Photometric Redshifts and Galaxy Clusters for DES DR2, DESI DR9, and HSC-SSP PDR3 Data

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Abstract

Photometric redshift (photoz) is a fundamental parameter for multi-wavelength photometric surveys, while galaxy clusters are important cosmological probes and ideal objects for exploring the dense environmental impact on galaxy evolution. We extend our previous work on estimating photoz and detecting galaxy clusters to the latest data releases of the Dark Energy Spectroscopic Instrument (DESI) imaging surveys, Dark Energy Survey (DES) and Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP) imaging surveys and make corresponding catalogs publicly available for more extensive scientific applications. The photoz catalogs include accurate measurements of photoz and stellar mass for about 320, 293 and 134 million galaxies with $r < 23, i < 24$ and $i < 25$ in DESI DR9, DES DR2 and HSC-SSP PDR3 data, respectively. The photoz accuracy is about 0.017, 0.024 and 0.029 and the general redshift coverage is $z < 1$, $z < 1.2$ and $z < 1.6$, respectively for those three surveys. The uncertainty of the logarithmic stellar mass that is inferred from stellar population synthesis fitting is about 0.2 dex. With the above photoz catalogs, galaxy clusters are detected using a fast cluster-finding algorithm. A total of 532,810, 86,963 and 36,566 galaxy clusters with the number of members larger than 10 is discovered for DESI, DES and HSC-SSP, respectively. Their photoz accuracy is at the level of 0.01. The total mass of our clusters is also estimated by using the calibration relations between the optical richness and the mass measurement from X-ray and radio observations. The photoz and cluster catalogs are available at ScienceDB (https://www.doi.org/10.11922/sciencedb.o00069.00003) and PaperData Repository (https://doi.org/10.12149/101089).

Key words: galaxies: clusters: general – galaxies: distances and redshifts – galaxies: photometry

1. Introduction

Our understanding of the formation and evolution of the universe owes a great deal to modern large-scale imaging and spectroscopic surveys. One of the important parameters to be measured for astronomical objects is redshift (or equivalently distance), which is crucial to explore galaxy evolution and cosmology. Although spectroscopic observations can provide accurate redshift measurements, they are time-consuming and flux-limited. The techniques of estimating photometric redshift (photoz) become more and more important and even indispensable to the successes for some wide and deep imaging surveys, such as Dark Energy Survey (DES; The Dark Energy Survey Collaboration 2005), Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP; Aihara et al. 2018), Legacy Survey of Space and Time (LSST; LSST Science Collaboration et al. 2009) and the Euclid mission (Laureijs et al. 2010). One of the photoz applications is to detect galaxy clusters, which are also important scientific objects in the above surveys. Galaxy clusters have been formed on the cosmic web. They trace the large-scale structure and are ideal laboratories to study the environmental effect on galaxy formation and evolution. As the largest gravitationally bound systems in the universe, galaxy clusters have been effectively detected in large-scale imaging surveys (Hao et al. 2010; Rykoff et al. 2014, 2016; Zou et al. 2021).

In January 2021, DES made the second public data release (hereafter DES DR2; Abbott et al. 2021). This release covers a sky area of $\sim$5000 deg$^2$ in the South Galactic Cap. The 10σ $i$-band magnitude limit is about 23.8 mag. In August 2021, HSC-SSP announced the third public release (hereafter HSC-SSP PDR3; Aihara et al. 2022). The PDR3 release covers about 670 deg$^2$ in the wide layer at the 5σ depth of $i \sim 26$ mag and more than 30 deg$^2$ in the deep/ultra deep layer at the 5σ depth of $i \sim 27$ mag. In January 2021, the imaging team of the Dark Energy Spectroscopic Instrument (DESI) project published the ninth data release (hereafter DESI DR9). It covers a sky area of $\sim$20,000 deg$^2$ in both the South and North Galactic Caps. The 5σ magnitude limit is about $r \sim 23.9$ mag.

DESI has not published the catalogs of photoz and galaxy clusters yet. Although the HSC-SSP data releases previous to PDR3 have photoz products, the associated PDR3 photoz catalogs have not been delivered. The PDR3 significantly increases the sky area with all five filters to the required depths relative to the previous releases. We have successfully applied a local linear regression algorithm to accurately estimate the
photos for galaxies from the South Galactic u-band Sky Survey (SCUSS) and DESI Legacy Imaging Surveys (Gao et al. 2018; Zou et al. 2019). The resulting photoz accuracy is at the level of 0.02. With these photoz catalogs, we also developed a new cluster-finding method to identify galaxy clusters. A total of about 20,000 clusters in SCUSS and 540,000 clusters in DESI have been found (Gao et al. 2020; Zou et al. 2021).

In this paper, we will generate new photoz catalogs specifically for DES DR2 and HSC-SSP PDR3 data and update our photometric redshifts for the DESI imaging surveys to the latest DR9 data. Meanwhile, based on these photoz measurements, we will derive reliable stellar masses for galaxies and detect a large number of galaxy clusters. Combining all these data, we can substantially extend the mass and redshift coverages of both galaxies and galaxy clusters. The catalogs can be made publicly available immediately, which will be superbly useful for further sciences. The structure of this paper is organized as follows. Section 2 describes the photometric and spectroscopic data. Section 3 presents the photoz and stellar mass measurements. Section 4 shows the detection of galaxy clusters. Section 5 gives a summary. Throughout this paper, we assume a ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. Data

2.1. Photometric Data and Galaxy Sample

2.1.1. DES DR2

DES is an imaging survey of about 5000 deg$^2$ in the southern sky (The Dark Energy Survey Collaboration 2005), using the wide-field Dark Energy Camera (Flaugher et al. 2015) installed on the 4 m Blanco telescope. The main goal of DES is to study dark energy via constructing the three-dimensional (3-D) distribution of galaxies using photometric redshifts. The adopted photometric system includes five optical broad filters (i.e., $grizY$). The first data release, DES DR1, was published in 2018 (Abbott et al. 2018). It includes the observations taken in the first three years. The DES DR2 was made publicly available in 2021. It includes the data products assembled over all six years of DES science observations (Abbott et al. 2021). The sky coverage with all five-band photometry is about 4900 deg$^2$. The magnitude limits at signal to noise ratio (S/N) = 5 for point sources are $g = 25.4$, $r = 25.1$, $i = 24.5$, $z = 23.8$ and $Y = 22.4$.

Galaxies in DES DR2 are selected using the following criteria:

1. mag$_{\text{auto}}-i$ $< 24$ (magnitude cut for $i$ band)
2. imaflags$-i = 0$ (good photometric flag in $i$ band)
3. flags$-i < 4$ (good photometric flag in $i$ band)
4. extended_class_coadd $\geq 2$ (galaxy type)

Note that all the photometric magnitudes used in the following of this paper are corrected for the Galactic extinction. Finally, we select 292,636,425 galaxies with $i < 24$.

2.1.2. HSC-SSP PDR3

HSC-SSP uses a wide-field imaging camera deployed on the 8.2 m Subaru telescope to carry out a wide and deep imaging survey (Aihara et al. 2018). The survey includes three layers. The Wide layer is planned to cover about 1400 deg$^2$ in five broad bands of $grizY$. The Deep and UltraDeep layers will cover more than 30 deg$^2$ in the five broad-band filters and four narrow-band filters. The 5σ magnitude limits are one and two magnitudes deeper than the Wide layer, respectively. The latest data release of HSC-SSP is PDR3 (Aihara et al. 2022), which was publicly accessible in August 2021. This release increases the sky coverage with full five-band photometry by two times more than PDR2. We only consider the Wide layer in this paper. The 5σ depths for point sources in the Wide layer are $g = 26.5$, $r = 26.5$, $i = 26.2$, $z = 25.2$, and $Y = 24.4$.

In HSC-SSP PDR3, we use the forced measurements in which common object centroids and shape parameters are utilized for photometry in all filters. Galaxies in PDR3 “forced” catalogs are selected utilizing the following criteria:

1. isprimary = True (no duplicates)
2. i$_{\text{cmdflag}}-m < 25$ (magnitude cut in $i$ band)
3. [ri]$_{\text{extendedness}}-value = 1$ (galaxy type in both $r$ and $i$ bands)
4. [ri]$_{\text{cmdflag}}$ = False (good photometric flag in both $r$ and $i$ bands)
5. [ri]$_{\text{extendedness}}$ = False (good classification in both $r$ and $i$ bands)
6. [ri]$_{\text{pixelflags}}$-saturatedcenter (no saturated objects)

In this way, we select 133,554,787 galaxies with $i < 25$.

2.1.3. DECaLS DR9

The legacy imaging surveys of DECaLS consist of three independent optical surveys conducted by three teams using three different telescopes (Dey et al. 2019): the Beijing-Arizona Sky Survey (BASS; Zou et al. 2017), Mayall z-band Legacy Survey (MzLS), and DECam Legacy Survey (DECaLS). BASS employs the 2.3 m Bok telescope on Kitt Peak, Arizona to survey a sky area of 5000 deg$^2$ with $g$ and $r$ bands in the North Galactic Cap. MzLS covers the same area using the 4 m Mayall telescope on Kitt Peak with z band. DECaLS relies on the 4 m Blanco telescope to take $grizY$-band imaging over 9000 deg$^2$ along the equator in both North and South Galactic Caps. In addition, the DECaLS imaging team makes new coadds of WISE.

3 https://des.ncsa.illinois.edu/releases/dr2

4 https://hsc-release.mtk.nao.ac.jp/doc/
W1 and W2 observations and performs forced photometry on these near-infrared images. These imaging surveys provide optical and near-infrared photometric data that are mainly used for the target selections of the DESI spectroscopic survey. The latest data release is DR9, which was published in January 2021.\(^5\) The optical-band depths at 5\(\sigma\) are about \(g = 24.7\), \(r = 23.9\), and \(z = 23.0\) mag. The WISE data contain all 6 yr imaging and the 5\(\sigma\) depths are \(W1 = 20.7\) and \(W2 = 20.0\) in AB mag, which are 1 mag deeper than AllWISE.\(^6\) The sky area with all 5-band photometry in DR9 is about 19,000 deg\(^2\).

