



The HectoMAP Cluster Survey. I. redMaPPer Clusters

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Received 2017 November 30; revised 2018 February 12; accepted 2018 February 18; published 2018 April 5

Abstract

We use the dense HectoMAP redshift survey to explore the properties of 104 redMaPPer cluster candidates. The redMaPPer systems in HectoMAP cover the full range of richness and redshift ($0.08 < z < 0.60$). Fifteen of the systems included in the *Subaru*/Hyper Suprime-Cam public data release are bona fide clusters. The median number of spectroscopic members per cluster is ~ 20 . We include redshifts of 3547 member candidates listed in the redMaPPer catalog whether they are cluster members or not. We evaluate the redMaPPer membership probability spectroscopically. The purity (number of real systems) in redMaPPer exceeds 90% even at the lowest richness. Three massive galaxy clusters ($M \sim 2 \times 10^{13} M_{\odot}$) associated with X-ray emission in the HectoMAP region are not included in the public redMaPPer catalog with $\lambda_{\text{rich}} > 20$, because they lie outside the cuts for this catalog.

Key words: cosmology: observations – galaxies: clusters: general – large-scale structure of universe

Supporting material: machine-readable tables

1. Introduction

Galaxy clusters are important probes of the formation and evolution of large-scale structure in the universe. The cluster luminosity function and the masses of galaxy clusters provide strong constraints on model for the development of large-scale structure. Beginning with Abell (1958), Abell et al. (1989), and Zwicky et al. (1968), large cluster candidate catalogs have been based on various techniques including optical catalogs (e.g., Gladders & Yee 2000; Koester et al. 2007; Rykoff et al. 2014; Oguri et al. 2018), X-ray samples (e.g., Edge et al. 1990; Gioia et al. 1990; Ebeling et al. 1998, 2010; Böhringer et al. 2000, 2001, 2004, 2017; Pacaud et al. 2016), Sunyaev–Zel’dovich samples (e.g., Melin et al. 2006; Vanderlinde et al. 2010; Marriage et al. 2011; Bleem et al. 2015; Planck Collaboration et al. 2015, 2016), and weak lensing samples (Oguri et al. 2018).

Many cluster surveys use sophisticated techniques along with photometric redshifts to construct robust cluster candidate catalogs and to avoid systematic biases (Koester et al. 2007; Wen et al. 2009, 2012; Hao et al. 2010; Szabo et al. 2011; Oguri 2014; Rykoff et al. 2014, 2016; Durret et al. 2015; Oguri et al. 2018). These surveys identify cluster candidates based on characteristic features of clusters, including overdensities on the sky, identification of the brightest cluster galaxy (BCG), and sampling of the red-sequence defined by potential cluster members. Generally, these catalogs determine cluster membership based on photometric redshifts of individual galaxies. The photometric redshifts remove some but not all chance alignments. The typical error in a photometric redshift is generally large compared with the typical velocity dispersion of even the most massive clusters.

Here we compare a photometrically selected sample, redMaPPer (Rykoff et al. 2014, 2016), with the dense redshift survey, HectoMAP. redMaPPer (the red-sequence Matched-filter Probabilistic Percolation) is a red-sequence cluster finding survey covering the Sloan Digital Sky Survey (SDSS) Data

Release 8 (DR8) data. redMaPPer identifies the red-sequence of galaxies with the guidance of photometric redshifts. The redMaPPer catalog provides an important testbed for these identification algorithms because it includes membership probabilities of individual galaxies along with cluster richness. The richness is a potential mass proxy that has been tested with shallower redshift surveys (Rozo et al. 2015b; K. Rines et al. 2017, in preparation). Here we test the full redshift and richness range of the catalog.

Previous tests of redMaPPer include Rozo & Rykoff (2014) and Sadibekova et al. (2014) who examine the properties of redMaPPer clusters coincident with X-ray and SZ cluster candidates. Rozo et al. (2015a) compare the redMaPPer and the *Planck* SZ cluster candidate catalog. Rozo et al. (2015b) compare the redMaPPer photometric membership probability estimate with spectroscopically determined membership from the SDSS and Galaxy and Mass Assembly (GAMA) surveys. They suggest that there is a small ($\sim 2.4\%$) systematic offset between the redMaPPer membership probability and the spectroscopic assessment. They also find only a small contamination of the richness by noncluster galaxies. These comparisons are largely restricted to $z \lesssim 0.3$.

K. Rines et al. (2017, in preparation) examine the spectroscopic properties of 23 high-richness redMaPPer clusters in the redshift range 0.08 to 0.25 based on dense cluster redshift surveys, including ~ 75 members per cluster. In contrast with Rozo et al. (2015b), their spectroscopic membership identification shows that the redMaPPer membership probability is substantially overestimated for high-probability members and is substantially underestimated for low-probability members. In spite of this disagreement, the redMaPPer richness is well-correlated with the velocity dispersion derived from the spectroscopy.

HectoMAP (Geller et al. 2005, 2011; Hwang et al. 2016) is a unique sample for examining the spectroscopic properties

of redMaPPer clusters throughout the redshift range they cover. Here, we study the 104 redMaPPer cluster candidates in the 53 deg² HectoMAP field. We examine the purity and completeness of redMaPPer catalog based on the dense HectoMAP spectroscopy.

We describe the HectoMAP redshift survey and the redMaPPer cluster sample in Section 2. We investigate the spectroscopic properties of the redMaPPer clusters, including the accuracy of the photometric cluster redshifts, in Section 3. We discuss the implications of the spectroscopic study of photometrically identified clusters, including the photometric richness and completeness of the redMaPPer catalog, in Section 4. We summarize in Section 5. We use the standard Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ throughout this paper.

2. Data

In Section 2.1, we describe the dense redshift survey HectoMAP. We review the photometrically identified clusters in the HectoMAP region in Section 2.2.

2.1. HectoMAP

HectoMAP is a dense redshift survey with a median redshift, $z = 0.39$. The average number density of galaxies with spectroscopic redshifts is $\sim 2000 \text{ deg}^{-2}$ ($\sim 1200 \text{ galaxies deg}^{-2}$ are in the highly complete red-selected subsample; Geller et al. 2011; Geller & Hwang 2015; Hwang et al. 2016; Sohn et al. 2018). HectoMAP covers 52.97 deg² within the boundaries $200 < \text{R.A. (deg)} < 250$ and $42.5 < \text{decl. (deg)} < 44.0$. The SDSS Data Release 9 (DR9) photometric catalog (Ahn et al. 2012) is the photometric basis for the survey. The primary survey targets are red galaxies with $(g - r)_{\text{model},0} > 1.0$, $(r - i)_{\text{model},0} > 0.5$, $r_{\text{petro},0} < 21.3$, and $r_{\text{fiber},0} < 22.0$ galaxies. The color selection efficiently filters out galaxies with $z \lesssim 0.2$, where the SDSS Main Galaxy Sample is reasonably dense. The $r_{\text{fiber},0}$ selection removes low surface brightness galaxies that are beyond the limit of our spectroscopy.

We measured redshifts with the 300-fiber spectrograph Hectospec mounted on the MMT 6.5 m telescope (Fabricant et al. 1998, 2005) from 2009 to 2016. The Hectospec yields ~ 250 spectra within a $\sim 1 \text{ deg}^2$ field of view in a single observation. We used the 270 mm⁻¹ grating, yielding a wavelength coverage of 3700–9150 Å with a resolution of 6.2 Å. The typical exposure time for an observation is 0.75–1.5 hr; each observation is composed of three subexposures for cosmic-ray removal. We used the HSRED v2.0 package originally developed by R.Cool and revised by the SAO Telescope Data Center (TDC) staff to reduce the data. We measured the redshifts by applying the cross-correlating code RVSAO (Kurtz & Mink 1998). Based on visual inspection of each spectrum, we classified redshifts into three categories: high quality spectra (Q), ambiguous fits (?), and poor fits (X). We use only redshifts with “Q” for scientific analyses. We obtained 58,211 redshifts for red galaxies with $r_{\text{petro},0} < 21.3$ and a total of 97,929 redshifts (with no color selection) in the HectoMAP region. The internal redshift error normalized by $(1 + z)$ is $\sim 32 \text{ km s}^{-1}$.

HectoMAP is remarkably complete within the red galaxy selection limits: the survey is 98% complete to $r_{\text{petro},0} < 20.5$ and it is 89% complete to $r_{\text{petro},0} < 21.3$. Figure 1 shows the two-dimensional completeness map for HectoMAP red galaxies. The coverage is uniform over the entire survey region.

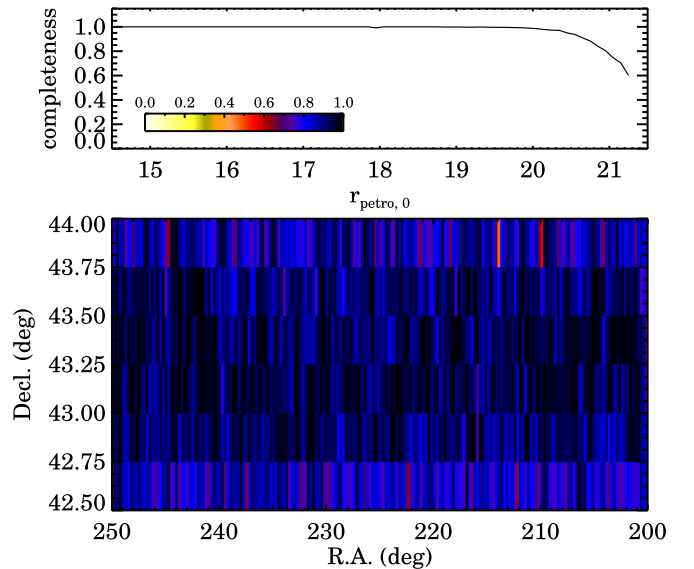


Figure 1. (Upper) Spectroscopic survey completeness for HectoMAP galaxies as a function of r -band magnitude. (Lower) Two-dimensional completeness map (200×6 pixels) of HectoMAP for galaxies with $r_{\text{petro},0} \leq 21.3$, $(g - r)_{\text{fiber},0} > 1.0$, and $(r - i)_{\text{fiber},0} > 0.5$.

These objects are the main galaxies that enter into the evaluation of the redMaPPer algorithm for cluster identification.

Outside the red color selection, the survey completeness is patchy. We use the bluer galaxies to maximize the number of galaxies that are potential redMaPPer cluster members. Below $z \sim 0.2$ the SDSS Main Sample is the primary redshift source of potential redMaPPer cluster members. The SDSS is also uniform over the HectoMAP region and the average completeness, regardless of color, is $\gtrsim 90\%$.

Public *Subaru*/Hyper Suprime Cam (HSC) imaging covers $\sim 7 \text{ deg}^2$ of the HectoMAP region. Eventually, the entire region will be covered (Aihara et al. 2017). We use the public images in Section 3 as a partial test of the redMaPPer algorithm. In Section 3.2, we highlight the properties of the 15 redMaPPer cluster candidates imaged with *Subaru*.

2.2. Photometrically Identified Cluster Catalogs: redMaPPer

Many studies identify galaxy cluster candidates based on photometric measures, including the red-sequence, the over-density based on photometric redshifts, and the identification of red objects associated with weak lensing peaks (Koester et al. 2007; Wen et al. 2009, 2012; Hao et al. 2010; Szabo et al. 2011; Oguri 2014; Rykoff et al. 2014, 2016; Durret et al. 2015; Oguri et al. 2018). The SDSS plays an important role in these photometric cluster surveys thanks to its wide sky coverage. Several previous catalogs based on the SDSS include cluster candidates within the HectoMAP field.

