean density of a cluster is 500 times the critical density of the universe \(\rho_c\). According to the definition, \(M_{500}\) and \(R_{500}\) satisfy the following relation:

\[
M_{500} = \frac{4\pi}{3} R_{500}^3 \times 500 \rho_c. \tag{2}
\]

We collect 3157 clusters with reliable estimations of \(M_{500}\) and \(R_{500}\), which spreads over the whole celestial sphere. They are listed in a separate table, Table 3 in Appendix B, which we call the calibration catalog.

As described in Gao et al. (2020), \(L_{1\text{Mpc}}\) is used as an optical proxy of the cluster mass. We also use \(L_{1\text{Mpc}}\) to estimate the total mass of our clusters. The galaxy clusters detected in this work are cross-matched with the clusters in the calibration catalog of Table 3, following a similar procedure in Bleem et al. (2020): (1) ranking the clusters in the calibration catalog by decreasing mass (equivalent to the richness), (2) matching each cluster in the calibration catalog to the richest cluster in our catalog with a redshift error of \(\Delta z = 0.06 (1 + z)\) and a projected separation error of 1 Mpc, (3) removing each matched cluster from our catalog and repeating the above matching process for all clusters in the calibration catalog. As a result, we find 1797 matched clusters that can be used to determine the relation between \(L_{1\text{Mpc}}\) and \(M_{500}\). The left panel of Figure 3 shows \(M_{500}\) as a function of \(L_{1\text{Mpc}}\). We can see that there is a tight correlation between these two quantities. The correlation can be described by the following equation:

\[
\log(M_{500}) = a \log(L_{1\text{Mpc}}) + b \log(1 + z) + c,
\]

or \(M_{500} = 10^c L_{1\text{Mpc}}^b (1 + z)^a\), \tag{3}

where \(a\), \(b\), and \(c\) are constants to be determined, and the term \((1 + z)\) is regarded as the correction term for the redshift evolution and incompleteness.

The above luminosity–mass relation suffers from Malmquist bias, but also induces the complication of the bias correction. We hope to further investigate this problem in the future. Considering the bias, we assign the data with a weight of \(L_{1\text{Mpc}}/z\) when fitting the data with Equation (3). This will put more weight on the clusters with larger richness and at lower redshift.

The residual is biased at high redshift, partly reflecting the Malmquist bias. We apply Equation (3) to estimate \(M_{500}\) and Equation (2) to estimate \(R_{500}\) for our detected clusters. We also use Equation (17) in Wen & Han (2015) to estimate the richness. These parameters are included in Table 2.

### 3.4. Cluster Statistics and Photo-z Accuracy

Figure 4 shows the parameter distributions for the 540,432 galaxy clusters detected in this paper. The median redshift is about 0.53, and the number density decreases at \(z > \sim 0.6\), where the cluster detection should be more incomplete. The median richness is about 22.5. The range of the total mass \(\log(M_{500})\) is 13.5–14.8, and the median is about 14.1 (equivalent to \(1.23 \times 10^{14} M_\odot\)). The characteristic radius of \(R_{500}\) ranges from about 0.4 to 1.0 Mpc, and the median value is about 0.63 Mpc.

Figure 5 displays both the distributions of \(r\)-band depth and number density of our clusters over the DESI imaging footprint. Note that the depth is referred to as the 5\(\sigma\) \(r\)-band magnitude limit for extended sources with the correction of the Galactic extinction. The depth map in Figure 5(a) shows three distinct regions with different imaging depths, which reflects the fact that the observing data were obtained by different facilities. The general depth differences among these three components are about 0.6 mag. Although the depth is inhomogeneous across the survey footprint, we still obtain uniformly distributed cluster samples, attributed to the relatively conservative magnitude cut of our photo-z catalog (see Figure 5(b)). In order to more clearly show the effect of the imaging depth on our cluster detection, we present the number densities as a function of redshift for three subsamples of our
clusters under different $r$-band depths in Figure 6. From this figure, we can see that the imaging depth only affects the cluster detection at $z > 0.4$. More clusters are detected in the deeper area, and it becomes more pronounced as the redshift increases.