We select the galaxies in DESI DR9 applying the following criteria:

1. \(\text{mag}_r < 23\) (model magnitude cut in \(r\) band)
2. type \(! =\) PSF (galaxy type)
3. fracmasked\([g,r,z]\) < 0.5 (clean photometric cuts)
4. fracflux\([g,r,z]\) < 0.5 (clean photometric cuts)
5. fracin\([g,r,z]\) > 0.3 (clean photometric cuts)

A total of 320,060,206 galaxies with \(r < 23\) is retained. The magnitude cuts for the above three surveys are roughly selected according to S/N of about 10.

Unless otherwise specified, hereafter we refer to DESI, DES and HSC-SSP for short to DESI DR9, DES DR2 and HSC-SSP PDR3, respectively. Figure 1 presents the sky coverages of all above imaging surveys. The sky areas with full five-band photometry are 19,876, 5194 and 1128 deg\(^2\) for DESI, DES and HSC-SSP, respectively. Table 1 summarizes the survey characteristics.

### 2.2. Spectroscopic Data

The galaxies with spectroscopic redshifts are collected as the training sample to build a photo\(\bar{z}\) estimator and to assess the photo\(\bar{z}\) quality. As described in Zou et al. (2019), we have compiled a spectroscopic redshift catalog from different spectroscopic surveys. Please refer to Table 2 in Zou et al. (2019) for the information and corresponding quality cuts. This redshift catalog is matched with the galaxy catalogs of DES and DESI using a matching radius of 1\(\arcsec\). The numbers of matched galaxies are 469k and 2.8 million for DES and DESI, respectively. The HSC-SSP contains a value-added catalog of public spectroscopic redshifts (Aihara et al. 2022). This catalog supplements galaxies with higher redshift and fainter magnitudes, which can be more suitable for the photo\(\bar{z}\) estimation of the deeper HSC-SSP photometry. We select the galaxies in this value-added catalog with “redshift > 0 & specz_flag_homogeneous = True” and obtain 636k galaxies with spectroscopic redshifts. Figure 2 plots the redshift and magnitude distributions of those spectroscopic galaxy samples in different surveys.

### Table 1

| Survey   | Sky Area (deg\(^2\)) | Depth\(^a\) (mag) |
|----------|----------------------|------------------|
| DESI     | 19,876               | \(g = 24.7, r = 23.9, z = 23.0, W1 = 20.7, W2 = 20.0\) |
| DES      | 5194                 | \(g = 25.4, r = 25.1, i = 24.5, z = 23.8, Y = 22.4\) |
| HSC-SSP  | 1128                 | \(g = 26.5, r = 26.5, i = 26.2, z = 25.2, y = 24.4\) |

Note. \(^a\) The depth here refers to the 5\(\sigma\) limiting magnitude in AB mag.

\(^5\) https://www.legacysurvey.org/dr9/
\(^6\) https://wise2.ipac.caltech.edu/docs/release/allwise/
3. Photoz and Stellar Mass

3.1. Photoz Estimation

The photoz estimation relies on the multi-wavelength photometric data that can construct spectral energy distributions (SEDs) for galaxies. The methods to compute photoz include template-fitting and machine learning. The template-fitting method uses different types of modeled galaxy spectra to match the observed SED (Benítez 2000; Bolzonella et al. 2000; Brammer et al. 2008; Ilbert et al. 2009). It is vital to construct proper theoretical spectral evolutionary models and to eliminate systematic bias in different photometric data when different survey data are combined. The machine learning method tries to establish an empirical relation between the photometric SED and redshift with a training sample that contains galaxies with known redshifts (Carliles et al. 2010; Hogan et al. 2015; Sadeh et al. 2016). This method is usually very efficient in both speed and accuracy, but it is usually difficult to build a fairly representative training sample. This problem is greatly alleviated due to a large number of wide and deep extragalactic spectroscopic surveys.

The photoz estimation algorithm we adopt in this paper is similar to the local linear regression in Beck et al. (2016), which has been utilized for the photoz estimation with ugriz photometry of the Sloan Digital Sky Survey (SDSS). We have applied this method to compute the photoz with 7-band photometry of ugrizW1W2 by combining the SCUSS, SDSS and WISE survey data (Gao et al. 2018) and with 5-band photometry of grzW1W2 from DESI and WISE (Zou et al. 2019). The local linear regression method assumes the relation between the photometric SED and redshift is linear in the local multi-dimensional color space. The locality of a galaxy is determined by the k-nearest neighbors (KNN) algorithm, which selects K galaxies in the training sample with shortest distances in color space. We use these K nearest neighbors with known spectroscopic redshifts to derive the linear regression relation. This relation is then applied to the galaxy whose photoz needs to be measured. During fitting the regression model, we apply a

| Survey      | mag Cut^a | Number^b | Redshift Range^c | Bias     | Dispersion | P_{3σ} | P_{0.15} |
|-------------|------------|-----------|------------------|----------|------------|--------|----------|
| DESI        | r < 23     | 320,060,206 | z < 1.0    | 1.42e-4  | 1.72e-2    | 6.26%  | 0.85%    |
| DES         | r < 24     | 292,636,425 | z < 1.2    | 7.36e-5  | 2.40e-2    | 8.02%  | 2.63%    |
| HSC-SSP     | r < 25     | 133,554,787 | z < 1.6    | -2.72e-4 | 2.92e-2    | 10.02% | 5.24%    |

Notes.

^a Magnitude cut for selecting galaxies to determine the photoz.
^b Number of galaxies selected using the magnitude cut.
^c General photoz range.
3\(\sigma\) clipping algorithm to remove outliers. The root mean square error for the regression is considered as the phot\(z\) uncertainty (Beck et al. 2016; Gao et al. 2018). The number of neighbors (\(K\)) is an important parameter to be determined. For a specified training set, a too large value of \(K\) might destroy the locality and increase the running rate of the phot\(z\) algorithm. Conversely, a too-small value of \(K\) might lead to inadequate neighbors to represent the locality in the color space and hence reduce the phot\(z\) accuracy. We use a small subset of 10,000 galaxies in the training sample to determine \(K\). The phot\(z\) of these galaxies is estimated by the above method using a series of \(K\) values ranging from 25 to 300 (interval of 25). The phot\(z\) accuracy and outlier rate (see corresponding definitions in Section 3.2) are calculated and the best \(K\) is chosen to make sure that the value is as small as possible and at the same time the phot\(z\) accuracy and outlier rate approach their lowest values. As a result, the selection of \(K\) is different for different photometric data sets, which are 200 for DESI, 100 for DES and 150 for HSP-SSP.

3.2. Phot\(z\) Quality

The following quantities are defined to characterize the phot\(z\) quality:

1. bias: the systematic offset between the spectroscopic and photometric redshifts. The offset is defined as
### Table 3

| $z_{\text{spec}}$ | DESI | DES | HSC-SSP |
|------------------|------|-----|---------|
|                  | Bias | Dispersion | $P_{3\sigma}$ | $P_{0.15}$ | Bias | Dispersion | $P_{3\sigma}$ | $P_{0.15}$ | Bias | Dispersion | $P_{3\sigma}$ | $P_{0.15}$ |
| (0.0,0.2)        | $-4.00 \times 10^{-4}$ | $1.37 \times 10^{-2}$ | 4.74% | 0.53% | $1.17 \times 10^{-3}$ | $1.54 \times 10^{-2}$ | 6.83% | 1.71% | $5.23 \times 10^{-3}$ | $2.68 \times 10^{-2}$ | 9.29% | 5.76% |
| (0.2,0.4)        | $1.42 \times 10^{-3}$ | $1.42 \times 10^{-2}$ | 10.20% | 1.76% | $1.47 \times 10^{-3}$ | $2.17 \times 10^{-2}$ | 13.57% | 5.98% | $-2.98 \times 10^{-4}$ | $3.22 \times 10^{-2}$ | 8.63% | 4.42% |
| (0.4,0.6)        | $-1.53 \times 10^{-4}$ | $1.67 \times 10^{-2}$ | 5.01% | 0.29% | $7.99 \times 10^{-4}$ | $1.91 \times 10^{-2}$ | 8.22% | 1.73% | $3.55 \times 10^{-4}$ | $2.31 \times 10^{-2}$ | 8.67% | 1.78% |
| (0.6,0.8)        | $1.89 \times 10^{-3}$ | $2.17 \times 10^{-2}$ | 4.78% | 0.53% | $4.21 \times 10^{-3}$ | $2.76 \times 10^{-2}$ | 5.94% | 1.51% | $-9.89 \times 10^{-4}$ | $2.66 \times 10^{-2}$ | 8.26% | 2.80% |
| (0.8,1.0)        | $-3.16 \times 10^{-3}$ | $2.83 \times 10^{-2}$ | 3.09% | 1.06% | $-5.26 \times 10^{-3}$ | $3.01 \times 10^{-2}$ | 4.00% | 1.25% | $-7.43 \times 10^{-3}$ | $2.90 \times 10^{-2}$ | 7.91% | 3.32% |
| (1.0,1.2)        | $-3.62 \times 10^{-3}$ | $4.39 \times 10^{-2}$ | 4.91% | 0.53% | $1.89 \times 10^{-3}$ | $2.17 \times 10^{-2}$ | 5.94% | 1.51% | $-1.43 \times 10^{-3}$ | $5.01 \times 10^{-2}$ | 7.84% | 8.42% |
| (1.2,1.4)        | $-2.75 \times 10^{-2}$ | $5.38 \times 10^{-2}$ | 13.74% | 17.07% | $2.75 \times 10^{-2}$ | $5.38 \times 10^{-2}$ | 13.74% | 17.07% | $-7.79 \times 10^{-2}$ | $9.98 \times 10^{-2}$ | 14.30% | 35.74% |
| (1.4,1.6)        | $-3.16 \times 10^{-3}$ | $2.83 \times 10^{-2}$ | 3.09% | 1.06% | $1.89 \times 10^{-3}$ | $2.17 \times 10^{-2}$ | 5.94% | 1.51% | $-1.43 \times 10^{-3}$ | $5.01 \times 10^{-2}$ | 7.84% | 8.42% |

Note.