We first summarize the numbers of previous photometrically identified clusters within the HectoMAP region. Table 1 lists the number of cluster candidates in HectoMAP from MaxBCG (Koester et al. 2007), GMBCG (Hao et al. 2010), AMF (Szabo et al. 2011), WHL (Wen et al. 2009, 2012), CAMIRA (Oguri 2014), and redMaPPer (Rykoff et al. 2014, 2016). For WHL and redMaPPer (v6.3), we use the most recent versions from Wen et al. (2012) and Rykoff et al. (2016), respectively.

The number of cluster candidates in the HectoMAP region varies from 104 to 544. The number of cluster candidates

Table 1
Photometrically Identified Cluster Candidates in HectoMAP

Catalogs	N_{cand}^a	z Range	References
MaXBCG	133	$0.12 < z < 0.30$	Koester et al. (2007)
GMBCG	361	$0.13 < z < 0.54$	Hao et al. (2010)
AMF	421	$0.06 < z < 0.67$	Szabo et al. (2011)
WHL	544	$0.08 < z < 0.74$	Wen et al. (2012)
CAMIRA	285	$0.11 < z < 0.60$	Oguri (2014)
redMaPPer	104	$0.09 < z < 0.60$	Rykoff et al. (2016)

Note.

^a Number of cluster candidates within the HectoMAP area.

depends in part on the cluster identification algorithm, the limiting survey redshift, and the richness range of candidate clusters. Table 1 shows that cluster surveys covering wider redshift ranges tend to identify more cluster candidates as expected. Within a fixed redshift range, a cluster catalog including low richness candidates contains a larger number of candidate systems. However, we do not compare the richness distributions of the various catalogs, because the definitions of richness vary substantially.

As a test of photometric catalogs, we focus on redMaPPer, a catalog that has already been compared with X-ray observations (Roza & Rykoff 2014), SZ observations (Roza & Rykoff 2014; Roza et al. 2015a), and weak lensing (Simet et al. 2017). The catalog has also been compared with the SDSS and GAMA (Driver et al. 2009) spectroscopic surveys (Roza et al. 2015b). In contrast with HectoMAP, GAMA has a median redshift of ~ 0.2 (Hopkins et al. 2013). K. Rines et al. (2017, in preparation) have made a detailed test of the redMaPPer algorithm for a set on nearby rich clusters with redshifts $0.08 < z < 0.25$.

HectoMAP allows for the extension of the tests of redMaPPer to the catalog limit, $z \sim 0.6$. Conveniently, the magnitude limit of HectoMAP ($r_{\text{petro},0} = 21.3$) at $z = 0.5$ corresponds to $M_r = -20.96$ comparable with the L_* of massive clusters (Sohn et al. 2017). Thus HectoMAP contains only redshifts of the brightest few cluster members for candidates at $z > 0.5$. However, even at $z > 0.5$ HectoMAP provides a test of the redMaPPer membership probability assignments.

As a first view of the relationship between the redMaPPer cluster sample and HectoMAP, the upper panel of Figure 2 compares the redshift distribution of HectoMAP galaxies with the distribution of redMaPPer cluster photometric redshifts. The peaks of the two redshift distributions are not coincident. For example, HectoMAP has its maximum at $z \sim 0.28$, but the corresponding redMaPPer peak is at lower redshift. HectoMAP red galaxies are abundant at higher redshift, $z > 0.4$, where redMaPPer identifies few candidates. The lower panel of Figure 2 shows that the difference diminishes when we plot the distribution of spectroscopic redshifts of redMaPPer clusters (determined in Section 3).

3. redMaPPer Clusters in HectoMAP

There are 104 redMaPPer cluster candidates in the HectoMAP region. Hereafter, we refer to these cluster candidates as HectoMAP-red clusters. The redshift of the HectoMAP-red cluster sample is $0.08 < z < 0.60$, and the richness (redMaPPer λ_{rich} parameter) ranges from 20 to 106.

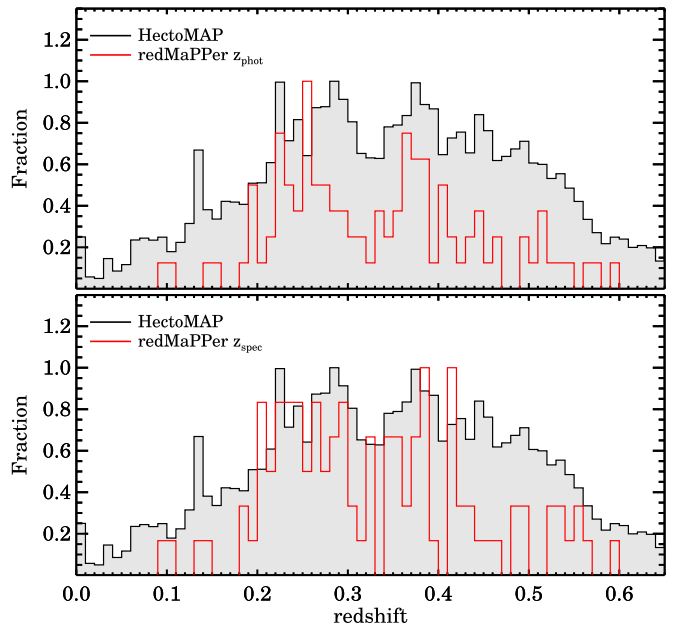


Figure 2. (Upper) Spectroscopic redshift distribution of individual HectoMAP targets (black filled histogram) and the photometric redshift distribution of HectoMAP-red clusters from redMaPPer (red open histogram, 104 systems). (Lower) Same as the upper panel, but with the spectroscopic redshift distribution of HectoMAP-red clusters from this paper (red open histogram).

The redshift and richness ranges for HectoMAP-red clusters are distinctive in covering the full ranges of the redMaPPer cluster candidate catalog.

We summarize the HectoMAP-red clusters in Table 2. We list the redMaPPer ID, R.A., decl., redMaPPer richness (λ_{rich}), photometric redshift (z_{phot}), HectoMAP spectroscopic redshift (z_{spec}), the number of redMaPPer members with $P_{\text{mem}} > 0$ ($N_{\text{RM,mem}}$), the number of spectroscopically identified members ($N_{\text{Spec,mem}}$), the spectroscopic completeness ($f_{\text{RM,mem}}$), and the spectroscopically identified member fraction among redMaPPer members ($f_{\text{Spec,mem,cl}}$, Section 4.1). Table 3 also lists the SDSS object ID, R.A., decl., redMaPPer membership probability, redshift, source of redshift, and spectroscopic membership for the 3547 redMaPPer objects with $P_{\text{mem}} > 0$ with HectoMAP redshift. Here we refer to the total membership probability as the redMaPPer membership probability (see the Note for Table 7 in Rykoff et al. 2016). The total membership probability is the radius and luminosity weighted probability: $P_{\text{mem}} = P \times P_{\text{free}} \times \theta_I \times \theta_R$, where P is raw membership probability, P_{free} is the probability that the member is not a member of a higher ranked cluster, θ_i is the i -band luminosity weight, and θ_r is the radial weight. Table 3 includes objects whether or not they are spectroscopically identified members.

The HectoMAP census of the 104 redMaPPer cluster candidates includes 2641 cluster members defined by straightforward cuts in redshift space. These members yield a mean redshift for each cluster and a spectroscopic measure of the richness that we investigate further in Section 4.2. The HectoMAP redshift survey demonstrates that foreground and background structures can be captured as potential cluster members.

3.1. Subaru/HSC SSP Imaging

Fifteen systems lie within the the HSC Subaru Strategic Program DR1 (Aihara et al. 2017), which covers 7 deg^2 ($\sim 13\%$)

Table 2
HectoMAP-red Clusters

Cluster ID	R.A.	Decl.	$\lambda_{\text{rich}}^{\text{a}}$	$z_{\text{phot}}^{\text{a}}$	$z_{\text{spec}}^{\text{b}}$	$N_{\text{RM,mem}}^{\text{a}}$	$N_{\text{Spec-mem}}^{\text{b}}$	$f_{\text{comp}}^{\text{c}}$	$f_{\text{spec-mem,cl}}^{\text{d}}$
05570	14:13:43.5	43:38:41	25.37	0.0901	0.0894	31	51	0.94	0.90
05706	14:17:54.2	43:23:16	27.66	0.1054	0.1060	42	41	0.81	0.76
08065	16:21:26.9	42:45:40	26.55	0.1424	0.1380	40	43	0.43	0.88
09448	15:32:39.7	43:03:28	22.29	0.1542	0.1430	35	24	0.49	0.82
03312	16:26:42.5	42:40:11	41.28	0.1871	0.1870	56	54	0.64	0.89
09234	16:26:23.8	42:53:20	24.92	0.1913	0.1867	52	42	0.81	0.50
13503	16:19:18.4	42:46:10	23.37	0.1959	0.1936	38	8	0.34	0.31
09874	15:12:57.4	43:18:41	22.25	0.1978	0.2059	50	26	0.54	0.52
18313	15:12:18.7	43:33:14	21.86	0.1983	0.2095	39	20	0.49	0.53
07253	14:51:29.5	42:35:34	33.58	0.2098	0.2044	52	13	0.52	0.37

Notes.

^a Richness, photometric redshift of redMaPPer clusters, and the number of cluster members with $P_{\text{mem}} > 0$ given in Rykoff et al. (2016).

^b Spectroscopically determined redshift and the number of spectroscopically identified members derived in this study.

^c Spectroscopic completeness for redMaPPer clusters (Equation (1)).

^d Spectroscopically identified member fraction in redMaPPer clusters (Equation (2)).

(This table is available in its entirety in machine-readable form.)

Table 3
HectoMAP-red Clusters

Cluster ID	SDSS Object ID	R.A.	Decl.	P_{mem}	z_{spec}	z Source	Spec. Mem
05570	1237661361301684348	213.523263	43.472578	0.6437	0.08888 ± 0.00002	SDSS	N
05570	1237661434317242581	213.573735	43.599875	0.2995	0.08996 ± 0.00002	SDSS	N
05570	1237661434317242611	213.661584	43.639202	0.5661	0.09040 ± 0.00007	MMT	N
05570	1237661361301684354	213.560132	43.530140	0.8786	0.08956 ± 0.00005	MMT	N
05570	1237661434317242524	213.581176	43.749526	0.7643	0.11388 ± 0.00002	SDSS	N
05570	1237661434317176918	213.354990	43.759024	0.7093	0.08890 ± 0.00003	SDSS	N
05570	1237661434317176951	213.420309	43.761725	0.9106	0.09206 ± 0.00002	SDSS	N
05570	1237661434317176965	213.411436	43.709942	0.9576	0.08951 ± 0.00002	SDSS	N
05570	1237661434317176989	213.423029	43.682213	0.9559	0.08877 ± 0.00003	SDSS	N
05570	1237661434317176998	213.444344	43.714732	0.9337	0.08559 ± 0.00002	SDSS	N

(This table is available in its entirety in machine-readable form.)

of the HectoMAP region. Figure 3 shows the HSC images of the individual systems. Each thumbnail image displays a $2' \times 2'$ field of view around the redMaPPer center, except for HMRM08268 at $z = 0.5133$. Because HMRM08268 is at the edge of the public archive, we show only a $1'5 \times 1'5$ field of view for this cluster.