The photo-$z$ accuracy of our galaxy clusters is estimated by comparing the photometric redshifts of the BCGs in our catalog with the spectroscopic redshifts collected by Zou et al. (2019). There are a total of 122,390 BCGs with spectroscopic redshifts. The top panel of Figure 7 shows the comparison between the photometric redshift ($z_{\text{phot}}$) and spectroscopic redshift ($z_{\text{spec}}$). The bottom panel presents the photo-$z$ accuracy of $\Delta z_{\text{norm}} = (z_{\text{phot}} - z_{\text{spec}})/(1 + z_{\text{spec}})$ as a function of $z_{\text{spec}}$. We can see that the photo-$z$ accuracy changes from about 0.01 at $z \sim 0.1$ to about 0.024 at $z \sim 0.9$. The redshift histogram in Figure 8 shows the distribution of $\sigma_{\Delta z_{\text{norm}}}$ of the total sample. The overall photo-$z$ accuracy is $\sigma_{\Delta z_{\text{norm}}} = 0.012$. In addition, most of the galaxy clusters used for mass calibration as described in Section 3.3 have reliable redshifts. We also estimate our cluster photo-$z$ accuracy using these confirmed clusters, which is shown in the blue histogram of Figure 8. Such a comparison also gives a similar photo-$z$ accuracy of $\sigma_{\Delta z_{\text{norm}}} = 0.013$. 

Figure 4. Distributions of redshift (a), richness (b), log($M_{200}$) (c), and $R_{500}$ (d) for our clusters.

Figure 5. (a) The $r$-band depth map in Mollview projection. (b) Number density distribution of our detected clusters.

Figure 6. Number density as a function of redshift for three subsamples of our clusters under different $r$-band imaging depths. The redshift bin is 0.1.

Figure 7. (a) Comparison between photometric and spectroscopic redshifts of the BCGs in our cluster catalog. The diagonal line denotes $z_{\text{phot}} = z_{\text{spec}}$. (b) $\Delta z_{\text{norm}}$ as a function of $z_{\text{spec}}$. The red diamonds and blue crosses display the medians and standard deviations in different redshift bins.

Figure 8. Redshift histogram of the total sample.
4. Matching with Other Cluster Catalogs

The most famous cluster catalog is the Abell catalog, which was constructed by visual identification on the photographic plates. There are also several catalogs of galaxy clusters identified from the SDSS photometric data. These catalogs are either based on the red-sequence feature or the overdensity feature in the photo-z space. By matching our catalog with these catalogs, we can check the detected repeatability of the clusters from both shallower photometric data and deeper DESI imaging data. Such comparisons can also indicate the reliability of our cluster detection. The Abell clusters were visually identified as galaxy overdensities (Abell et al. 1989). Among other catalogs that are based on SDSS data, the clusters of MaxBCG (Koester et al. 2007), GMBCG (Hao et al. 2010), and redMaPPer (Rykoff et al. 2014) were identified through the red-sequence feature, while the clusters of AMF (Rykoff et al. 2014) and WHL15 (Wen & Han 2015) were obtained using the overdensity feature. We summarize the redshift range, adopted method, and number of clusters in the DESI footprint of these catalogs in Table 1. If the clusters in the Abell catalog have spectroscopic redshifts, we use their spectroscopic redshifts as the distance indicator. For those clusters without redshifts in the Abell catalog, we only use our photo-z as the distance tracer to match the clusters. The projected separation is limited to 1 Mpc, which is set to be a little larger than the characteristic radius $R_{500}$ of most clusters as shown in Figure 9). For the SDSS cluster catalogs, we match them with our cluster catalog using a redshift tolerance of $\Delta z < 0.06 (1 + z)$ and the same separation tolerance. The larger the separation tolerance is set, the more real clusters would be matched in consideration of the uncertainty of the cluster center, while more possible false association would occur and vice versa. The matching results with our catalog are listed in Table 1.

As checked, most of the mismatched clusters in those catalogs based on the SDSS data are the clusters with lower richness or at higher redshift, which are possible false detections. We select two representative catalogs, redMaPPer and WHL15, to show the matching rates as a function of redshift and richness and present the comparison of richness and redshift with those in our catalog in Figure 9. Generally, the matching rate increases as the richness increases or the redshift decreases. The richnesses among these catalogs show good correlations, although there are somewhat large scatters. The photo-z also shows pretty good correlations. Compared to the WHL15 photo-z, the photo-z of the redMaPPer clusters is more consistent with that of our clusters.

5. Summary

Galaxy clusters are excellent probes for studying galaxy formation and evolution in dense environments, and they can be also used to constrain cosmological parameters. Using the photometric redshift catalog of Zou et al. (2019), we identify a catalog of galaxy clusters over the 20,000 deg$^2$ sky footprint of the DESI legacy imaging surveys. This sample of clusters will be used to statistically study the galaxy clusters at $z < 1$, the galaxy environment, ICM, large-scale structures of the universe, etc. As the first in a series of works, this paper is focused on cluster detection.