- The magnitude refers to $r$ band for DESI and $i$ band for others.
Figure 5. Photometric filter set and two example SEDs for each of the three imaging surveys. The upper panels depict the filter responses scaled to their maximums. The lower and middle panels feature two example SEDs, which are displayed in solid circles with error bars. The size of the error bar presents the photometric error. The photoz and stellar mass of each SED are marked in the bottom-right corner of each panel. The best-fit template spectra are displayed in dark-blue curves.

Figure 6. Comparisons of the stellar mass in logarithm between our measurements and those from the COSMOS catalog (left for DESI and right for HSC-SSP). The dispersion of the mass difference ($\sigma_{\Delta \log M_\ast}$) is also displayed.
\[ \Delta z_{\text{norm}} = \frac{z_{\text{phot}} - z_{\text{spec}}}{1 + z_{\text{spec}}} \]

where \( z_{\text{phot}} \) is the photometric redshift and \( z_{\text{spec}} \) is the spectroscopic redshift. The bias \( \langle \Delta z_{\text{norm}} \rangle \) is calculated as the median value of \( \Delta z_{\text{norm}} \) by iteratively applying a 3\( \sigma \) clipping algorithm to remove outliers.

2. dispersion: the dispersion \( \sigma_{\Delta z_{\text{norm}}} \) of \( \Delta z_{\text{norm}} \), which is also calculated by applying the 3\( \sigma \) clipping algorithm.

3. outlier rate: the fraction of galaxies with photometric redshifts deviating substantially from their spectroscopic redshifts. We adopt two definitions: one is \( P_{0.15} \) that is defined as the fraction of galaxies with \( |\Delta z_{\text{norm}}| > 0.15 \) and the other is \( P_{3\sigma} \) that is defined as the fraction of galaxies with \( |\Delta z_{\text{norm}}| > 3\sigma_{\Delta z_{\text{norm}}} \) after applying the 3\( \sigma \) clipping algorithm.

We present the photometric quality in Table 2. The overall biases are ignorable and overall accuracies for DESI, DES and HSC-SSP are 0.017, 0.024 and 0.029, respectively. The factors affecting the photometric quality are complicated, which may include the adopted photometric system, photometric quality, galaxy samples, spectroscopic training samples, etc.

Figure 3 presents the comparisons between \( z_{\text{phot}} \) and \( z_{\text{spec}} \) for the three survey data sets. Table 3 lists the biases, dispersions, and outlier rates in different bins of \( z_{\text{spec}} \) and \( z_{\text{phot}} \). The DESI photometric accuracy is best, partly because the inclusion of WISE infrared photometry tends to select more red galaxies and depress the color-redshift degeneracy as discussed in Zou et al. (2019). The HSC-SSP data have a higher redshift coverage.

Figure 4 depicts the photometric accuracy as a function of magnitude and Table 4 lists corresponding photometric qualities in different magnitude ranges. As expected, both photometric accuracy and outlier rate increase with magnitude.

### 3.3. Stellar Mass

Stellar mass is a fundamental physical quantity for galaxies. It can be derived by fitting the observed multi-wavelength SED with theoretical stellar population synthesis models. We adopt the LePhare software\(^7\) to estimate the stellar mass. The redshift is fixed to \( z_{\text{phot}} \) as obtained in this paper. The default stellar population templates are utilized, which are constructed using the BC03 evolutionary models (Bruzual & Charlot 2003) and Chabrier (2003) initial mass function. These templates include the spectral models with three metallicities (0.004, 0.008, and 0.02), 29 ages (0.01 Myr to 13.5 Gyr), and nine exponentially declining star formation histories (timescale from 0.1 to 30 Gyr). Emission lines are added in the models. In addition, the

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\(^7\) https://www.cfht.hawaii.edu/~arnouts/LEPHARE/lephare.html

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model spectra are reddened using the extinction curve of Calzetti et al. (2000) and five $E(B-V)$ values of 0, 0.1, 0.2, 0.3, and 0.5 mag are adopted. The SED fitting provides both stellar mass and absolute magnitude in this paper. Figure 5 shows some examples of the SED fitting.

We compare our stellar mass ($M_*$) with that of Laigle et al. (2016), who obtained accurate photometric and stellar masses for galaxies in the COSMOS field. This field was covered by a total of 32 photometric bands ranging from ultraviolet to infrared, which ensures more convincing determination of stellar population properties from SED fitting. As adopted in this paper, the LePhare software was also employed by Laigle et al. (2016). To exclude the galaxies with large photometric uncertainties and hence large uncertainties of stellar mass, we select galaxies with photometric errors less than 0.1(1 + $z_{\text{phot}}$) in our catalogs and less than 0.05(1 + $z_{\text{phot}}$) in the COSMOS catalog. Figure 6 shows the comparisons of the stellar mass. The general dispersion of the $\log M_*$ difference between our measurements and the COSMOS ones is about 0.2 dex. Although the COSMOS is out of the DES coverage, we believe that the mass dispersion for DES should be at a similar level, because the photometric systems of DES and HSC-SSP are similar, the photometric accuracies of these two surveys are at a similar level, and the photometric depths are even better than DESI.

4. Galaxy Clusters

As the largest gravitationally bound systems in the universe, galaxy clusters have been effectively detected in large-scale optical surveys. There are two kinds of detection methods. One is based on the overdensity feature of the galaxy spatial distribution (Szabo et al. 2011; Wen et al. 2012; Gao et al. 2020; Zou et al. 2021). This detection method needs relatively accurate photometric data to probe the overdensities of galaxies above the average density of foreground and background galaxies. The other is based on the red-sequence feature of red galaxies, whose star formation has been quenched (Koester et al. 2007; Hao et al. 2010; Rykoff et al. 2014). This method recognizes the tight color distribution of red member galaxies in a cluster. It may lose some clusters without the red-sequence feature, which are very common at high redshift. We adopt a new fast cluster-finding algorithm as used in our previous papers to identify galaxy clusters for the DESI, DES, and HSC-SSP data. This cluster-finding method belongs to the detection methods based on the overdensity feature.

4.1. Selection of Galaxy Sample

In order to identify galaxy clusters, we only select the galaxies with relatively good photometric and SED fitting: (1) the photometric ranges are limited to $z_{\text{phot}} < 1.5$ for DESI and DES and $z_{\text{phot}} < 2$ for HSC-SSP; (2) the photometric error is set to less than 0.1(1 + $z_{\text{phot}}$); (3) the range of the r-band absolute magnitude is $-25 < M_r < -16$; (4) the stellar mass range is $6 < \log M_*/M_\odot < 13$; (5) the logarithmic mass uncertainty is less than 0.4 dex. There are about 222, 221, and 101 million remaining galaxies for DESI, DES, and HSC-SSP, respectively.

4.2. Detecting Clusters and Assessing Photoz Quality

The cluster detection method adopted here is a new clustering algorithm that can effectively find the overdensities of the galaxies over the sky. We give a brief introduction of this method as below. For more details, please refer to Zou et al. (2021).

1. Galaxies in the photoz catalog are subdivided into equal-area sky pixels in HEALPix format. The pixel area is about 0.84 deg$^2$.
2. The local density ($\rho$) of each galaxy in a sky pixel is calculated. It is defined as the number of galaxies with distance to this galaxy less than 0.5 Mpc and $\Delta_{\text{norm}} < 0.04$. When calculating the local density for a given galaxy, galaxies from the specified pixel and all its neighbor pixels are taken into account to avoid the boundary effect (area of about $9 \times 0.84 = 7.56$ deg$^2$).
3. The background density of this galaxy ($\rho_{\text{bkg}}$) is calculated in the above sky pixel and its neighbor pixels (total area is about 7.6 deg$^2$). It is the number of galaxies with distances to the specified galaxy larger than 1 Mpc and $\Delta_{\text{norm}} < 0.04$.
4. For each galaxy, a parameter $\theta$ is defined as the distance of the nearest galaxy with higher local density.
5. The density peaks (or locations of galaxy clusters) are identified as the galaxies with large enough local density and distant enough away from other peaks, i.e., $\rho > n \times \rho_{\text{bkg}}$ and $\theta > 1$ Mpc, where $n$ is to be set. The brightest galaxy with distance to the peak smaller than 0.5 Mpc is considered as the brightest cluster galaxy (BCG, i.e., the cluster center).

Because the larger photometric uncertainty for DESI and HSC-SSP data suppresses the cluster overdensity relative to the

\begin{table}[ht]
\centering
\caption{Calibrations of the Total Mass for Different Surveys}
\begin{tabular}{lccc}
Survey & $N^0$ & $a$ & $b$ & $\sigma_{\Delta \log M_*/a}$ \\
\hline
DESI & 1747 & 0.92 ± 0.06 & 11.41 ± 0.80 & 0.21 \\
DES & 310 & 0.93 ± 0.06 & 12.41 ± 0.21 & 0.19 \\
HSC-SSP & 88 & 0.63 ± 0.09 & 13.08 ± 0.20 & 0.21 \\
\hline
\end{tabular}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{The comparisons of the stellar mass.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{The comparisons of the stellar mass.}
\end{figure}

8 https://cosmos.astro.caltech.edu/

9 https://healpix.sourceforge.io/
background, a smaller threshold of $\rho$ is chosen. We set $n$ to 4 for DESI, 3.5 for DES, and 3 for HSC-SSP, which are roughly determined to assure relatively low false detection rates. The above process can be easily executed in parallel mode. For each galaxy cluster, we calculate the number of member galaxies with distance to the center less than 1 Mpc ($N_{\text{1 Mpc}}$). $N_{\text{1 Mpc}}$ is subtracted from the background density and is considered as a first-order estimate of the cluster richness. We only reserve relatively rich galaxy clusters with $N_{\text{1 Mpc}} > 10$. The total numbers of detected galaxy clusters for DESI, DES, and HSC-SSP are shown in Figure 8.