The HSC images demonstrate that most HectoMAP-red clusters are obvious rich clusters. In a few cases, including the systems (HMRM13503, HMRM32708, HMRM34710), there are only a few red objects in the image possibly suggesting that the system is a poor group rather than a rich cluster. We note that HMRM13503 at $z_{\text{phot}} = 0.1959$ and HMRM32708 at $z_{\text{phot}} = 0.4122$ have very low redMaPPer richness $\lambda_{\text{rich}} \sim 23$. For HMRM34710 at $z_{\text{phot}} = 0.4933$, the richness ($\lambda_{\text{rich}} = 38.05$) appears to be overestimated based both on the *Subaru*/HSC image and on the HectoMAP spectroscopy.

The imaging suggests that 3/15 of these redMaPPer candidates may not be rich clusters. One would expect that in these deep images the faint cluster population, invisible to the SDSS limiting magnitude, would be apparent. We comment further on the spectroscopy of these systems in Section 3.2.

3.2. HectoMAP Spectroscopy and redMaPPer Members

As a first step in evaluating the redMaPPer candidate clusters, we measure the spectroscopic completeness for

individual HectoMAP-red clusters as a function of redshift and richness (Figure 4). We define the spectroscopic completeness as

$$f_{\text{comp}} = \frac{N_{\text{RM,spec}}}{N_{\text{RM}}}, \quad (1)$$

where $N_{\text{RM,spec}}$ is the number of redMaPPer member candidates (redMaPPer membership probability $P_{\text{mem}} > 0$) with spectra, and N_{RM} is the total number of redMaPPer member candidates brighter than $r_{\text{petro},0} = 21.3$, the limiting apparent magnitude of HectoMAP.

For $\sim 90\%$ of the clusters, HectoMAP includes redshifts for $\gtrsim 50\%$ of the member candidates. There are no strong trends of spectroscopic completeness with redshift or richness. This independence results from the $r = 21.3$ limit of HectoMAP that is reasonably close to the limiting $r \sim 22$ used by redMaPPer. Thus, measurement of the spectroscopic properties of the HectoMAP-red clusters should be insensitive to any HectoMAP sampling biases.

With the HectoMAP sample for each HectoMAP-red cluster, we identify spectroscopic members and revise the cluster mean redshift. We identify cluster members in the phase space defined by the rest-frame relative velocity difference as a function of clustercentric distance, the R - v diagram. In the R - v

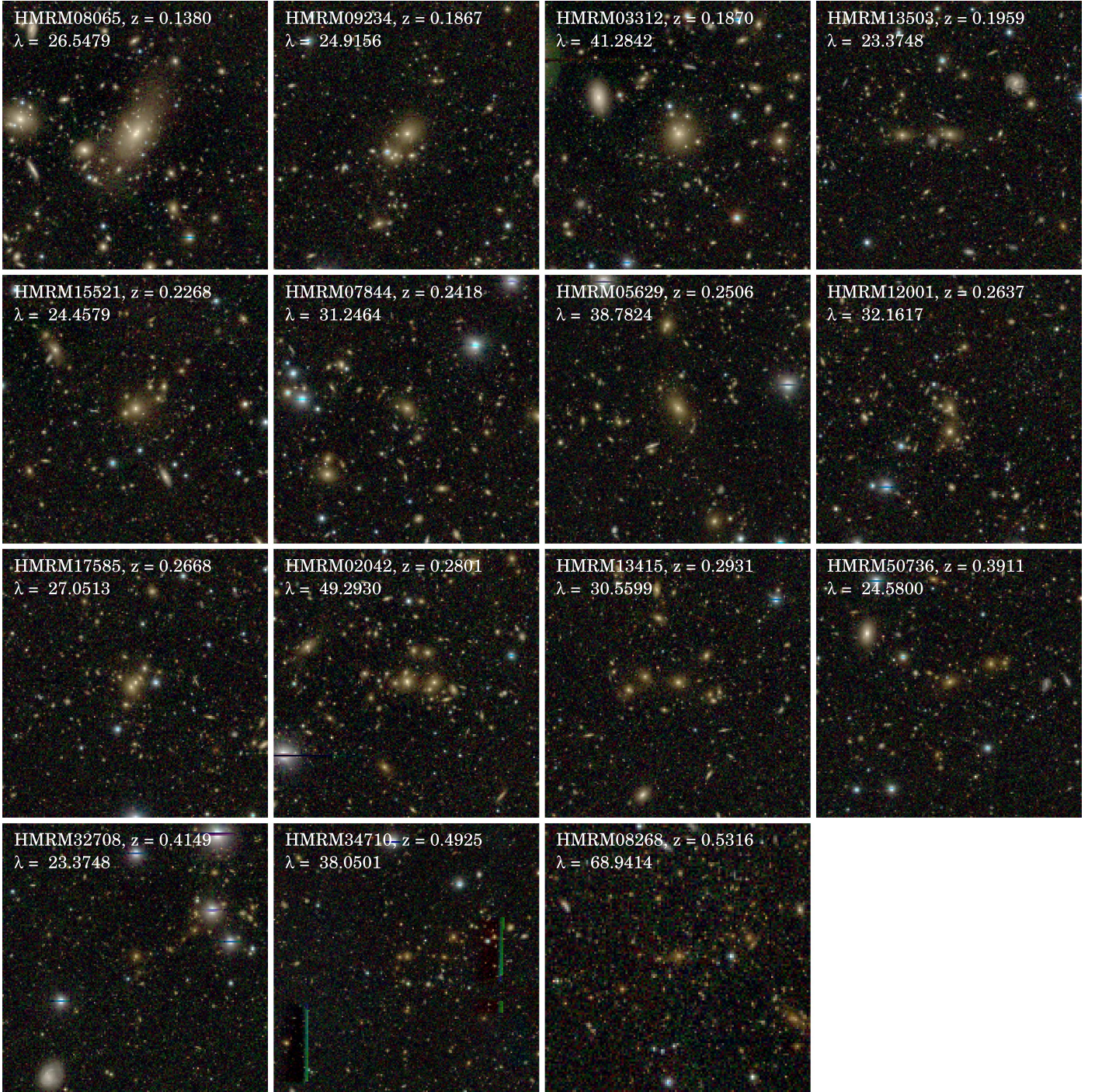


Figure 3. *Subaru*/*HSC* thumbnail images of HectoMAP redMaPPer clusters in the *HSC* public archive sorted by their redshifts. The image sizes are $2 \text{ arcmin} \times 2 \text{ arcmin}$, except HMRM08268 ($1.5 \text{ arcmin} \times 1.5 \text{ arcmin}$). The color channels R, G, and B of the thumbnails are HSC-i, HSC-r, and HSC-G, respectively.

diagram, the cluster members show a strong concentration around the cluster center (e.g., Diaferio & Geller 1997; Rines & Diaferio 2006; Rines et al. 2013, 2016; Serra & Diaferio 2013; Sohn et al. 2018).

Following previous studies, we identify cluster members based on the R - v diagrams. Here we apply a simple boundary because many systems are not very well populated: $R_{\text{cl}} < 1.5 \text{ Mpc}$ and $|\Delta c(z_{\text{galaxy}} - z_{\text{cl}})/(1 + z_{\text{cl}})| < 2000 \text{ km s}^{-1}$, where R_{cl} is the clustercentric distance, z_{galaxy} is the spectroscopic redshift of galaxies in the field, z_{cl} is the cluster central redshift. We set the

R_{cl} limit based on the maximum R_{cl} of redMaPPer members with $P_{\text{mem}} > 0$ and the $|\Delta c(z_{\text{galaxy}} - z_{\text{cl}})/(1 + z_{\text{cl}})|$ limit based on the maximum range of spectroscopically identified members in known massive clusters (e.g., HeCS, Rines et al. 2013, 2016). The redMaPPer spectroscopic membership is insensitive to the redshift cut from ~ 1500 – 2500 km s^{-1} . This cut is 60% or less of the photometric redshift window. The spatial and redshift limits are necessarily generous compared with techniques applicable to better sampled systems (e.g., Rines & Diaferio 2006; Rines et al. 2016; Sohn et al. 2018).

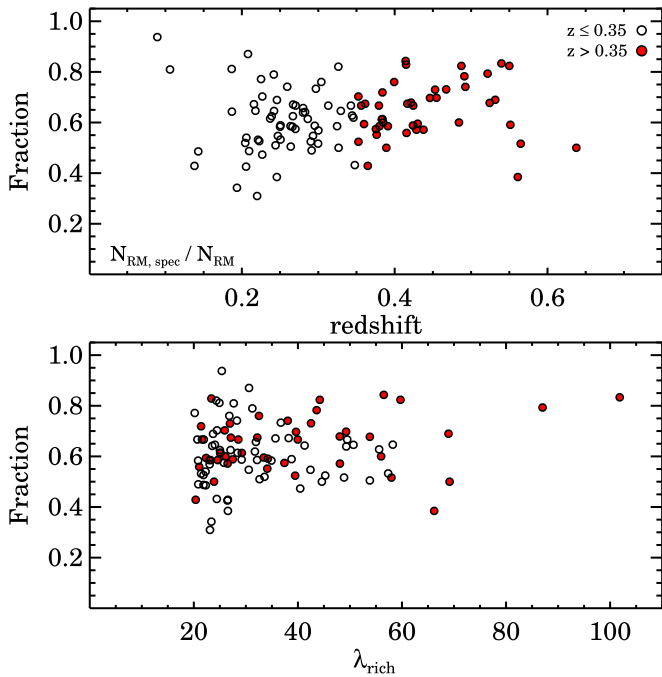


Figure 4. Spectroscopic completeness of redMaPPer members ($P_{\text{mem}} > 0$) in HectoMAP as a function of redshift (upper panel) and richness, λ_{rich} (lower panel).

To identify cluster members, we examine the R - v diagrams based on the cluster center from the original redMaPPer cluster catalog (Rykoff et al. 2016). For the cluster central redshift, we first check the redshift of the central galaxy identified by redMaPPer, z_{central} . The HectoMAP redshift survey includes spectroscopic redshifts of 100 (96%) of the HectoMAP-red central galaxies. If there is a redshift for the central galaxy, we identify cluster members by applying the R_{cl} and $|\Delta c(z_{\text{galaxy}} - z_{\text{central}})/(1 + z_{\text{central}})|$ window. For some clusters, including the four systems without a spectroscopic redshift of the central galaxy, there are still only a few spectroscopically confirmed redMaPPer members around the central galaxy.

We estimate the median spectroscopic redshift, z_{med} , of the redMaPPer members with $P_{\text{mem}} > 0$. We reidentify the spectroscopic members from the R - v diagrams centered on this revised z_{med} . Finally, we take either z_{central} or z_{med} as the estimate of the cluster mean. We choose the estimate based on the largest number of plausible spectroscopic members. Hereafter, the cluster redshift ($z_{\text{spec,cl}}$) is the central redshift of a HectoMAP-red cluster determined from spectroscopically identified members.

Figure 5 compares the spectroscopic ($z_{\text{spec,cl}}$) and photometric redshifts ($z_{\text{phot,cl}}$) of all of the HectoMAP-red clusters. The photometric redshifts are generally consistent with the spectroscopic redshifts with a few significant offsets. The mean difference ($|\Delta c(z_{\text{phot,cl}} - z_{\text{spec,cl}})/(1 + z_{\text{spec,cl}})|$) is $\sim 3800 \text{ km s}^{-1}$, comparable with the mean cluster photometric redshift uncertainty for a single cluster in the redMaPPer catalog (i.e., $\sim 3800 \text{ km s}^{-1}$). It is noteworthy that the 3σ photometric error is comparable with the diameter of smaller voids in the HectoMAP survey (see Section 4.3). For the 11 systems with $|\Delta c(z_{\text{phot,cl}} - z_{\text{spec,cl}})/(1 + z_{\text{spec,cl}})| > 6000 \text{ km s}^{-1}$, our spectroscopic survey is relatively incomplete ($< 50\%$). The redMaPPer catalog identified ~ 48 – 75 members for these 11 systems, but we identify only ~ 6 – 35 spectroscopic members.