In total, we identify 540,432 galaxy clusters with $z \lesssim 1$. These clusters are uniformly distributed over the imaging footprint. Monte Carlo simulations show that the false-detection rate is about 3.1%, and it becomes worse as the redshift increases or the richness decreases. The false rate at high redshift or low richness can reach up to about 8%. We utilize the mass measurements from X-ray and radio observations to calibrate the total mass and richness of the detected clusters.
clusters by using the optical luminosity $L_{1\text{Mpc}}$. The median mass and richness are about $1.23 \times 10^{14} M_\odot$ and 22.5, respectively. Comparing our catalog with the Abell catalog, we can recover almost all Abell clusters. We also compare our detected clusters with those based on the SDSS data that are about 2 mag shallower than the DESI imaging surveys. We found that we can recognize most of the clusters identified from SDSS, especially those with high richness.

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The Legacy Surveys consist of three individual and complementary projects: the Dark Energy Camera Legacy Survey (DECaLS; NOAO Proposal ID # 2014B-0404; PIs: David Schlegel and Arjun Dey), the Beijing-Arizona Sky Survey (BASS; NOAO Proposal ID # 2015A-0801; PIs: Zhou Xu and Xiaohui Fan), and the Mayall z-band Legacy Survey (MzLS; NOAO Proposal ID # 2016A-0453; PI: Arjun Dey). DECaLS, BASS, and MzLS together include data obtained, respectively, at the Blanco telescope, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory (NOAO); the Bok Telescope, Steward Observatory, University of Arizona; and the Mayall telescope, Kitt Peak National Observatory, NOAO. The Legacy Surveys project is honored to be permitted to conduct astronomical research on Iolkam Du’ag (Kitt Peak), a mountain with particular significance to the Tohono O’odham Nation.

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Appendix A
Information about Our Cluster Catalog

In total, we obtain 540,432 galaxy clusters with a false-detection rate of about 3.1%. Table 2 lists the content contained in our catalog. It includes the position and redshift of the cluster center, which is the galaxy at the local density peak. The catalog also includes basic information on the BCG including the position, redshift, observed magnitudes, absolute magnitudes, and stellar mass, which are inherited from the photo-z catalog. The cluster properties estimated in this paper are also contained in this catalog. This catalog will be uploaded to CDS, and it is also available at http://batc.bao.ac.cn/~zouhu/doku.php?id=projects:desi_clusters:start.

Table 2
Column Description for Our Cluster Catalog

| Column       | Unit   | Format | Description                                                                 |
|--------------|--------|--------|-----------------------------------------------------------------------------|
| CLUSTER_ID   |        | Long   | Cluster ID                                                                  |
| RA_PEAk      | degree | Double | R.A. for the density peak (J2000)                                           |
| DEC_PEAk     | degree | Double | Decl. for the density peak (J2000)                                          |
| PZ_PEAk      | Float  |        | Photometric redshift for the density peak                                  |
| SZ_PEAk      | Float  |        | Spectroscopic redshift for the density peak if existing; set to −10 if null |
| DEN_PEAk     | Integer|        | Local density Φ for the density peak                                       |
| BKG_PEAk     | Float  |        | Local background density Φ_bkg for the density peak                        |
| RA_MEAN      | degree | Double | Mean R. A. of possible members                                              |
| DEC_MEAN     | degree | Double | Mean decl. of possible members                                              |
| N_1MPC       | Integer|        | Number of member galaxies within 1 Mpc from the cluster center             |
| L_1MPC       | Float  |        | Total luminosity of member galaxies within 1 Mpc from the cluster center   |
| M_500        | log10(M_*) | Float | Total mass of the cluster M_500                                            |
| R_500        | Mpc    | Float  | Characteristic radius R_500                                                |
| RICHNESS     | Float  |        | Cluster richness                                                            |
| RA_BCG       | degree | Double | R.A. for the BCG (J2000)                                                    |
| DEC_BCG      | degree | Double | Decl. for the BCG (J2000)                                                   |
| PZ_BCG       | Float  |        | Photometric redshift for the BCG                                            |
| PZERR_BCG    | Float  |        | Photometric redshift error for the BCG                                      |
| SZ_BCG       | Float  |        | Spectroscopic redshift for the BCG if existing; set to −10 if null         |
| MAG_G_BCG    | mag    | Float  | g-band magnitude for the BCG                                                |
| MAG_R_BCG    | mag    | Float  | r-band magnitude for the BCG                                                |
| MAG_Z_BCG    | mag    | Float  | z-band magnitude for the BCG                                                |
| MAG_W1_BCG   | mag    | Float  | W1-band magnitude for the BCG                                               |
| MAG_W2_BCG   | mag    | Float  | W2-band magnitude for the BCG                                               |
| MAGERR_G_BCG | mag    | Float  | g-band magnitude error for the BCG                                          |
| MAGERR_R_BCG | mag    | Float  | r-band magnitude error for the BCG                                          |
| MAGERR_Z_BCG | mag    | Float  | z-band magnitude error for the BCG                                          |
| MAGERR_W1_BCG| mag    | Float  | W1-band magnitude error for the BCG                                         |
| MAGERR_W2_BCG| mag    | Float  | W2-band magnitude error for the BCG                                         |
| MAG_ABS_G_BCG| mag    | Float  | g-band absolute magnitude for the BCG                                       |
| MAG_ABS_R_BCG| mag    | Float  | r-band absolute magnitude for the BCG                                       |