Figure 8. The left column shows the logarithmic calibration relations between $M_{500}$ and $L_{1\text{ Mpc}}$ for DESI (row 1), DES (row 2), and HSC-SSP (row 3). The middle and right columns depict $\Delta \log M_{500}$ as functions of $\log L_{1\text{ Mpc}}$ and redshift, respectively. Here $\Delta \log M_{500}$ is the difference between the measurements and the linear predictions. The red solid lines display $\Delta \log M_{500} = 0$ and the red dashed lines signify the 1σ dispersion of $\Delta \log M_{500}$, which is also marked on the rightmost panel.
SSP are 532,810, 86,963, and 36,566, respectively. The number of clusters for DESI DR9 is somewhat smaller than that of DESI DR8 as presented in Zou et al. (2021), which is partly due to slightly different photometric data and selection of the galaxy samples. The photoz accuracy of galaxy clusters is determined by comparing the $z_{\text{phot}}$ and $z_{\text{spec}}$ of BCGs. Figure 7 plots these comparisons and displays the photoz accuracies. Table 5 summarizes the photoz qualities of galaxy clusters for the three data sets.

We follow the same process as described in Zou et al. (2021) to estimate the false detection rate of our cluster-finding method. A Monte Carlo simulation based on the actual photometric data is performed to generate a mock catalog: (1) galaxies are redistributed by randomly moving away from their original positions within the distance of 1–2.5 Mpc; (2) the properties including redshift of galaxies are shuffled. The shuffled galaxies could be regarded as a random redistribution of their original positions in the 3-D space and meanwhile maintain the correlated large-scale structure to some degree. In this way, the overdensity of galaxy clusters should be shuffled out. Then we apply the same detecting method as used in this paper to the mock catalog to assess the false detection. We should note that this kind of simulation might underestimate the false detection, because the projection effects include the impacts from both correlated and uncorrelated large-scale structures. The false detection rate $F$ is defined as the ratio of the number of clusters detected in the mock catalog to that of the original catalog. The last column of Table 5 lists the false rate for each survey.

4.3. Total Mass

The total mass of galaxy clusters (including baryon and dark matters) can be effectively estimated from the measurements of weak gravitational lensing or observations of X-ray emission and Sunyaev-Zel’dovich (SZ) effect in microwave band. We have compiled a catalog of 3157 galaxy clusters with the total mass ($M_{500}$) estimated using the X-ray and SZ observations (Zou et al. 2021). It can be used for calibrating the mass of our detected clusters. The optical luminosity of member galaxies in a cluster is a good proxy of the cluster richness and hence can be utilized to estimate the total mass. We define $L_{1\text{ Mpc}}$ as the total r-band luminosity of member galaxies. $L_{1\text{ Mpc}}$ is also subtracted from the background luminosity, which is calculated in the same way as $N_{1\text{ Mpc}}$. We find that the richness $L_{1\text{ Mpc}}$ presents a good linear relation with the total mass in the logarithmic space and this relation is independent of the redshift (see Figure 8). The calibration relation is described as $\log(M_{500}) = a \log(L_{1\text{ Mpc}}) + b$, where $a$ and $b$ are coefficients to be fitted. We derive these calibration relations for different surveys and apply them to our detected clusters. The overall calibration accuracy is about 0.2 dex. Here we assume that the above linear calibration relations are applicable for the clusters with richness and redshift out of the coverage of the calibration catalog. Note that the calibrations might suffer a little from the Malmquist bias as the cluster sample is constructed with flux-limited X-ray and SZ observations. Table 6 lists the calibration coefficients for different survey data. The characteristic radius $R_{500}$ is calculated from the relation of $M_{500} = \frac{4\pi}{3} R_{500}^3 \times 500 \rho_c$, where $\rho_c$ is the critical density of the universe.

Figure 9 presents the redshift and mass distributions of our clusters. The median redshifts for DESI, DES, and HSC-SSP are 0.52, 0.52, and 0.96, respectively. The median logarithmic masses for DESI, DES, and HSC-SSP are 14.13, 14.23, and 14.36, respectively. The HSC-SSP survey is deeper and can extend to higher redshift, so the average total mass of HSC-SSP clusters should be larger than can be detected.

4.4. Comparison with RedMaPPer Clusters

As a representative cluster-finding method based on the red-sequence feature, redMaPPer has been designed to identify galaxy clusters in a few large-scale photometric surveys (Rykoff et al. 2014, 2016). The redMaPPer cluster catalog for the SDSS DR8 is used for comparison with our catalogs. The latest version of v6.3 (2016) is obtained, which includes 29,947 clusters and covers the redshift range of $0.08 < z < 0.55$. The photometric redshift uncertainty of the redMaPPer clusters is at the level of $\sigma_{\text{phot}} < 0.01$. There are 25,840, 1979, and 2222 redMaPPer clusters covered by DESI, DES, and HSC-SSP, respectively.

We match our catalogs with the redMaPPer catalog using a redshift tolerance of $\Delta z_{\text{norm}} < 0.06$ and a projection separation of 1 Mpc. The numbers of matched clusters are 25,096 (97.1%), 1319 (66.6%), and 1338 (60.2%) for DESI, DES, and HSC-SSP, respectively. The relatively lower matching rates for DES and HSC-SSP are mainly due to larger photoz uncertainties, which smooth out some of the low-level overdensities. Figure 10 features comparisons of richness and photoz between our catalogs and the redMaPPer catalog. The richnesses of matched clusters in these catalogs present good correlations. We obtain the following relations by linear fitting:

$$R_{\text{DESI}} = 2.74 R_{\text{redMaPPer}} + 36.45,$$
$$R_{\text{DES}} = 2.82 R_{\text{redMaPPer}} + 31.77,$$
$$R_{\text{HSC--SSP}} = 2.94 R_{\text{redMaPPer}} + 31.81,$$

where $R$ is the richness. We can also see from Figure 10 that the photoz of our cluster catalogs exhibit excellent consistency with that of the redMaPPer catalog. The general dispersion of $\Delta z_{\text{norm}}$ is about 0.017.

5. Summary

As more and more wide and deep imaging surveys have been carried out, the photoz technique has become critical to

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10 http://risa.stanford.edu/redmapper/
Figure 9. Left: normalized redshift distribution of our clusters. Right: normalized mass distribution of our clusters.

Figure 10. Richness (upper panels) and redshift (lower panels) comparisons of our detected clusters with the SDSS DR8 redMaPPer cluster catalog. The red lines in the upper panels are the best linear fits of the relation between two richness measurements. The red lines in the lower panels present $y = x$. The dispersions ($\sigma_{\Delta z}$) are displayed in these panels, where photo$z$ from the redMaPPer is regarded as $z_{\text{spec}}$. 
their scientific achievements. Photometric properties can be effectively derived from multi-wavelength photometric observations and it is a basic parameter to infer other physical properties of galaxies and to explore galaxy evolution, especially in the early universe, where spectroscopic observations are difficult.

Recently, several large-scale wide and deep imaging surveys, including DESI, DES, and HSC-SSP, have released their latest data. For certain reasons, DES and HSC-SSP have not published photometric measurements. We have successfully applied a local linear regression algorithm to estimate the photometric redshifts of these surveys using a fast cluster-finding method. The photoz uncertainties for DESI, DES, and HSC-SSP are about 0.017, 0.024, and 0.029, respectively. In addition to photoz, a series of stellar population properties of galaxies including the stellar mass is derived by following the SED fitting method. The redshifts of galaxies are fixed to their latest value for each galaxy in the local color space and estimate the photometric redshifts using this model. The photoz uncertainties for DESI, DES, and HSC-SSP are about 0.017, 0.024, and 0.029, respectively. In addition to photoz, a series of stellar population properties of galaxies including the stellar mass is derived by following the SED fitting method. The redshifts of galaxies are fixed to photoz derived from these surveys. The uncertainty of logarithmic stellar mass is about 0.2 dex.

With the photoz catalogs, we try to detect galaxy clusters using a fast cluster-finding method, which was also successfully applied to the SCUSS and DESI DR8 data. Galaxy clusters are considered as the overdensities with large-enough local galaxy densities and substantial separations from each other. The numbers of detected galaxy clusters with members larger than 10 are 532,810, 86,963, and 36,566 for DESI DR9, DES, and HSC-SSP, respectively. The number of galaxy clusters we detected is by far the largest. Monte Carlo simulations present the false detection rate of about 6%–8%. The photoz accuracy for our galaxy clusters is about 0.011–0.014. Both redshift and richness show good consistency with those of the well-known redMaPPer clusters.

The catalogs we construct in this paper will be made publicly accessible at the Science Data Bank (ScienceDB) and PaperData Repository. The series of work on photoz and galaxy clusters we conduct can be extended to future imaging surveys using Chinese space-based and ground-based facilities, such as the China Space Station Telescope (CSST; Zhan 2021), SiTian Project (Liu et al. 2021), Multi-channel Photometric Survey Telescope (Mephisto), and Wide Field Survey Telescope (WFST).

Here we provide some general guidelines and notes for users to utilize the photoz and cluster catalogs. In the future studies with these catalogs, we will have further investigations of all possible issues that are not fully analyzed in this paper.

1. From the photoz statistics, it seems that the HSC-SSP and DES photoz accuracies are worse than the DESI one. Actually, this is not quite true. As mentioned before, the inclusion of WISE photometry tends to select redder galaxies whose colors are more sensitive to redshift. If we select the same galaxies for comparison, the photoz accuracies for these three surveys are similar. However, the HSC-SSP and DES data are much deeper than DESI. If the users need the photoz and corresponding stellar population properties of fainter and more distant galaxies, the HSC-SSP and DES data are better choices.