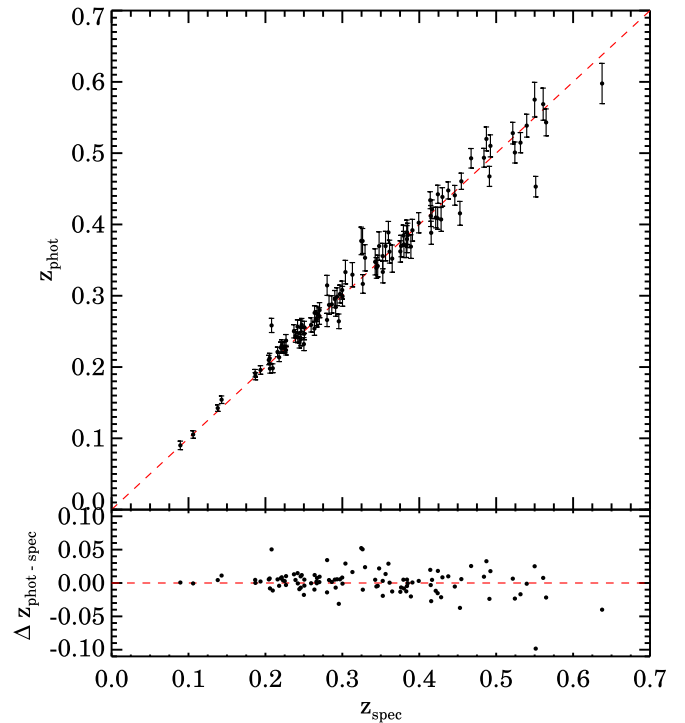


Figure 5. (Upper) Photometric redshifts vs. spectroscopic redshifts of HectoMAP redMaPPer clusters and (lower) the difference between them. Here, spectroscopic redshift indicates the mean spectroscopic redshift of cluster members (if any).

Figure 6 shows the R - v diagrams of the 15 HectoMAP-red clusters with HSC images. We use the redMaPPer center and the spectroscopically determined cluster redshift.

Figure 6 includes the R - v diagrams for the three systems that are not apparent rich clusters in the HSC images. HMRM13503 ($z_{\text{phot}} = 0.1959$) contains only eight spectroscopic members within the membership window. The redMaPPer algorithm identifies more members in the field, but these redMaPPer members are foreground and background objects. HMRM32708 ($z_{\text{phot}} = 0.4122$) has 34 spectroscopic members, but the redMaPPer richness is quite low. There are 14 spectroscopic members in the HMRM34710 ($z_{\text{phot}} = 0.4933$) field. However, only six members are located around the BCG and eight members are well separated from the BCG. Thus, HMRM13503 and HMRM34710 are poor groups as both the HSC imaging and the R - v diagrams suggest.

In 76 of the 104 clusters, the spectroscopic BCG is identical to the redMaPPer central galaxy. For four systems, we lack a spectroscopic redshift for the redMaPPer central galaxy. However, in 24 systems ($\sim 23\%$), the spectroscopy identifies a BCG that is not the redMaPPer central galaxy. This fraction of offset BCGs is comparable with the redMaPPer estimate of the number of probable central galaxy misidentifications (15%–20%, Rykoff et al. 2016).

In Figure 6, gray dots mark the spectroscopic targets and red filled circles indicate HectoMAP-red member candidates with $P_{\text{mem}} > 0.5$. The dashed lines indicate the photometric redshifts of the clusters assigned by redMaPPer. Note that the photometric redshifts are often significantly offset from the mean spectroscopic redshift of the HectoMAP-red member candidates (red filled circles).

redMaPPer members generally cluster around the BCG. Interestingly, some redMaPPer members are not at the cluster

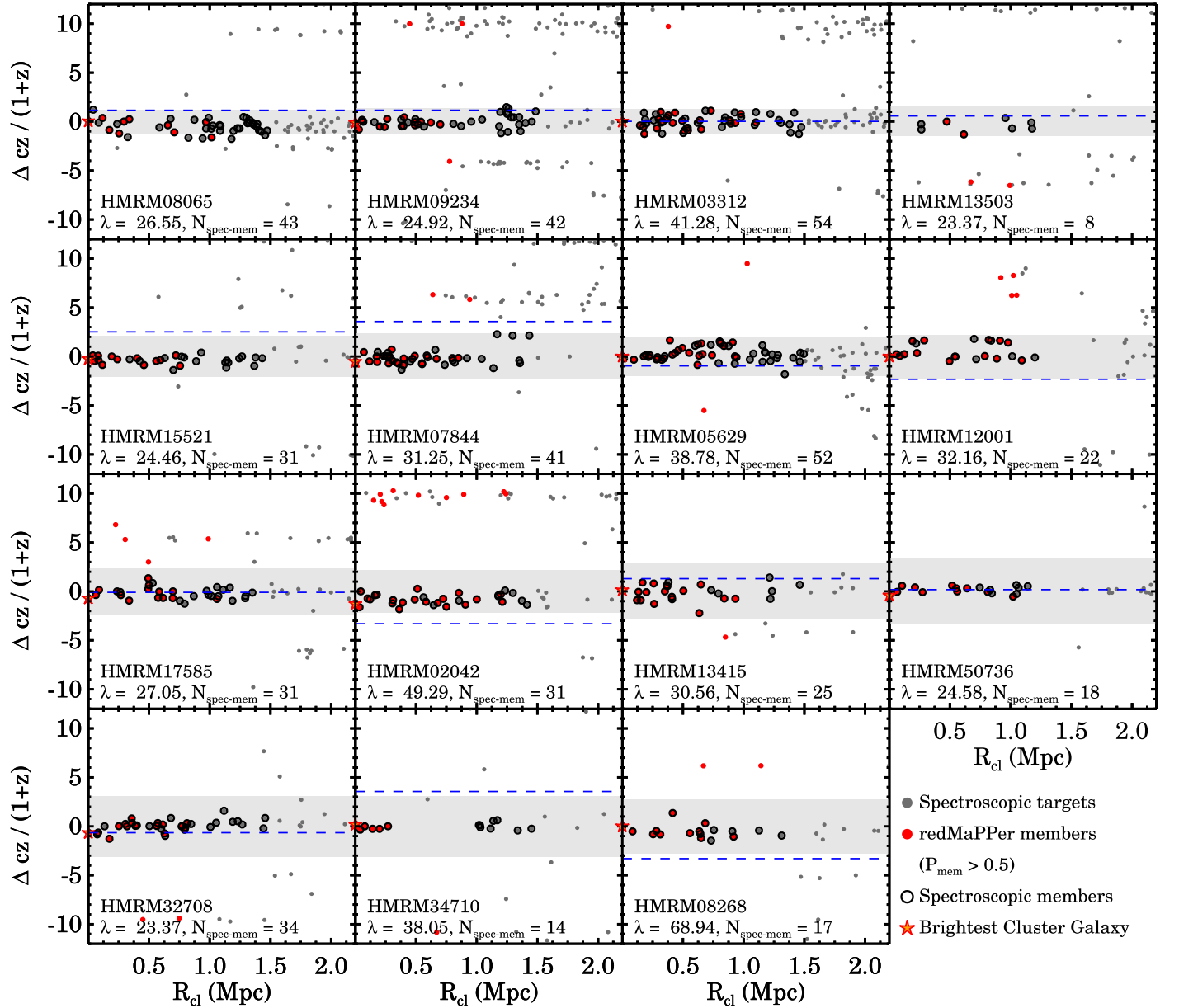


Figure 6. Rest-frame clustercentric radial velocities vs. clustercentric radius for HectoMAP redMaPPer clusters shown in Figure 3. Here, the spatial centers are from the redMaPPer catalog, and the central redshifts are spectroscopically determined. Gray dots are spectroscopic targets within the fields. Red filled circles and black open circles are redMaPPer members with $P_{\text{mem}} > 0.5$ and the spectroscopically identified members, respectively. Starlets indicate the brightest cluster galaxies. Dashed lines mark the cluster photometric redshift given in the redMaPPer catalog. Gray shaded regions show the uncertainty of the photometric redshift of the HectoMAP-red clusters from Rykoff et al. (2016). The $\Delta cz/(1+z_{\text{cl}})$ cuts for identifying spectroscopic members we use corresponds to $\sim 60\%$ of the photometric redshift uncertainty of the clusters.

redshift. These redMaPPer members tend to have low membership probability (see Section 4.1). Furthermore, a significant fraction of the spectroscopically identified members are not identified by the redMaPPer algorithm. The objects redMaPPer fails to evaluate are a mix of galaxies much bluer than the red sequence and of apparent failures of the redMaPPer algorithm to identify true red cluster members.

The R - v diagrams show some of the neighboring foreground and background structures in the line-of-sight direction toward the HectoMAP-red clusters. Figure 7 shows R - v diagrams of four HectoMAP-red clusters, where there are dense structures within the photometric redshift window for individual galaxies (indicated by gray shading). In these cases, the redMaPPer member candidate list includes large numbers of these foreground and

background objects (red dots). This inclusion of nearby structures artificially inflates the redMaPPer richness of these systems.

3.3. The Red Sequence of HectoMAP-red Clusters

The redMaPPer algorithm identifies clusters on the basis of the red sequence. To explore the prominence of the red sequence, Figure 8 shows the $(g-r)_{\text{model},0}$ versus $r_{\text{petro},0}$ color-magnitude diagrams of the 15 HectoMAP-red clusters with HSC images. We plot galaxies within 15 arcmin of each cluster center as gray dots. The red filled circles and black open circles indicate redMaPPer members and the full set of spectroscopically identified members, respectively. Following Rines et al. (2013), we determine the $g-r$ red sequence of each cluster by assuming a slope of -0.04 in the color-magnitude domain and fitting the spectroscopically identified