6 http://batc.bao.ac.cn/~zouhu/doku.php?id=projects:desi_photoz:start
Table 2 (Continued)

| Column                     | Unit  | Format | Description                      |
|----------------------------|-------|--------|----------------------------------|
| MAG_ABS_Z_BCG              | mag   | Float  | z-band absolute magnitude for the BCG |
| MAG_ABS_W1_BCG             | mag   | Float  | W1-band absolute magnitude for the BCG |
| MAG_ABS_W2_BCG             | mag   | Float  | W2-band absolute magnitude for the BCG |
| MASS_BEST_BCG              | log₁₀(Mₜₜ) | Float | Logarithmic stellar mass for the BCG |
| MASS_INF_BCG               | log₁₀(Mₜₜ) | Float | Lower limit of the logarithmic stellar mass with 68% confidence level for the BCG; set to −99 if null |
| MASS_SUP_BCG               | log₁₀(Mₜₜ) | Float | Upper limit of the logarithmic stellar mass with 68% confidence level for the BCG; set to −99 if null |

(This table is available in its entirety in FITS format.)

Table 3

| ID (1) | R.A. (2) | Decl. (3) | Z (4) | M500 (5) | E_M500 (6) | R500 (7) | E_R500 (8) | REF (9) |
|--------|----------|-----------|-------|----------|------------|----------|-----------|--------|
| 1      | 4.57107  | 16.29432  | 0.55  | 4.11     | 0.77       | 0.06     | W15       |        |
| 2      | 8.32687  | −21.41319 | 0.19  | 0.99     | 0.20       | 0.66     | 0.04      | T13     |
| 3      | 9.82501  | 0.69981   | 0.28  | 0.66     | 0.13       | 0.56     | 0.04      | W15     |
| 4      | 9.84351  | 0.80273   | 0.41  | 1.62     | 0.31       | 0.72     | 0.05      | T13, T16|
| 5      | 9.92591  | 0.75922   | 0.42  | 1.27     | 0.25       | 0.66     | 0.04      | T13, T16|
| 6      | 10.16344 | 25.51840  | 0.15  | 1.24     | 0.24       | 0.72     | 0.04      | T13     |
| 7      | 10.48690 | 25.53105  | 0.13  | 0.93     | 0.19       | 0.66     | 0.04      | T13     |
| 8      | 10.62969 | 0.85368   | 0.16  | 0.69     | 0.15       | 0.59     | 0.04      | T13, T16|
| 9      | 10.71922 | 0.71671   | 0.27  | 1.16     | 0.23       | 0.68     | 0.04      | T13, T16|
| 10     | 10.72397 | −9.57311  | 0.41  | 1.49     | 0.29       | 0.70     | 0.05      | T13     |

Note. (1) Sequence number. (2) R.A. in degrees (J2000). (3) Decl. in degrees (J2000). (4) Redshift. (5) Total mass Mₕₕₒ in 10¹⁴ Mₜₜ. (6) Error of Mₕₕₒ in 10¹⁴ Mₜₜ. (7) Rₕₕₒ in megaparsecs. (8) Error of Rₕₕₒ in megaparsecs. (9) References: P15 for Piffaretti et al. (2011), P15 for Planck Collaboration et al. (2016b), E15 for Wen & Han (2015), T13 for Takey et al. (2013), T14 for Takey et al. (2014), and T16 for Takey et al. (2016). (This table is also available at http://bact.bao.ac.cn/~zouhu/doku.php?id=projects:desi_clusters:start.)

This table is available in its entirety in FITS format.

Appendix B

Galaxy Clusters with the Total Mass Measurements from X-Ray and SZ-effect Observations

Table 3 lists the galaxy clusters detected by X-ray and SZ-effect observations, and their total masses are effectively estimated and rescaled by us to a unified calibration. The characteristic radius of Rₕₕₒ is calculated according to Equation (2).

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