2. The photoz qualities are dependent on the properties of galaxies. For example, we already know that at the same redshift, the photoz quality for blue galaxies might be twice worse than that for red galaxies. Before using the photoz catalog, we suggest that users could first apply the spec-z in our catalog to assess the quality of photoz in the color space and select specific galaxies they want.

3. The users should notice that we only select morphologically classified galaxies. It may lose some point-like galaxies, which might be faint or distant. In addition, the magnitude cuts of $r$ and $i$ bands may also lead to missing some high-redshift galaxies. Actually, we lack the training samples of faint and distant galaxies to reliably estimate their photoz. Future spectroscopic surveys would improve this situation.

4. For stellar population properties in the photoz catalog, the stellar mass is fully tested and should be most reliable. However, the users may be cautious in using other parameters such as star formation rate and stellar age.

5. Compared with the DESI clusters, the number of galaxy clusters we identified from DES and HSC-SSP surveys should be somewhat underestimated. This is because the worse photoz accuracy smooths the overdensity feature in the 3-D space and leads to less detections of low-richness clusters.

6. The BCG is identified as the brightest galaxy in a specified redshift slice with the distance from the density peak less than 0.5 Mpc. Whereas, the relatively large photoz uncertainty may cause a wrong identification. We have visually checked several hundred rich clusters and found that the false rate is quite low. More quantitative analyses will be conducted in the future.

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1. https://www.scidb.cn/s/2AjaEb
2. https://nadc.china-vo.org/article/20200722160959?id=101089
3. http://www.swifar.ynu.edu.cn/info/1015/1073.htm
4. http://wfst.ustc.edu.cn/
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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 Tohonoo O’odham Nation.

This project used public archival data from the Dark Energy Survey (DES). Funding for the DES Projects has been provided by the U.S. Department of Energy, the U.S. National Science Foundation, the Ministry of Science and Education of Spain, the Science and Technology Facilities Council of the United Kingdom, the Higher Education Funding Council for England, the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign, the Kavli Institute of Cosmological Physics at the University of Chicago, the Center for Cosmology and Astro-Particle Physics at the Ohio State University, the Mitchell Institute for Fundamental Physics and Astronomy at Texas A&M University, Financiadora de Estudos e Projetos, Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro, Conselho Nacional de Desenvolvimento Científico e Tecnológico and the Ministério da Ciência, Tecnologia e Inovação, the Deutsche Forschungsgemeinschaft, and the Collaborating Institutions in the Dark Energy Survey.

The Hyper Suprime-Cam (HSC) collaboration includes the astronomical communities of Japan and Taiwan, and Princeton University. The HSC instrumentation and software were developed by the National Astronomical Observatory of Japan (NAOJ), the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), the University of Tokyo, the High Energy Accelerator Research Organization (KEK), the Academia Sinica Institute for Astronomy and Astrophysics in Taiwan (ASIAA), and Princeton University. Funding was contributed by the FIRST program from the Japanese Cabinet Office, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the Japan Society for the Promotion of Science (JSPS), Japan Science and Technology Agency (JST), the Toray Science Foundation, NAOJ, Kavli IPMU, KEK, ASIAA, and Princeton University.

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Appendix A.
Data Availability

The photoz and cluster catalogs in this paper are available at ScienceDB. The download link is https://www.doi.org/10.11922/sciencedb.o00069.00003. The PaperDataRepository provides a backup accessing address (https://doi.org/10.12149/101089). The corresponding structure of the data storage is shown as below:

1. desdr2_galaxy_cspcat.fits (file): the total catalog of photoz and stellar mass for DES;
2. desdr9_galaxy_cspcat.fits (file): the total catalog of photoz and stellar mass for DESI;
3. hscpdr3_wide_galaxy_cspcat.fits (file): the total catalog of photoz and stellar mass for HSC-SSP;
4. photoz_desdr2 (directory): dividing desdr2_galaxy_cspcat.fits into small files with file names of desdr2_galaxy_cspcat_raXXX_YYY.fits, where XXX and YYY are the lower and upper limits of R.A. in degrees, respectively;
5. photoz_desdr9 (directory): dividing desdr9_galaxy_cspcat.fits into small files with file names of desdr9_galaxy_cspcat_raXXX_YYY.fits;
6. photoz_hscpdr3 (directory): dividing hscpdr3_wide_galaxy_cspcat.fits into small files with file names of hscpdr3_wide_galaxy_cspcat_raXXX_YYY.fits;
7. galaxy_clusters_desdr2.fits (file): the catalog of galaxy clusters for DES;
8. galaxy_clusters_desdr9.fits (file): the catalog of galaxy clusters for DESI;
9. galaxy_clusters_hscpdr3_wide.fits (file): the catalog of galaxy clusters for HSC-SSP;
10. readme.txt (file): a brief instruction of the data.

Appendix B.
The Photoz Catalogs

Tables B1–B3 present the content of the photoz catalogs for DESI, DES, and HSC-SSP, respectively. Note that the stellar population parameters other than stellar mass and absolute magnitude are not fully tested, but they are kept in the catalog in case users find that they are useful.
### Table B1

| Column          | Unit  | Description                                      |
|-----------------|-------|--------------------------------------------------|
| ID              |       | Unique object ID                                 |
| RA              | degree| R.A. in J2000                                    |
| DEC             | degree| Decl. in J2000                                   |
| MAG_G           | mag   | g-band magnitude                                 |
| MAG_R           | mag   | r-band magnitude                                 |
| MAG_Z           | mag   | z-band magnitude                                 |
| MAG_W1          | mag   | W1-band magnitude                                |
| MAG_W2          | mag   | W2-band magnitude                                |
| MAGERR_G        | mag   | g-band magnitude error                           |
| MAGERR_R        | mag   | r-band magnitude error                           |
| MAGERR_Z        | mag   | z-band magnitude error                           |
| SHAPE_R         | arcsec| Half-light radius of galaxy model for galaxy type|
| SHAPE_R_IVAR    | 1 arcsec$^{-2}$ | Inverse variance of SHAPE_R                       |
| SHAPE_E1        |       | Ellipticity component 1 of galaxy model         |
| SHAPE_E1_IVAR   |       | Inverse variance of SHAPE_E1                     |
| SHAPE_E2        |       | Ellipticity component 2 of galaxy model         |
| SHAPE_E2_IVAR   |       | Inverse variance of SHAPE_E2                     |
| SERSIC          |       | Power-law index for the Sérsic profile model     |
| SERSIC_IVAR     |       | Inverse variance of SERSIC                       |
| N_NEIGHBOUR     |       | Number of neighbors used for photometric estimate|
| N_FILTER        |       | Number of filters used                           |
| PHOTO_Z        |       | Estimated photometric redshift                   |
| PHOTO_ZERR     |       | Estimated photometric redshift error             |
| SPEC_Z         |       | Spectroscopic redshift if available              |
| MEAN_Z         |       | Mean spectroscopic redshift of $k$ nearest neighbors |
| SIGMA_Z        |       | Standard deviation of the spectroscopic redshifts of $k$ nearest neighbors |
| NEAREST_Z      |       | Spectroscopic redshift of the nearest neighbor   |
| MEAN_DIS       |       | Mean Euclidean distance in the color space of neighbors |
| CHI_BEST       |       | $\chi^2$ of the best BC03 model fitting          |
| MOD_BEST       |       | ID of the best-fitted BC03 model                 |
| EBV_BEST       | mag   | Best estimated $E(B-V)$ in three values of 0, 0.5, and 1.0 mag |
| SCALE_BEST     |       | Scaling factor between observed SED and model SED |
| MAG_ABS_G      | mag   | g-band absolute magnitude                        |
| MAG_ABS_R      | mag   | r-band absolute magnitude                        |
| MAG_ABS_Z      | mag   | z-band absolute magnitude                        |
| MAG_ABS_W1     | mag   | W1-band absolute magnitude                       |
| MAG_ABS_W2     | mag   | W2-band absolute magnitude                       |
| AGE_BEST       | yr    | Best estimated age                               |
| AGE_INF        | yr    | Lower limit of age with 68% confidence level     |
| AGE_MED        | yr    | Median age                                       |
| AGE_SUP        | yr    | Upper limit of age with 68% confidence level     |

### Table B1 (Continued)

| Column          | Unit  | Description                                      |
|-----------------|-------|--------------------------------------------------|
| COADD_OBJECT_ID |       | Unique object ID in DES                          |
| RA              | degree| R.A. in J2000                                    |
| DEC             | degree| Decl. in J2000                                   |
| MAG_G           | mag   | g-band magnitude                                 |
| MAG_R           | mag   | r-band magnitude                                 |
| MAG_Z           | mag   | z-band magnitude                                 |
| MAG_W1          | mag   | W1-band magnitude                                |
| MAG_W2          | mag   | W2-band magnitude                                |
| MAGERR_G        | mag   | g-band magnitude error                           |
| MAGERR_R        | mag   | r-band magnitude error                           |
| MAGERR_Z        | mag   | z-band magnitude error                           |
| LUM_NUV_BEST    | dex   | Best estimated log NUV luminosity ($L_{\odot}$)  |
| LUM_R_BEST      | dex   | Best estimated log R-band luminosity ($L_{\odot}$) |
| LUM_K_BEST      | dex   | Best estimated log K-band luminosity ($L_{\odot}$) |