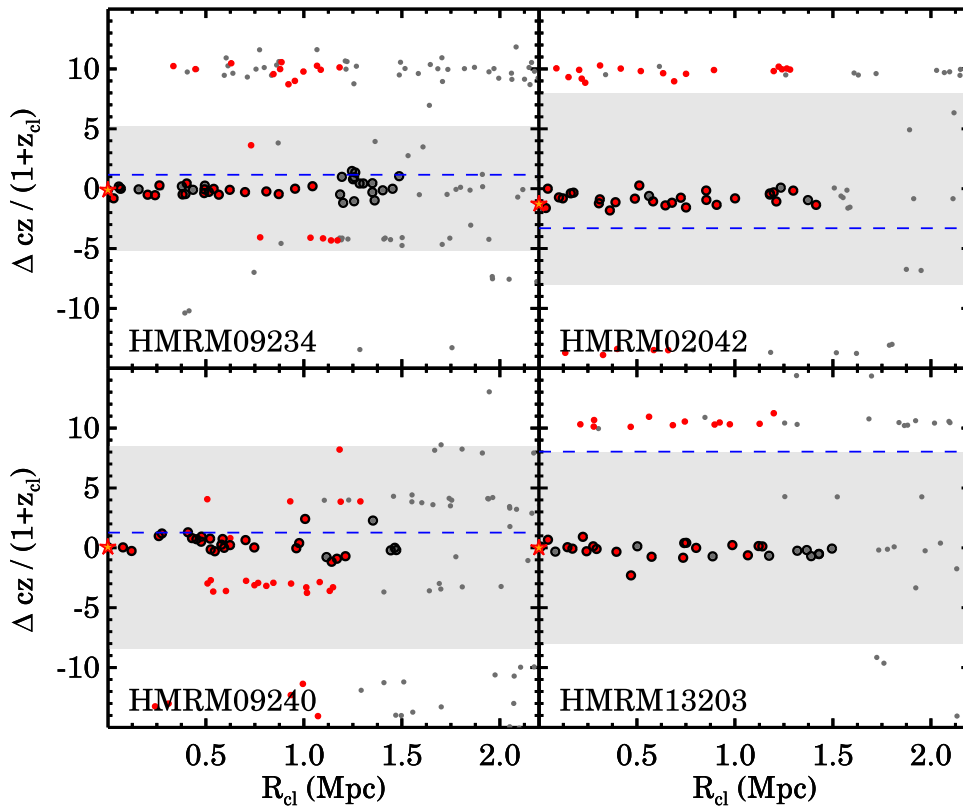


Figure 7. $R-v$ diagrams of example HectoMAP-red clusters with dense superimposed structure along the line of sight. The symbols are the same as those in Figure 6 except for the red filled circles and the gray shaded regions. The red filled circles show the redMaPPer members with $P_{\text{mem}} > 0$. The shaded region displays the uncertainty in the photometric redshift error for individual galaxies (Figure 7 of Rykoff et al. 2014). Note that foreground/background structures contain a number of galaxies comparable with the main cluster.

member galaxies; we then identify red-sequence members as objects within ± 0.2 mag of the red sequence. The slope of the red sequence may change at higher redshift, but galaxies in the well-populated HectoMAP X-ray clusters ($z \lesssim 0.4$, Sohn et al. 2018) are consistent with this definition of the red sequence.

The red sequence we use differs from the one used by redMaPPer. We determine the red sequence in the $(g-r)_{\text{model},0} - r_{\text{model},0}$ space; redMaPPer derives the multi-color red-sequence model based on all of the SDSS bands. Here, we use the red sequence only to show the impact of spectroscopy on redMaPPer cluster identification. We do not use the red sequence itself to identify real systems. However, for 11 of the 15 clusters the $g-r$ versus r red sequence is well-defined. When this red sequence is not readily visible, the richness of the system appears to be substantially overestimated by redMaPPer and/or the system is at $z \geq 0.4$ where the scatter in the red sequence is substantial in this color-magnitude space.

We examine the $(r-i)_{\text{model},0} - i_{\text{petro},0}$ color-magnitude diagrams for clusters with $z \geq 0.35$. For the clusters at $z > 0.35$, we determine the $r-i$ red sequence for each cluster by assuming a slope -0.01 and we select red-sequence members within ± 0.1 of the red sequence. This choice of slope provides a reasonable representation of the data. In general, the red sequences of clusters with $z \geq 0.35$ are flatter and tighter in the $r-i$ color domain (e.g., Figure 3 from Rykoff et al. 2014). The scatter around the red sequence increases with redshift (e.g., Figure 4 from Rykoff et al. 2014).

In the color-magnitude diagram for each cluster, a significant number of nonmembers (generally background objects) contaminate the apparent red sequence and bias the richness estimate upward. There are also spectroscopically determined members that lie on the approximate red sequence we define, but they do not have a redMaPPer membership probability. This problem may originate from large offsets between the photometric redshift reported by redMaPPer and the more accurate spectroscopic mean redshift.

4. Discussion

HectoMAP enables a direct examination of the spectroscopic properties of the 104 photometrically selected redMaPPer clusters (HectoMAP-red) covering the redshift range $0.08 < z < 0.6$. Because HectoMAP targets red galaxies, the redshift survey is particularly powerful for investigating clusters identified with a red-sequence technique like the one applied to identify redMaPPer candidate systems. HectoMAP includes redshifts for $\geq 60\%$ of the redMaPPer cluster candidate members with $P_{\text{mem}} > 0$.

Photometric cluster selection is obviously subject to contamination by unrelated structures along the line of sight. We examine the frequency of these line-of-sight structures in the 104 HectoMAP-red clusters (Section 4.1). In Section 4.2, we explore the spectroscopically determined richness relative to the redMaPPer richness of these systems. In Section 4.3, we discuss the fraction of HectoMAP-red clusters that are confirmed with spectroscopy and we discuss indications that

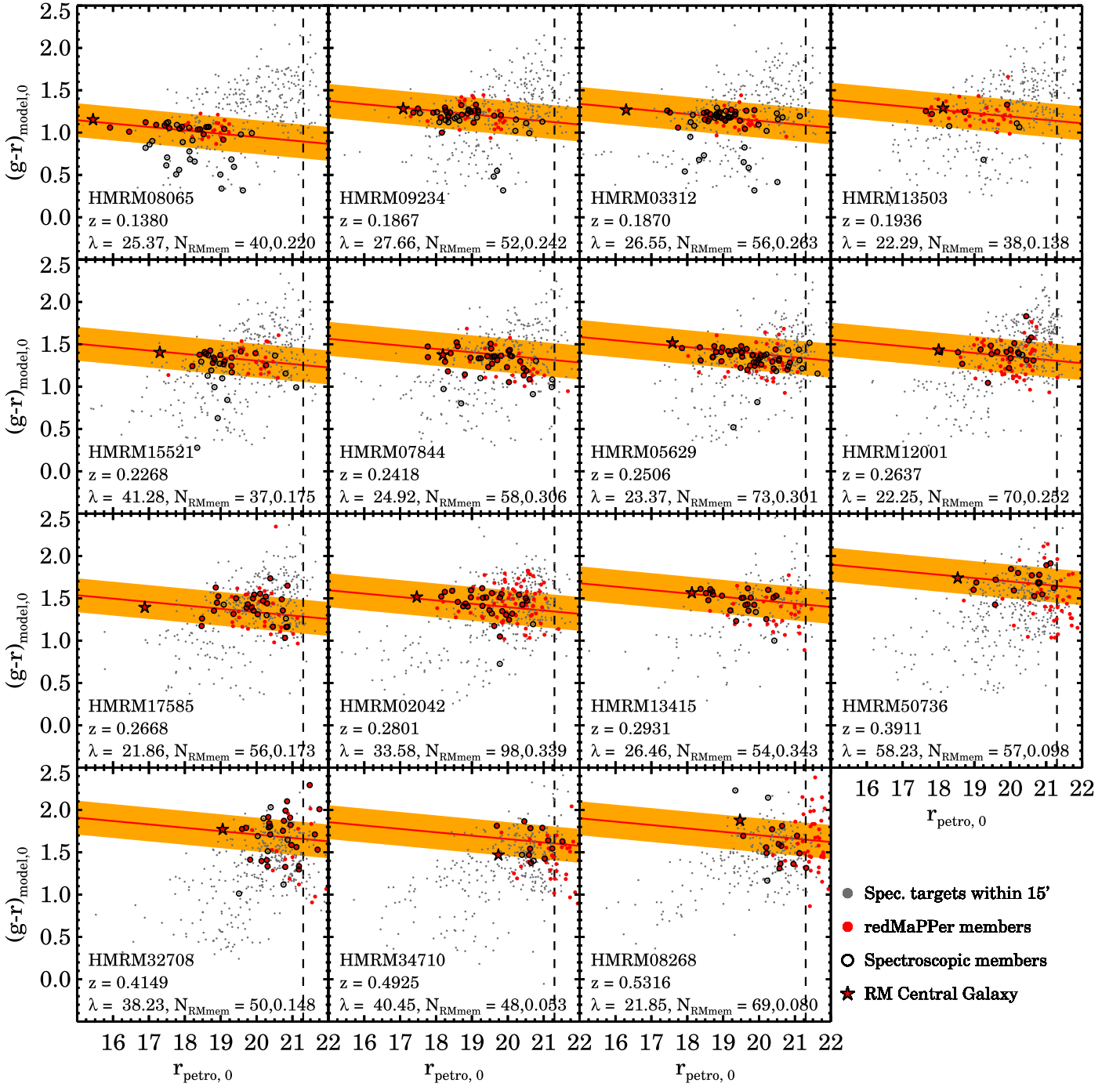


Figure 8. $(g-r)_{model,0}$ vs. $r_{petro,0}$ color–magnitude diagrams of HectoMAP-red clusters shown in Figure 3. Gray dots are spectroscopic targets within $15'$ of the cluster center and red filled circles are redMaPPer members with $P_{mem} > 0.5$. Black open circles indicate spectroscopically identified members. Shaded regions display the red sequence (solid line) ± 0.2 .

the redMaPPer catalog is not a complete census even of the richest clusters in the HectoMAP region.

4.1. Superpositions along the Line of Sight

Spectroscopic surveys of galaxy clusters allow for the estimation of the contamination of candidate members selected by color. Figure 9 shows the spectroscopically identified member fraction among the redMaPPer candidate members. We define the spectroscopically identified member fraction in

each cluster as

$$f_{spec-mem,cl} = \frac{N_{spec-mem,RM,spec}}{N_{RM,spec}}, \quad (2)$$

where $N_{spec-mem,RM,spec}$ is the number of spectroscopically identified members among the redMaPPer candidate members and $N_{RM,spec}$ is the total number of redMaPPer candidate members with $P_{mem} > 0$ and with spectra. The median $f_{spec-mem,cl}$ of the HectoMAP-red clusters is $\sim 59\%$. The median

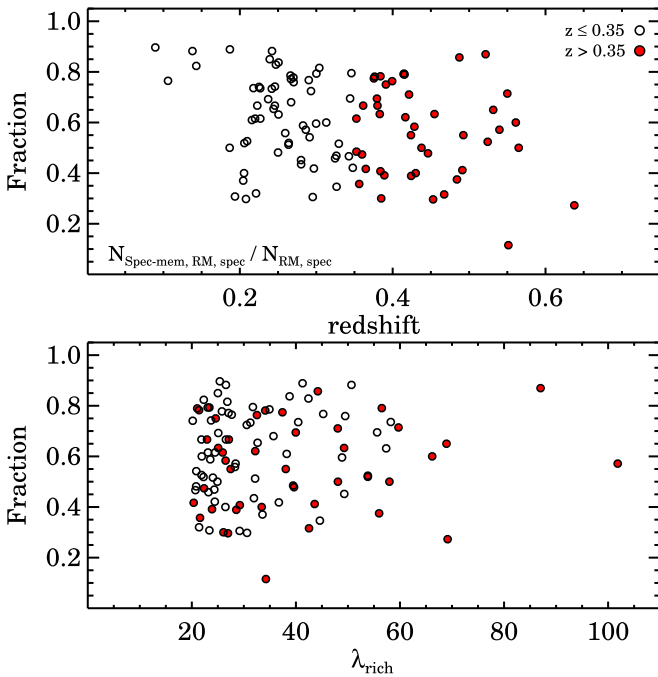


Figure 9. Fraction of spectroscopically identified members among redMaPPer members ($P_{\text{mem}} > 0$) with spectroscopic redshifts as a function of cluster redshift (upper) and richness (λ_{rich} , lower). More than 20% of redMaPPer members are contaminant foreground or background objects.

$f_{\text{spec-mem,cl}}$ increases for candidate members with $P_{\text{mem}} > 0.5$ ($\sim 72\%$) and $P_{\text{mem}} > 0.9$ ($\sim 91\%$). We find no dependence of the spectroscopically identified member fraction on redshift and richness.