### Table B2

| Column          | Unit  | Description                                      |
|-----------------|-------|--------------------------------------------------|
| RA              | degree| R.A. in J2000                                    |
| DEC             | degree| Decl. in J2000                                   |
| MAG_G           | mag   | g-band magnitude                                 |
| MAG_R           | mag   | r-band magnitude                                 |
| MAG_Z           | mag   | z-band magnitude                                 |
| MAG_W1          | mag   | W1-band absolute magnitude                       |
| MAG_W2          | mag   | W2-band absolute magnitude                       |
| AGE_BEST        | yr    | Best estimated age                               |
| AGE_INF         | yr    | Lower limit of age with 68% confidence level     |
| AGE_MED         | yr    | Median age                                       |
| AGE_SUP         | yr    | Upper limit of age with 68% confidence level     |
| SCALE_BEST      |       | Scaling factor between observed SED and model SED |
| MAG_ABS_G       | mag   | g-band absolute magnitude                        |
| MAG_ABS_R       | mag   | r-band absolute magnitude                        |
| MAG_ABS_Z       | mag   | z-band absolute magnitude                        |
| MAG_ABS_W1      | mag   | W1-band absolute magnitude                       |
| MAG_ABS_W2      | mag   | W2-band absolute magnitude                       |
| CHI_BEST        |       | $\chi^2$ of the best BC03 model fitting          |
| MOD_BEST        |       | ID of the best-fitted BC03 model                 |
| EBV_BEST        | mag   | Best estimated $E(B-V)$ in three values of 0, 0.5, and 1.0 mag |
| SCALE_BEST      |       | Scaling factor between observed SED and model SED |
| B_IMAGE         | pixel | Minor axis size based on an isophotal model      |
| THETA_J2000     | degree| Position angle of source in J2000 coordinates    |
| ERAA_IMAGE      | pixel | Error of major axis size based on an isophotal model |
| ERRB_IMAGE      | pixel | Error of minor axis size based on an isophotal model |
| ERRTHETA_IMAGE  | degree| Error of position angle of source                |
| KRON_RADIUS     | pixel | Kron radius measured from detection image        |
| FLUX_RADIUS_I   | pixel | Half-light radius for the object in $i$ band     |
| Column                  | Unit | Description                                                                 |
|------------------------|------|-----------------------------------------------------------------------------|
| N_NEIGHBOUR           |      | Number of neighbors used for photometric redshift estimation               |
| N_FILTER               |      | Number of filters used                                                     |
| PHOTO_Z               |      | Estimated photometric redshift                                              |
| PHOTO_ZERR            |      | Estimated photometric redshift error                                       |
| SPEC_Z                |      | Spectroscopic redshift if available                                         |
| MEAN_Z                |      | Mean spectroscopic redshift of k nearest neighbors                          |
| SIGMA_Z               |      | Standard deviation of the spectroscopic redshifts of k nearest neighbors    |
| NEAREST_Z             |      | Spectroscopic redshift of the nearest neighbor                              |
| MEAN_DIS              |      | Mean Euclidean distance in the color space of neighbors                    |
| CHI_BEST              |      | $\chi^2$ of the best BC03 model fitting                                    |
| MOD_BEST              | ID   | ID of the best-fitted BC03 model                                            |
| EBV_BEST              | mag  | Best estimated $E(B-V)$ in three values of 0, 0.5, and 1.0 mag              |
| SCALE_BEST            |      | Scaling factor between observed SED and model SED                           |
| MAG_ABS_G             | mag  | G-band absolute magnitude                                                  |
| MAG_ABS_R             | mag  | R-band absolute magnitude                                                  |
| MAG_ABS_I             | mag  | I-band absolute magnitude                                                  |
| MAG_ABS_Z             | mag  | Z-band absolute magnitude                                                  |
| MAG_ABS_Y             | mag  | Y-band absolute magnitude                                                  |
| AGE_BEST              | yr   | Best estimated age                                                          |
| AGE_INF               | yr   | Lower limit of age with 68% confidence level                               |
| AGE_MED               | yr   | Median age                                                                  |
| AGE_SUP               | yr   | Upper limit of age with 68% confidence level                               |
| MASS_BEST             | dex  | Best estimated log stellar mass ($M_\odot$)                                |
| MASS_INF              | dex  | Lower limit of log stellar mass with 68% confidence level                  |
| MASS_MED              | dex  | Median log stellar mass                                                     |
| MASS_SUP              | dex  | Upper limit of log stellar mass with 68% confidence level                  |
| SFR_BEST              | $M_\odot$ yr$^{-1}$ | Best estimated SFR |
| SFR_INF               | $M_\odot$ yr$^{-1}$ | Lower limit of SFR with 68% confidence level |
| SFR_MED               | $M_\odot$ yr$^{-1}$ | Median SFR |
| SFR_SUP               | $M_\odot$ yr$^{-1}$ | Upper limit of SFR with 68% confidence level |
| SSFR_BEST             | yr$^{-1}$ | Best estimated SSFR |
| SSFR_INF              | yr$^{-1}$ | Lower limit of SSFR with 68% confidence level |
| SSFR_MED              | yr$^{-1}$ | Median SSFR |
| SSFR_SUP              | yr$^{-1}$ | Upper limit of SSFR with 68% confidence level |
| LUM_NUV_BEST          | dex  | Best estimated log NUV luminosity ($L_\odot$)                              |
| LUM_R_BEST            | dex  | Best estimated log R-band luminosity ($L_\odot$)                           |
| LUM_K_BEST            | dex  | Best estimated log K-band luminosity ($L_\odot$)                           |

Table B3

| Column                  | Unit | Description                                                                 |
|------------------------|------|-----------------------------------------------------------------------------|
| OBJECT_ID              |      | Object ID in HSC-SSP                                                        |
| RA                     | degree | R.A. in J2000                                                              |
| DEC                    | degree | decl. in J2000                                                             |
| MAG_G                  | mag  | G-band magnitude                                                            |
| MAG_R                  | mag  | R-band magnitude                                                            |
| MAG_I                  | mag  | I-band magnitude                                                            |
| MAG_Z                  | mag  | Z-band magnitude                                                            |
| MAG_Y                  | mag  | Y-band magnitude                                                            |
| MAGERR_G               | mag  | G-band magnitude error                                                      |
| MAGERR_R               | mag  | R-band magnitude error                                                      |
| MAGERR_I               | mag  | I-band magnitude error                                                      |
| MAGERR_Z               | mag  | Z-band magnitude error                                                      |
| MAGERR_Y               | mag  | Y-band magnitude error                                                      |
| E11_I                  | arcsec$^2$ | weighted average of ellipse component in $i$ band |
| E12_I                  | arcsec$^2$ | weighted average of ellipse component in $i$ band |
| E22_I                  | arcsec$^2$ | weighted average of ellipse component in $i$ band |
| FRACDEV_I              |      | Fraction of flux for de Vaucouleurs component in $i$ band                   |
| N_NEIGHBOUR            |      | Number of neighbors used for photometric redshift estimation               |
| N_FILTER               |      | Number of filters used                                                     |
| PHOTO_Z               |      | Estimated photometric redshift                                              |
| PHOTO_ZERR            |      | Estimated photometric redshift error                                       |
| SPEC_Z                |      | Spectroscopic redshift if available                                         |
| MEAN_Z                |      | Mean spectroscopic redshift of k nearest neighbors                          |
| SIGMA_Z               |      | Standard deviation of the spectroscopic redshifts of k nearest neighbors    |
| NEAREST_Z             |      | Spectroscopic redshift of the nearest neighbor                              |
| MEAN_DIS              |      | Mean Euclidean distance in the color space of neighbors                    |
| CHI_BEST              |      | $\chi^2$ of the best BC03 model fitting                                    |
| MOD_BEST              | ID   | ID of the best-fitted BC03 model                                            |
| EBV_BEST              | mag  | Best estimated $E(B-V)$ in three values of 0, 0.5, and 1.0 mag              |
| SCALE_BEST            |      | Scaling factor between observed SED and model SED                           |
| MAG_ABS_G             | mag  | G-band absolute magnitude                                                  |
| MAG_ABS_R             | mag  | R-band absolute magnitude                                                  |
| MAG_ABS_I             | mag  | I-band absolute magnitude                                                  |
| MAG_ABS_Z             | mag  | Z-band absolute magnitude                                                  |
| MAG_ABS_Y             | mag  | Y-band absolute magnitude                                                  |
| AGE_BEST              | yr   | Best estimated age                                                          |
| AGE_INF               | yr   | Lower limit of age with 68% confidence level                               |
| AGE_MED               | yr   | Median age                                                                  |
| AGE_SUP               | yr   | Upper limit of age with 68% confidence level                               |
| MASS_BEST             | dex  | Best estimated log stellar mass ($M_\odot$)                                |
| MASS_INF              | dex  | Lower limit of log stellar mass with 68% confidence level                  |
| MASS_MED              | dex  | Median log stellar mass                                                     |
| MASS_SUP              | dex  | Upper limit of log stellar mass with 68% confidence level                  |
| SFR_BEST              | $M_\odot$ yr$^{-1}$ | Best estimated SFR |
| SFR_INF               | $M_\odot$ yr$^{-1}$ | Lower limit of SFR with 68% confidence level |
| SFR_MED               | $M_\odot$ yr$^{-1}$ | Median SFR |
| SFR_SUP               | $M_\odot$ yr$^{-1}$ | Upper limit of SFR with 68% confidence level |
| SSFR_BEST             | yr$^{-1}$ | Best estimated SSFR |
| SSFR_INF              | yr$^{-1}$ | Lower limit of SSFR with 68% confidence level |
| SSFR_MED              | yr$^{-1}$ | Median SSFR |
| SSFR_SUP              | yr$^{-1}$ | Upper limit of SSFR with 68% confidence level |
| LUM_NUV_BEST          | dex  | Best estimated log NUV luminosity ($L_\odot$)                              |
| LUM_R_BEST            | dex  | Best estimated log R-band luminosity ($L_\odot$)                           |
| LUM_K_BEST            | dex  | Best estimated log K-band luminosity ($L_\odot$)                           |
Appendix C.
The Cluster Catalogs

Tables C1–C3 list the content in our cluster catalogs for DESI, DES, and HSC-SSP, respectively.

### Table B3
(Continued)

| Column       | Unit | Description                                      |
|--------------|------|--------------------------------------------------|
| MASS_MED     | dex  | Median log stellar mass                          |
| MASS_SUP     | dex  | Upper limit of log stellar mass with 68% confidence level |
| SFR_BEST     | $M_\odot\,\text{yr}^{-1}$ | Best estimated SFR                              |
| SFR_INF      | $M_\odot\,\text{yr}^{-1}$ | Lower limit of SFR with 68% confidence level    |
| SFR_MED      | $M_\odot\,\text{yr}^{-1}$ | Median SFR                                       |
| SFR_SUP      | $M_\odot\,\text{yr}^{-1}$ | Upper limit of SFR with 68% confidence level    |
| SSFR_BEST    | yr\(^{-1}\) | Best estimated SSFR                             |
| SSFR_INF     | yr\(^{-1}\) | Lower limit of SSFR with 68% confidence level   |
| SSFR_MED     | yr\(^{-1}\) | Median SSFR                                      |
| SSFR_SUP     | yr\(^{-1}\) | Upper limit of SSFR with 68% confidence level   |
| LUM_NUV_BEST | dex  | Best estimated log NUV luminosity ($L_\odot$)    |
| LUM_R_BEST   | dex  | Best estimated log R-band luminosity ($L_\odot$) |
| LUM_K_BEST   | dex  | Best estimated log K-band luminosity ($L_\odot$) |
| Column                          | Unit   | Description                                                                 |
|--------------------------------|--------|-----------------------------------------------------------------------------|
| CLUSTER_ID                     |        | Cluster ID                                                                  |
| RA_PEAK                        | degree | R.A. for the density peak (J2000)                                          |
| DEC_PEAK                       | degree | decl. for the density peak (J2000)                                         |
| PHOTO_Z_PEAK                   |        | Photometric redshift for the density peak                                  |
| SPEC_Z_PEAK                    |        | Spectroscopic redshift for the density peak if existing                    |
| LOC_DEN_PEAK                   |        | Local density for the density peak                                          |
| LOC_BKG_PEAK                   |        | Local background density for the density peak                              |
| N_1MPC                         |        | Number of member galaxies within 1 Mpc from the cluster center             |
| L_1MPC                         | L      | Total luminosity of member galaxies within 1 Mpc from the cluster center   |
| M_500                          | log$_{10}$(M$_\odot$) | Total mass of the cluster $M_{500}$                                      |
| R_500                          | Mpc    | Characteristic radius $R_{500}$                                            |
| RICHNESS                       |        | Cluster richness that is equal to L_1MPC                                   |
| ID_BCG                         |        | Object ID for the BCG                                                      |
| RA_BCG                         | degree | R.A. for the BCG (J2000)                                                   |
| DEC_BCG                        | degree | decl. for the BCG (J2000)                                                  |
| PHOTO_Z_BCG                    |        | Photometric redshift for the BCG                                           |
| PHOTO_ZERR_BCG                 |        | Photometric redshift error for the BCG                                      |
| SPEC_Z_BCG                     |        | Spectroscopic redshift for the BCG if existing                             |
| MAG_G_BCG                      | mag    | $g$-band magnitude for the BCG                                              |
| MAG_R_BCG                      | mag    | $r$-band magnitude for the BCG                                              |
| MAG_Z_BCG                      | mag    | $z$-band magnitude for the BCG                                              |
| MAG_W1_BCG                     | mag    | $W_1$-band magnitude for the BCG                                            |
| MAG_W2_BCG                     | mag    | $W_2$-band magnitude for the BCG                                            |
| MAGERR_G_BCG                   | mag    | $g$-band magnitude error for the BCG                                         |
| MAGERR_R_BCG                   | mag    | $r$-band magnitude error for the BCG                                         |
| MAGERR_Z_BCG                   | mag    | $z$-band magnitude error for the BCG                                         |
| MAGERR_W1_BCG                  | mag    | $W_1$-band magnitude error for the BCG                                       |
| MAGERR_W2_BCG                  | mag    | $W_2$-band magnitude error for the BCG                                       |
| GALDEPTH_G_BCG                 | mag    | 5σ galaxy depth in $g$ band for the BCG                                    |
| GALDEPTH_R_BCG                 | mag    | 5σ galaxy depth in $r$ band for the BCG                                    |
| GALDEPTH_Z_BCG                 | mag    | 5σ galaxy depth in $z$ band for the BCG                                    |
| TYPE_BCG                       |        | Morphological type for the BCG                                             |
| SHAPE_R_BCG                    | arcsec | Half-light radius of galaxy model for the BCG                              |
| SHAPE_R_IVAR_BCG               | 1 arcsec$^{-2}$ | Inverse variance of SHAPE_R for the BCG                                  |
| SHAPE_E1_BCG                   |        | Ellipticity component 1 of galaxy model for the BCG                        |
| SHAPE_E1_IVAR_BCG              |        | Inverse variance of SHAPE_E1 for the BCG                                  |
| SHAPE_E2_BCG                   |        | Ellipticity component 2 of galaxy model for the BCG                        |
| SHAPE_E2_IVAR_BCG              |        | Inverse variance of SHAPE_E2 for the BCG                                  |
| SERSIC_BCG                     |        | Power-law index of the Sérsic profile model for the BCG                   |
| SERSIC_IVAR_BCG                |        | Inverse variance of SERSIC for the BCG                                     |
| MAG_ABS_G_BCG                  | mag    | $g$-band absolute magnitude for the BCG                                     |
| MAG_ABS_R_BCG                  | mag    | $r$-band absolute magnitude for the BCG                                     |
| MAG_ABS_Z_BCG                  | mag    | $z$-band absolute magnitude for the BCG                                     |
| MAG_ABS_W1_BCG                 | mag    | $W_1$-band absolute magnitude for the BCG                                   |
| MAG_ABS_W2_BCG                 | mag    | $W_2$-band absolute magnitude for the BCG                                   |
| AGE_BEST_BCG                   | yr     | Best estimated age for the BCG                                             |
| AGE_INF_BCG                    | yr     | Lower limit of age with 68% confidence level for the BCG                  |
| AGE_MED_BCG                    | yr     | Median age for the BCG                                                     |
| AGE_SUP_BCG                    | yr     | Upper limit of age with 68% confidence level for the BCG                   |
| MASS_BEST_BCG                  | dex    | Best estimated log stellar mass ($M_{\odot}$) for the BCG                 |
| MASS_INF_BCG                   | dex    | Lower limit of log stellar mass with 68% confidence level for the BCG      |
| MASS_MED_BCG                   | dex    | Median log stellar mass for the BCG                                         |
| MASS_SUP_BCG                   | dex    | Upper limit of log stellar mass with 68% confidence level for the BCG      |
| SFR_BEST_BCG                   | $M_{\odot}$ yr$^{-1}$ | Best estimated SFR for the BCG                                      |
| SFR_INF_BCG                    | $M_{\odot}$ yr$^{-1}$ | Lower limit of SFR with 68% confidence level for the BCG                |
| SFR_MED_BCG                    | $M_{\odot}$ yr$^{-1}$ | Median SFR for the BCG                                                    |
| SFR_SUP_BCG                    | $M_{\odot}$ yr$^{-1}$ | Upper limit of SFR with 68% confidence level for the BCG                   |
| SSFR_BEST_BCG                  | yr$^{-1}$ | Best estimated SSFR for the BCG                                         |
Table C1 (Continued)

| Column           | Unit      | Description                                                                 |
|------------------|-----------|-----------------------------------------------------------------------------|
| SSFR_INF_BCG    | yr⁻¹      | Lower limit of SSFR with 68% confidence level for the BCG                   |
| SSFR_MED_BCG    | yr⁻¹      | Median SSFR for the BCG                                                     |
| SSFR_SUP_BCG    | yr⁻¹      | Upper limit of SSFR with 68% confidence level for the BCG                   |
| LUM_NUV_BEST_BCG| dex       | Best estimated log NUV luminosity ($L_{\odot}$) for the BCG                 |
| LUM_R_BEST_BCG  | dex       | Best estimated log R-band luminosity ($L_{\odot}$) for the BCG              |
| LUM_K_BEST_BCG  | dex       | Best estimated log K-band luminosity ($L_{\odot}$) for the BCG              |