The R - v diagrams in Figure 10 show how the distribution of the spectroscopic HectoMAP-red cluster members depends on P_{mem} . We plot stacked R - v diagrams of the 61 low redshift ($z \leq 0.35$) and 43 high-redshift ($z > 0.35$) HectoMAP-red clusters within three different P_{mem} bins: $P_{\text{mem}} \geq 0.9$, $0.9 > P_{\text{mem}} \geq 0.5$, and $0.5 > P_{\text{mem}}$. For $P_{\text{mem}} \geq 0.9$, there is a strong concentration of spectroscopically identified members toward the cluster center. Even for these high confidence objects, $\sim 11\%$ have a rest-frame relative velocity that differs from the cluster center by $(|\Delta cz / (1 + z_{\text{cl}})| \geq 2000 \text{ km s}^{-1})$. The typical velocity dispersion derived from the stacked $P_{\text{mem}} \geq 0.9$ members is $\sim 650 \text{ km s}^{-1}$ comparable with the typical rich cluster line-of-sight velocity dispersion ($\sim 700 \text{ km s}^{-1}$, Rines et al. 2013). The candidate members with lower P_{mem} generally lie at larger radius if they are within the redshift range for spectroscopic membership. The fraction of objects with large $|\Delta cz / (1 + z_{\text{cl}})|$ increases as P_{mem} decreases: $\sim 35\%$ are outliers when $0.9 > P_{\text{mem}} \geq 0.5$ and $\sim 66\%$ outliers are when $0.5 > P_{\text{mem}}$.

Based on the fraction of spectroscopically identified members among redMaPPer member candidates, we provide a correction function for redMaPPer cluster membership. Rozo et al. (2015b) also estimate the spectroscopic member fraction among redMaPPer members, but they use only red galaxies from various spectroscopic samples.

Figure 11 shows the spectroscopically identified member fractions as a function of P_{mem} . A large fraction, but not all of the objects with $P_{\text{mem}} > 0.9$ tend to be spectroscopically identified members. We examine the spectroscopically

identified member fractions at various clustercentric radii within different magnitude ranges, but the overall fractions have little dependence on these observables. The spectroscopically identified member fractions are also insensitive to the redshift and the richness of clusters.

We fit the spectroscopically identified member fraction with a simple linear relation,

$$f_{\text{spec-mem}} = (0.25 \pm 0.02) + (0.66 \pm 0.02)P_{\text{mem}}. \quad (3)$$

This relation provides a spectroscopically determined correction to the redMaPPer membership probability. It is interesting that at the lowest redMaPPer probabilities, there are more real spectroscopic members ($\sim 14\%$) than the redMaPPer algorithm would suggest.

We compare the $f_{\text{spec-mem}}$ from the HectoMAP-red sample to a similar relation derived from the HeCS-red sample (K. Rines et al. 2017, in preparation). The HeCS-red sample includes 23 high-richness ($\lambda \geq 64$) redMaPPer clusters in the redshift range $0.08 < z < 0.25$. K. Rines et al. (2017, in preparation) examine the spectroscopically identified member fraction of the HeCS-red sample based on extensive SDSS and MMT/Hectospec redshift data. The blue dotted line in Figure 11 shows the linear relation for the HeCS-red sample; this relation is much shallower than for the HectoMAP-red sample. In the HeCS-red sample, fewer high P_{mem} galaxies are spectroscopically identified members and more low P_{mem} galaxies are spectroscopically identified members.

The HeCS-red clusters include the highest richness systems at low redshift; in contrast, the HectoMAP-red clusters are low richness systems covering a much wider redshift range. In its redshift range $0.08 < z < 0.25$, the redshift survey for the HeCS-red has more complete ($\sim 90\%$) coverage of the red sequence, but reaches only $r \leq 20.5$. The r - i cut in HectoMAP leads to undersampling of the red sequence in this redshift range. In addition, K. Rines et al. (2017, in preparation) use the caustic technique (Diaferio & Geller 1997; Diaferio 1999; Serra & Diaferio 2013) for identifying spectroscopic members. This approach is more stringent than our coarse membership determination. These substantial differences in samples and member identification probably explain the differences in the spectroscopically identified member fractions.

4.2. Richness of HectoMAP-red Clusters

Spectroscopy of the HectoMAP-red clusters confirms the identification of most redMaPPer systems. Of these systems, 90% or more show a concentration in the R - v diagram, and the R - v diagram identifies more than 10 members. Overall, the redMaPPer catalog has impressive purity: $\gtrsim 90\%$ of the candidate systems are condensations in redshift space. Based on the spectroscopy, we refine the cluster mean redshift and richness.

The upper panel of Figure 12 shows the number of spectroscopically identified members in the HectoMAP-red clusters as a function of redMaPPer richness, λ_{rich} . We next test the correlation between the number of spectroscopically identified members and the redMaPPer richness (λ_{rich}). The Pearson correlation coefficient (0.13 ± 0.10) is very low. If we divide the samples at $z = 0.35$, where redMaPPer identifies clusters based on a different color-magnitude domain, neither sample shows a significant correlation (0.49 ± 0.11 and 0.21 ± 0.15 , respectively).

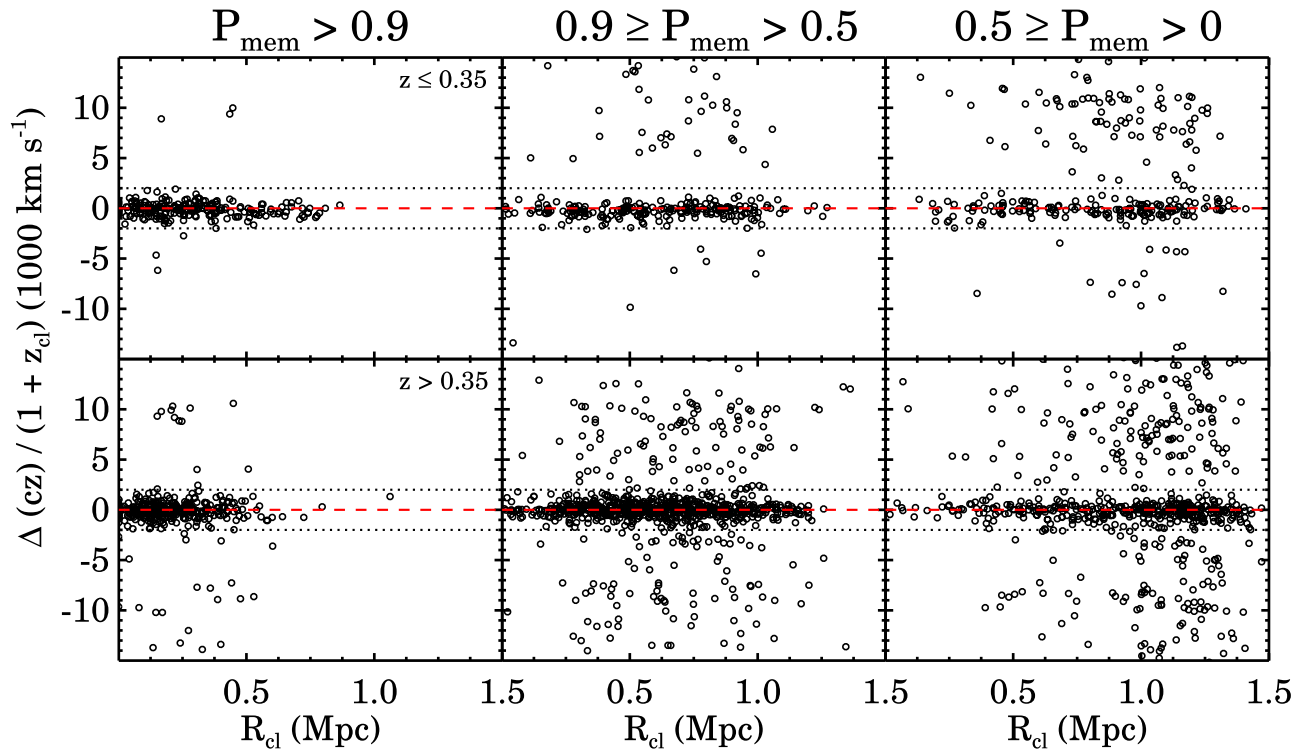


Figure 10. Stacked R - v diagrams of 104 HectoMAP-red clusters for three different bins of membership probability: $P_{\text{mem}} \geq 0.9$, $0.9 > P_{\text{mem}} > 0.5$, $0.5 > P_{\text{mem}} > 0$ for clusters with $z \leq 0.35$ (upper) and with $z > 0.35$ (lower). The dotted lines show the redshift window we use for identifying spectroscopic members. Note that there are many galaxies with $P_{\text{mem}} > 0.5$ offset from the cluster center along the line of sight.

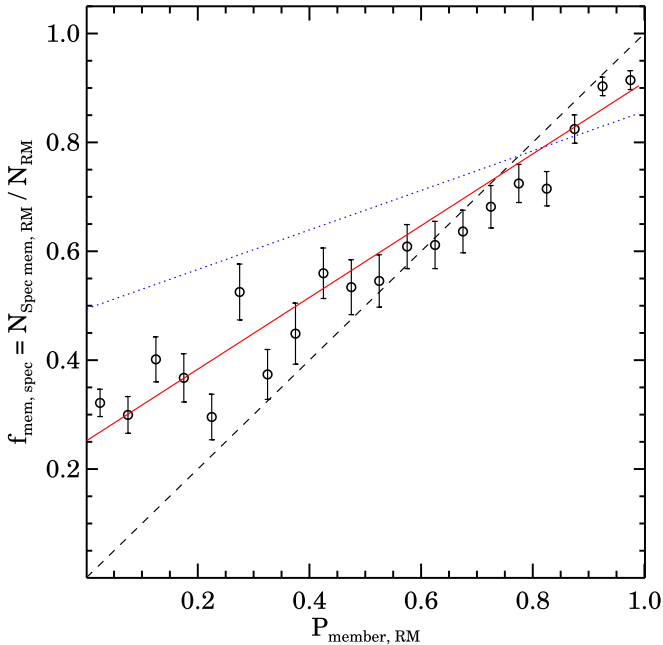


Figure 11. Fraction of spectroscopically identified members among redMaPPer members with spectroscopic redshifts as a function of redMaPPer membership probability (P_{mem}). Error bars indicate the standard deviation for 1000 bootstrap samplings. The dashed line is the one-to-one relation and the solid line shows the linear fit to the spectroscopically identified member fraction with P_{mem} . The dotted line displays a similar relation derived from the HeCS-red sample (K. Rines et al. 2017, in preparation).

The 10 HectoMAP-red clusters with fewer than 10 spectroscopic members cover a wide redMaPPer richness range $20 < \lambda_{\text{rich}} < 70$. Some of these systems may be poor groups.

The HSC image of one of these candidate systems, HM13503, shows that only a few (~ 5) redMaPPer candidate members are luminous ellipticals. Eight high-redshift ($z > 0.35$) candidates with fewer than 10 spectroscopic members may be poorly sampled; many members have $r > 21.3$.

Based on the spectroscopy, we construct a corrected redMaPPer richness ($\lambda_{\text{rich,cor}}$). To compute this corrected richness, we use spectroscopically identified members that also have a redMaPPer membership probability ($P_{\text{mem}} > 0$). At redshift $z > 0.3$, nearly all spectroscopically identified members have a redMaPPer membership probability; at $z \lesssim 0.4$, the median fraction is $\sim 70\%$. The global fraction of spectroscopically identified members without a redMaPPer P_{mem} is $\sim 25\%$.