Table C2

| Column Description of the Cluster Catalog for DES |
|---------------------------------------------------|
| CLUSTER_ID                                       | Cluster ID |
| RA_PEAK degree                                   | R.A. for the density peak (J2000)          |
| DEC_PEAK degree                                  | decl. for the density peak (J2000)         |
| PHOTO_Z_PEAK                                     | Photometric redshift for the density peak  |
| SPEC_Z_PEAK                                      | Spectroscopic redshift for the density peak if existing |
| LOC_DEN_PEAK                                     | Local density for the density peak         |
| LOC_BKG_PEAK                                     | Local background density for the density peak |
| N_1MPC                                          | Number of member galaxies within 1 Mpc from the cluster center |
| L_1MPC                                          | Total luminosity of member galaxies within 1 Mpc from the cluster center |
| M_500 log_{10}(M_{500})                          | Total mass of the cluster $M_{500}$         |
| R_500 Mpc                                       | Characteristic radius $R_{500}$            |
| RICHNESS                                         | Cluster richness that is equal to L_1MPC    |
| ID_BCG                                          | Object ID for the BCG                      |
| RA_BCG degree                                    | R.A. for the BCG (J2000)                   |
| DEC_BCG degree                                   | decl. for the BCG (J2000)                  |
| PHOTO_Z_BCG                                     | Photometric redshift for the BCG           |
| SPEC_Z_BCG                                      | Spectroscopic redshift for the BCG if existing |
| MAG_G_BCG mag                                   | $g$-band magnitude for the BCG             |
| MAG_R_BCG mag                                   | $r$-band magnitude for the BCG             |
| MAG_I_BCG mag                                   | $i$-band magnitude for the BCG             |
| MAG_Z_BCG mag                                   | $z$-band magnitude for the BCG             |
| MAG_Y_BCG mag                                   | $Y$-band magnitude for the BCG             |
| MAGERR_G_BCG mag                                | $g$-band magnitude error for the BCG       |
| MAGERR_R_BCG mag                                | $r$-band magnitude error for the BCG       |
| MAGERR_I_BCG mag                                | $i$-band magnitude error for the BCG       |
| MAGERR_Z_BCG mag                                | $z$-band magnitude error for the BCG       |
| MAGERR_Y_BCG mag                                | $Y$-band magnitude error for the BCG       |
| A_IMAGE_BCG pixel                               | Major axis size based on an isophotal model for the BCG |
| B_IMAGE_BCG pixel                               | Minor axis size based on an isophotal model for the BCG |
| THETA_J2000_BCG degree                           | Position angle of source in J2000 coordinates for the BCG |
| ERR_RA_IMAGE_BCG pixel                           | Error of major axis size based on an isophotal model for the BCG |
| ERR_B_IMAGE_BCG pixel                            | Error of minor axis size based on an isophotal model for the BCG |
| ERRTHETA_IMAGE_BCG degree                        | Error of position angle of source for the BCG |
| KRON_RADIUS_BCG pixel                            | Kron radius measured from detection image for the BCG |
| FLUX_RADIUS_I_BCG pixel                          | Half-light radius for the object in $i$ band for the BCG |
| MAG_ABS_G_BCG mag                                | $g$-band absolute magnitude for the BCG    |
| MAG_ABS_R_BCG mag                                | $r$-band absolute magnitude for the BCG    |
| MAG_ABS_I_BCG mag                                | $i$-band absolute magnitude for the BCG    |
| MAG_ABS_Z_BCG mag                                | $z$-band absolute magnitude for the BCG    |
| MAG_ABS_Y_BCG mag                                | $Y$-band absolute magnitude for the BCG    |
| AGE_BEST_BCG yr                                  | Best estimated age for the BCG             |
| AGE_INF_BCG yr                                   | Lower limit of age with 68% confidence level for the BCG |
| AGE_MED_BCG yr                                   | Median age for the BCG                     |
| AGE_SUP_BCG yr                                   | Upper limit of age with 68% confidence level for the BCG |
**Table C2**
(Continued)

| Column                  | Description                                                      |
|-------------------------|------------------------------------------------------------------|
| MASS_BEST_BCG dex       | Best estimated log stellar mass ($M_\odot$) for the BCG         |
| MASS_INF_BCG dex        | Lower limit of log stellar mass with 68% confidence level for the BCG |
| MASS_MED_BCG dex        | Median log stellar mass for the BCG                              |
| MASS_SUP_BCG dex        | Upper limit of log stellar mass with 68% confidence level for the BCG |
| SFR_BEST_BCG $M_\odot$ yr$^{-1}$ | Best estimated SFR for the BCG                                   |
| SFR_INF_BCG $M_\odot$ yr$^{-1}$ | Lower limit of SFR with 68% confidence level for the BCG      |
| SFR_MED_BCG $M_\odot$ yr$^{-1}$ | Median SFR for the BCG                                          |
| SFR_SUP_BCG $M_\odot$ yr$^{-1}$ | Upper limit of SFR with 68% confidence level for the BCG   |
| SSFR_BEST_BCG yr$^{-1}$ | Best estimated SSFR for the BCG                                  |
| SSFR_INF_BCG yr$^{-1}$ | Lower limit of SSFR with 68% confidence level for the BCG      |
| SSFR_MED_BCG yr$^{-1}$ | Median SSFR for the BCG                                         |
| SSFR_SUP_BCG yr$^{-1}$ | Upper limit of SSFR with 68% confidence level for the BCG      |
| LUM_NUV_BEST_BCG dex    | Best estimated log NUV luminosity ($L_\odot$) for the BCG       |
| LUM_R_BEST_BCG dex      | Best estimated log R-band luminosity ($L_\odot$) for the BCG    |
| LUM_K_BEST_BCG dex      | Best estimated log K-band luminosity ($L_\odot$) for the BCG    |

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**Table C3**
Column Description of the Cluster Catalog for HSC-SSP

| Column                  | Unit     | Description                                                      |
|-------------------------|----------|------------------------------------------------------------------|
| CLUSTER_ID              |          | Cluster ID                                                       |
| RA_PEAK degree          |          | R.A. for the density peak (J2000)                                |
| DEC_PEAK degree         |          | decl. for the density peak (J2000)                               |
| PHOTO_Z_PEAK            |          | Photometric redshift for the density peak                        |
| SPEC_Z_PEAK             |          | Spectrophotometric redshift for the density peak if existing    |
| LOC_DEN_PEAK            |          | Local density for the density peak                               |
| LOC_BKG_PEAK            |          | Local background density for the density peak                    |
| N_1MPC                  |          | Number of member galaxies within 1 Mpc from the cluster center  |
| L_1MPC                  | $L'$     | Total luminosity of member galaxies within 1 Mpc from the cluster center |
| M_500                   | $\log_{10}(M_\odot)$ | Total mass of the cluster $M_{500}$ |
| R_500                   | Mpc      | Characteristic radius $R_{500}$                                  |
| RICHNESS                |          | Cluster richness that is equal to L_1MPC                         |
| ID_BCG                  |          | Object ID for the BCG                                           |
| RA_BCG degree           |          | R.A. for the BCG (J2000)                                        |
| DEC_BCG degree          |          | decl. for the BCG (J2000)                                       |
| PHOTO_Z_BCG             |          | Photometric redshift for the BCG                                 |
| PHOTO_ZERR_BCG          |          | Photometric redshift error for the BCG                           |
| SPEC_Z_BCG              |          | Spectrophotometric redshift for the BCG if existing              |
| MAG_G_BCG mag           |          | $g$-band magnitude for the BCG                                   |
| MAG_R_BCG mag           |          | $r$-band magnitude for the BCG                                   |
| MAG_I_BCG mag           |          | $i$-band magnitude for the BCG                                   |
| MAG_Z_BCG mag           |          | $z$-band magnitude for the BCG                                   |
| MAG_Y_BCG mag           |          | $y$-band magnitude for the BCG                                   |
| MAGERR_G_BCG mag        |          | $g$-band magnitude error for the BCG                             |
| MAGERR_R_BCG mag        |          | $r$-band magnitude error for the BCG                             |
| MAGERR_I_BCG mag        |          | $i$-band magnitude error for the BCG                             |
| MAGERR_Z_BCG mag        |          | $z$-band magnitude error for the BCG                             |
| MAGERR_Y_BCG mag        |          | $y$-band magnitude error for the BCG                             |
| E11_I_BCG arcsec$^2$    |          | weighted average of ellipse component in $i$ band for the BCG   |
| E12_I_BCG arcsec$^2$    |          | weighted average of ellipse component in $i$ band for the BCG   |
| E22_I_BCG arcsec$^2$    |          | weighted average of ellipse component in $i$ band for the BCG   |
| FRACDEV_I_BCG           |          | Fraction of flux for de Vaucouleurs component in $i$ band for the BCG  |
| MAG_ABS_G_BCG mag       |          | $g$-band absolute magnitude for the BCG                           |
| MAG_ABS_R_BCG mag       |          | $r$-band absolute magnitude for the BCG                           |
| MAG_ABS_I_BCG mag       |          | $i$-band absolute magnitude for the BCG                           |

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Table C3 (Continued)

| Column                  | Unit   | Description                                      |
|-------------------------|--------|--------------------------------------------------|
| MAG_ABS_Z_BCG           | mag    | z-band absolute magnitude for the BCG           |
| MAG_ABS_Y_BCG           | mag    | y-band absolute magnitude for the BCG           |
| AGE_BEST_BCG            | yr     | Best estimated age for the BCG                  |
| AGE_INF_BCG             | yr     | Lower limit of age with 68% confidence level for the BCG |
| AGE_MED_BCG             | yr     | Median age for the BCG                          |
| AGE_SUP_BCG             | yr     | Upper limit of age with 68% confidence level for the BCG |
| MASS_BEST_BCG           | \( \log_{10}(M) \) | Logarithmic stellar mass for the BCG |
| MASS_INF_BCG            | \( \log_{10}(M) \) | Lower limit of logarithmic stellar mass with 68% confidence level for the BCG |
| MASS_MED_BCG            | dex    | Median log stellar mass for the BCG             |
| MASS_SUP_BCG            | \( \log_{10}(M) \) | Upper limit of logarithmic stellar mass with 68% confidence level for the BCG |
| SFR_BEST_BCG            | \( M_\odot \text{yr}^{-1} \) | Best estimated SFR for the BCG                  |
| SFR_INF_BCG             | \( M_\odot \text{yr}^{-1} \) | Lower limit of SFR with 68% confidence level for the BCG |
| SFR_MED_BCG             | \( M_\odot \text{yr}^{-1} \) | Median SFR for the BCG                          |
| SFR_SUP_BCG             | \( M_\odot \text{yr}^{-1} \) | Upper limit of SFR with 68% confidence level for the BCG |
| SSFR_BEST_BCG           | \( \text{yr}^{-1} \) | Best estimated SSFR for the BCG                 |
| SSFR_INF_BCG            | \( \text{yr}^{-1} \) | Lower limit of SSFR with 68% confidence level for the BCG |
| SSFR_MED_BCG            | \( \text{yr}^{-1} \) | Median SSFR for the BCG                         |
| SSFR_SUP_BCG            | \( \text{yr}^{-1} \) | Upper limit of SSFR with 68% confidence level for the BCG |
| LUM_NUV_BEST_BCG        | dex    | Best estimated log NUV luminosity \((L_\odot)\) for the BCG |
| LUM_R_BEST_BCG          | dex    | Best estimated log R-band luminosity \((L_\odot)\) for the BCG |
| LUM_K_BEST_BCG          | dex    | Best estimated log K-band luminosity \((L_\odot)\) for the BCG |

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