The corrected richness is

$$\lambda_{\text{rich,cor}} = \sum f_{\text{spec-mem}} = \sum (0.25 + 0.66P_{\text{mem}}). \quad (4)$$

In Equation (3), we use only redMaPPer candidate members with $r_{\text{petro},0} < 21.3$, the limiting apparent magnitude of the HectoMAP survey. The corrected richness indicates the total number of redMaPPer members after correction for contamination by line-of-sight objects brighter than the HectoMAP limit. The weighting of objects without spectroscopically confirmed membership reflects the original redMaPPer prescription with the correction to the probabilities that we derive from spectroscopy. We have checked that the correction to the redMaPPer membership probability (Figure 11) is insensitive to apparent magnitude, redshift, and color.

The lower panel of Figure 12 displays the corrected richness as a function of the original redMaPPer richness (λ_{rich}). For the overall and high- z ($z > 0.35$) samples, the corrected richness is not tightly correlated with the original redMaPPer richness; the

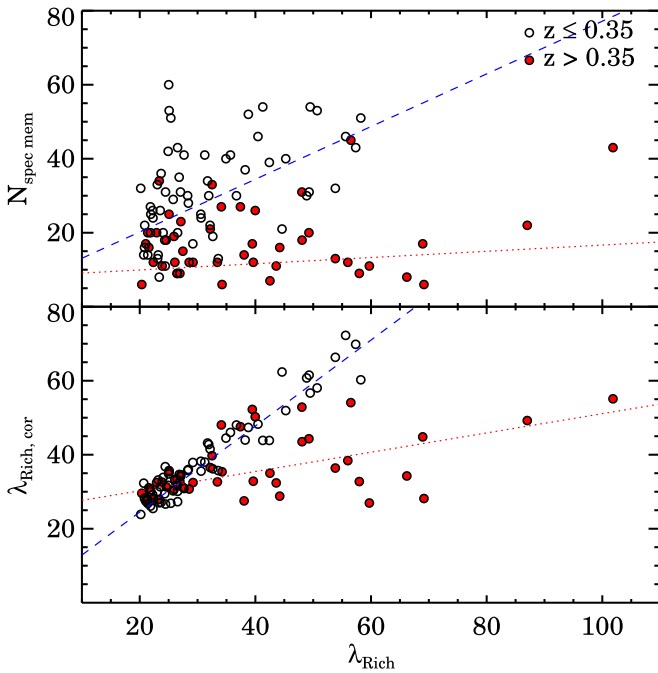


Figure 12. Number of spectroscopically identified members of redMaPPer clusters as a function of richness. The open and filled circles indicate HectoMAP-red clusters at $z \leq 0.35$ and $z > 0.35$, respectively. The dashed and dotted lines are linear fits for the lower and the higher redshift samples, respectively.

Pearson correlation coefficient is 0.57 ± 0.08 . The incompleteness of our spectroscopic sample at $21.3 < r < 22$, where most redMaPPer members in the high- z samples appear, may produce the lack of correlation. In contrast, the lower redshift sample shows a significant correlation with a coefficient of ~ 0.99 . For low- z samples, the HectoMAP redshift survey covers a significant fraction of redMaPPer members. The linear fit between λ and $\lambda_{\text{rich,cor}}$ for the $z \leq 0.35$ HectoMAP-red clusters (after 2σ clipping) is

$$\lambda_{\text{rich,cor}} = (1.3 \pm 7.8) + (1.2 \pm 0.2) \lambda_{\text{rich}}. \quad (5)$$

Figure 13 is similar to Figure 12, but for the raw redMaPPer richness (λ_{rich}/S). The raw richness indicates the effective number of redMaPPer members brighter than the limiting magnitude of the survey ($r \sim 22$). The richness (λ_{rich}) is a correction of the raw richness (λ_{rich}/S) for the geometric survey mask (including star holes and survey boundaries) within the survey area, or the missing galaxies below the redMaPPer magnitude limit $i < 21.0$ (Rykoff et al. 2014, 2016; Rozo et al. 2015b).

The raw richness shows a weak correlation with the number of spectroscopically identified members in both the low- and high-redshift samples. The Pearson correlation test yields marginal correlation coefficients: 0.48 ± 0.11 for $z \leq 0.35$ and 0.65 ± 0.12 for $z > 0.35$. The dashed and dotted lines in Figure 13 indicate linear fits for the low- and high-redshift samples, respectively. However, the spectroscopically corrected richness is tightly correlated with the raw richness, with high correlation coefficients (0.97 ± 0.03 and 0.97 ± 0.03). We derive linear fits between the spectroscopically corrected richness and the redMaPPer raw richness (λ_{rich}/S) for both

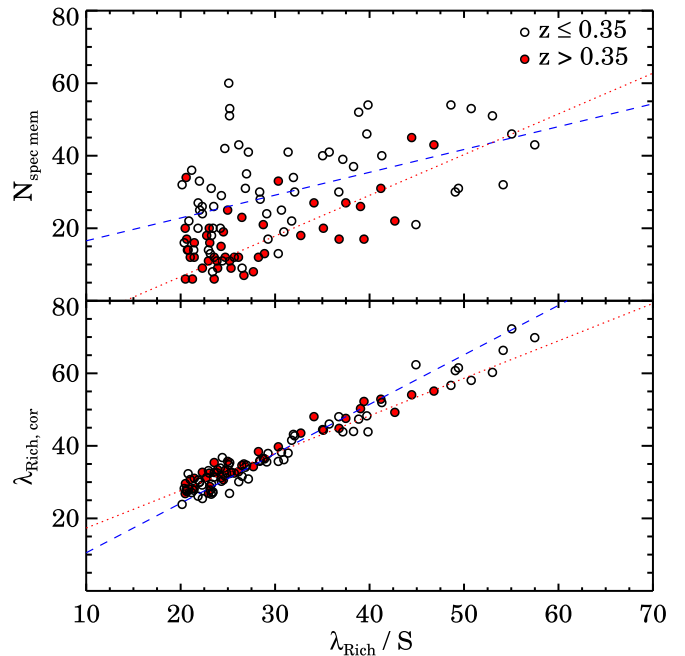


Figure 13. Number of spectroscopically identified members of redMaPPer clusters as a function of raw richness (λ_{rich}/S). The open and filled circles indicate HectoMAP-red clusters at $z \leq 0.35$ and $z > 0.35$, respectively. The dashed and dotted lines are linear fits for the lower and the higher redshift samples, respectively.

redshift ranges

$$\lambda_{\text{rich,cor}} = (-3.1 \pm 7.4) + (1.4 \pm 0.2)(\lambda_{\text{rich}}/S) \text{ for } z \leq 0.35, \quad (6)$$

and

$$\lambda_{\text{rich,cor}} = (7.0 \pm 7.5) + (1.0 \pm 0.2)(\lambda_{\text{rich}}/S) \text{ for } z > 0.35. \quad (7)$$

Several studies suggest that the redMaPPer λ_{rich} is a mass proxy (Roza et al. 2015a, 2015b; Simet et al. 2017). However, HectoMAP spectroscopy suggests that λ_{rich} is not tightly correlated with the spectroscopically corrected richness at $z > 0.35$. In this redshift range, the redMaPPer raw richness correction S is significant. Extension of the spectroscopy to fainter magnitudes for a sufficiently large sample of photometrically identified clusters would substantially improve the calibration of λ_{rich} as a mass proxy, in particular, at $z > 0.35$.

4.3. Completeness of HectoMAP-red Clusters

Figure 14 shows the position of the HectoMAP-red clusters in the cone diagram for the HectoMAP region. We mark the positions of the HectoMAP-red clusters (red circles) based on the HectoMAP-red spectroscopic redshifts. If we plotted the HectoMAP-red clusters based on the redMaPPer photometric redshift, the systems would be offset from the galaxy overdensities along the line of sight.

Figure 14 also shows that some of the obvious dense HectoMAP regions do not have HectoMAP-red clusters associated with them. In some of these regions, fingers in redshift space are apparent. For example, massive clusters associated with X-ray emission (cyan circles, Sohn et al. 2018) are missing from the HectoMAP-red cluster sample.

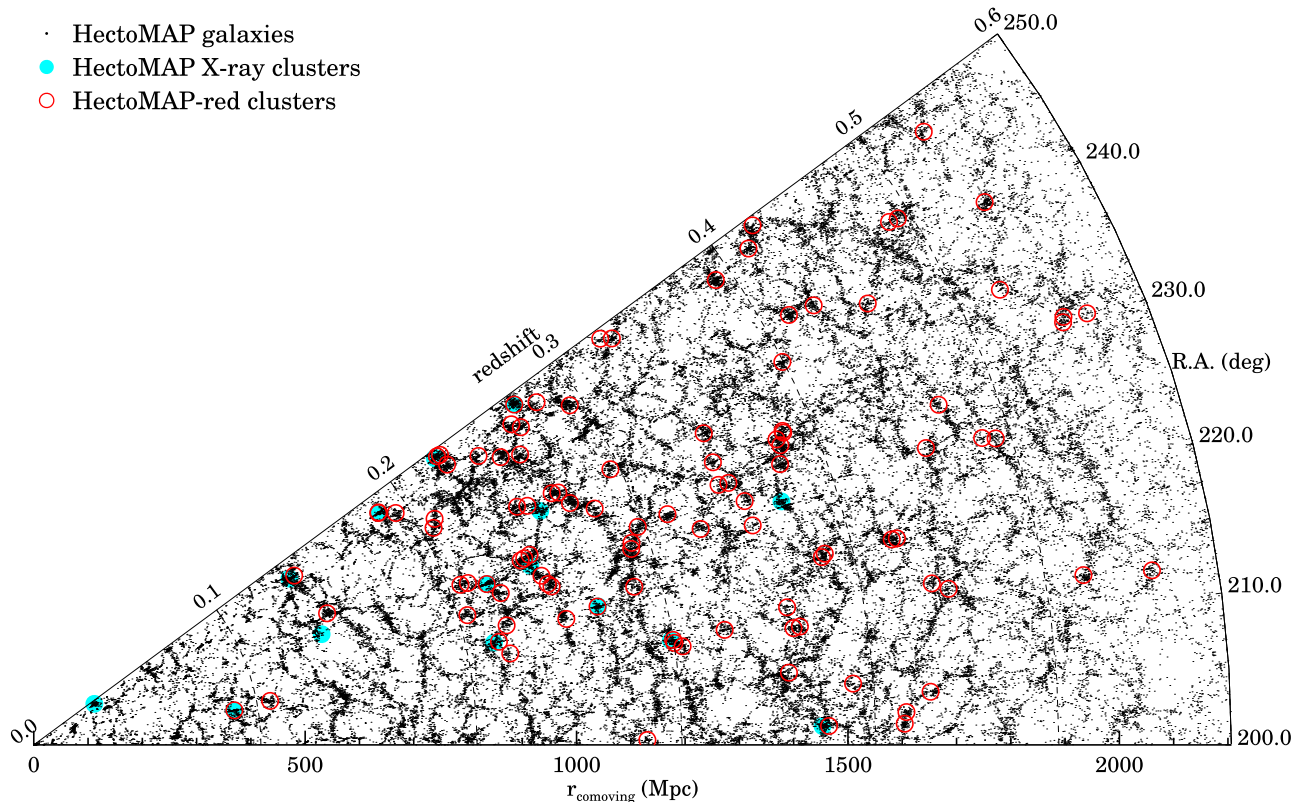


Figure 14. Cone diagram for HectoMAP projected on the R.A. plane. Black dots show individual galaxies and cyan filled circles indicate the HectoMAP X-ray clusters. Red open circles display HectoMAP-red clusters based on the spectroscopic redshifts we determine.

We can obtain some estimate of the completeness of the redMaPPer cluster survey by comparing it with the HectoMAP X-ray clusters (Sohn et al. 2018) that represent some of the most massive systems in the HectoMAP field with $M_{200} \gtrsim 2 \times 10^{13} M_{\odot}$. The X-ray clusters are identified by a coidentification method based on a friends-of-friends algorithm applied to HectoMAP along with X-ray source detection from the *ROSAT* all sky survey data. There are 15 HectoMAP X-ray clusters with $0.03 < z < 0.40$. All of these clusters have at least 18 spectroscopic members; the richest of them has 218 spectroscopically confirmed members.

We identify HectoMAP-red cluster counterparts to the X-ray systems if they are within 1.5 Mpc and $|\Delta cz / (1 + z_{cl})| < 1000 \text{ km s}^{-1}$. We set the 1.5 Mpc criterion to reflect the redMaPPer limiting size (Figure 6). Of the HectoMAP X-ray clusters, 11 have HectoMAP-red cluster counterparts in the public redMaPPer catalog. One HectoMAP X-ray cluster is at $z = 0.03$, below the redMaPPer survey limit. The three missing X-ray clusters are massive systems with large velocity dispersion ($\gtrsim 450 \text{ km s}^{-1}$, Sohn et al. 2018). The dynamical masses of two of the missing X-ray clusters are larger than the effective mass cut ($\gtrsim 1.24 \times 10^{14} M_{\odot}$, Simet et al. 2017) of the public redMaPPer catalog with $\lambda > 20$. These X-ray clusters show obvious $g - r$ or $r - i$ red sequences (Sohn et al. 2017 submitted). These missing X-ray clusters (20 \pm 11%) are listed in a private redMaPPer catalog with a lower richness threshold $\lambda > 5$ (E. Rozo 2018, private communication). Tests of photometric catalogs against all sky X-ray data with deeper and better resolution from e-ROSITA combined with a dense redshift survey for some significant sample can provide a much more robust foundation for cosmological applications than that currently available.

5. Summary

HectoMAP is a dense and a complete redshift survey covering $\sim 53 \text{ deg}^2$ and a redshift range $z < 0.6$. The survey is dense enough over a significant area to test various cluster identification techniques based on photometric data. Surprisingly, the number of photometrically cluster candidates with redshift $z \lesssim 0.6$ in the HectoMAP region varies from 104 to 544 among various catalogs.

We examine the 104 redMaPPer cluster candidates with $0.08 < z < 0.6$ in the HectoMAP region, i.e., the HectoMAP-red clusters. Although the redMaPPer catalog has been widely tested with multi-wavelength data, the HectoMAP-red clusters are unique in testing the robustness of the full richness range to the redMaPPer redshift range. The HectoMAP-red cluster sample complements the HeCS-red cluster sample (K. Rines et al. 2017, in preparation). The *Subaru*/HSC imaging archive includes 15 HectoMAP-red clusters. In the HSC images, most systems are apparent clusters with an obvious BCG near the cluster center.

The HectoMAP redshift survey yields a fairly complete ($>60\%$) sample of redshifts for redMaPPer candidate members in the HectoMAP-red clusters. We determine the cluster central redshift and the spectroscopic cluster membership based on redshifts of individual member candidates. The redMaPPer algorithm identifies 16–107 member candidates with $r \leq 21.3$ for each HectoMAP-red cluster; we identify ~ 6 –60 spectroscopic members. We include 3547 redshifts for member candidates listed in the redMaPPer catalog.

The redMaPPer central galaxies are identical to the spectroscopically determined BCGs in 76 of the 104 clusters.

The HectoMAP redshift survey does not include redshifts of central galaxies for four systems. In 24 systems ($\sim 23\%$), the central galaxies are not spectroscopic BCGs; sometimes they are not even cluster members. This fraction of offset BCG is consistent with the redMaPPer estimate of the central galaxy misidentifications ($\sim 15\%–20\%$).

We estimate the spectroscopically identified member fraction among redMaPPer member candidates. Overall, $\sim 60\%$ of redMaPPer member candidates are spectroscopically identified members. Interestingly, not all HectoMAP-red member candidates with the highest redMaPPer membership probability ($P_{\text{mem}} > 0.9$) are spectroscopically identified members. In fact, $\sim 15\%$ of the lowest P_{mem} galaxies ($P_{\text{mem}} < 0.1$) are spectroscopically identified members. Based on the spectroscopically identified member fraction, we provide a correction function for the redMaPPer membership probability.

We compare the photometrically estimated redMaPPer richness, λ_{rich} , with the spectroscopic richness. The richness, λ_{rich} , is not well-correlated with the spectroscopic richness at redshift $z > 0.35$. However, the spectroscopic richness correlates well with the raw richness (λ_{rich}/S) in the redMaPPer catalog throughout the HectoMAP redshift range.

The HectoMAP redshift survey demonstrates that $\sim 10\%$ of the HectoMAP-red clusters are possibly loose groups with fewer than 10 spectroscopically identified members. More importantly, the redMaPPer algorithm fails to identify all of the massive clusters in the HectoMAP region. For example, $\sim 20\% \pm 11\%$ (3 systems) of the well-populated massive clusters associated with *ROSAT* X-ray emission are not recovered by redMaPPer. Further tests of photometric cluster catalogs against a dense redshift and deeper X-ray data are crucial for providing a robust list of clusters for studying formation and evolution of large-scale structures and for limiting the cosmological parameters.

The authors are grateful to the referee, Eduardo Rozo, for his comments that improved the clarity of the paper. J.S. gratefully acknowledges the support of a CfA Fellowship. The Smithsonian Institution supports M.J.G., and A.D. acknowledges support from the INFN grant InDark. We thank David Reiman for assistance during the early stages of this work. We acknowledge Susan Tokarz for reducing the spectroscopic data and Perry Berlind and Mike Calkins for assisting with the observations. We also thank the telescope operators at the MMT and Nelson Caldwell for scheduling Hectospec queue observations. We thank the HSC help desk team, especially Michitaro Koike and Sogo Mineo, for making the useful tools available. This research has made use of NASA's Astrophysics Data System Bibliographic Services.

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 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.

This paper makes use of software developed for the Large Synoptic Survey Telescope. We thank the LSST Project for making their code available as free software at <http://dm.lsst.org>.

The Pan-STARRS1 Surveys (PS1) have been made possible through contributions of the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max-Planck Society and its participating institutes, the Max Planck Institute for Astronomy, Heidelberg and the Max Planck Institute for Extraterrestrial Physics, Garching, the Johns Hopkins University, Durham University, the University of Edinburgh, Queens University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, the National Aeronautics and Space Administration under grant No. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation under Grant No. AST-1238877, the University of Maryland, and Eotvos Lorand University (ELTE) and the Los Alamos National Laboratory.

Facility: MMT (Hectospec).

Appendix

R–*V* Diagrams and Color–Magnitude Diagrams of the Hectomap-red Clusters

There are 104 HectoMAP-red clusters in the HectoMAP region; in the main body of this paper, we show plots for the 16 clusters with the HSC public images. In this appendix, we display the *R*–*v* diagrams for the remaining 89 HectoMAP-red clusters (Figure 15). The symbols are the same as those in Figure 6. These figures paint a picture of the HectoMAP-red sample that is very similar to the sample of 15 clusters included in the main text. For most of the clusters, there is readily identifiable concentration in redshift space. However, the photometric redshift is often not representative. The full set of figures is available in the online journal.

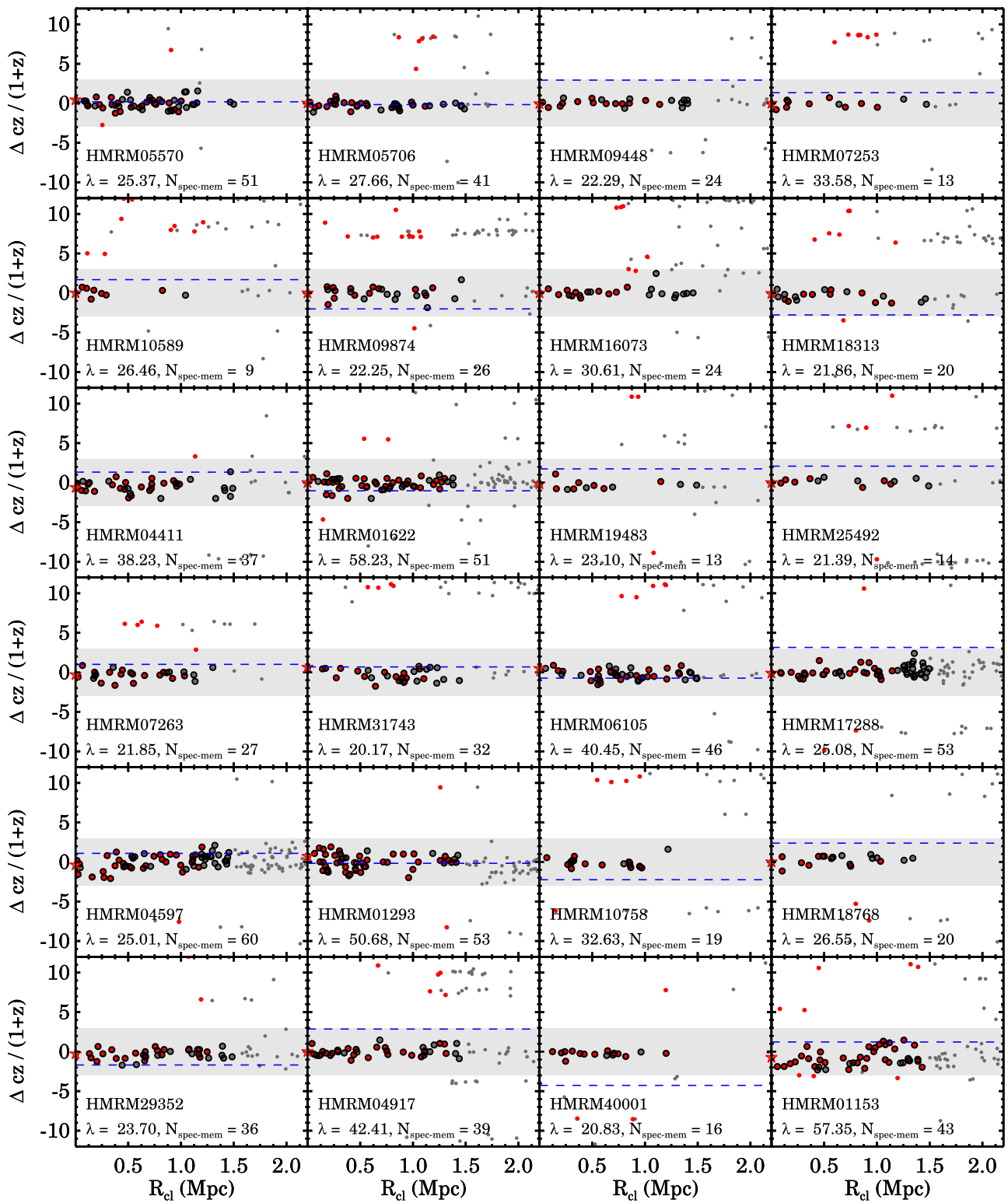


Figure 15. R - v diagrams for the HectoMAP-red clusters that do not appear in the HSC public archive. Symbols are the same in those in Figure 6.

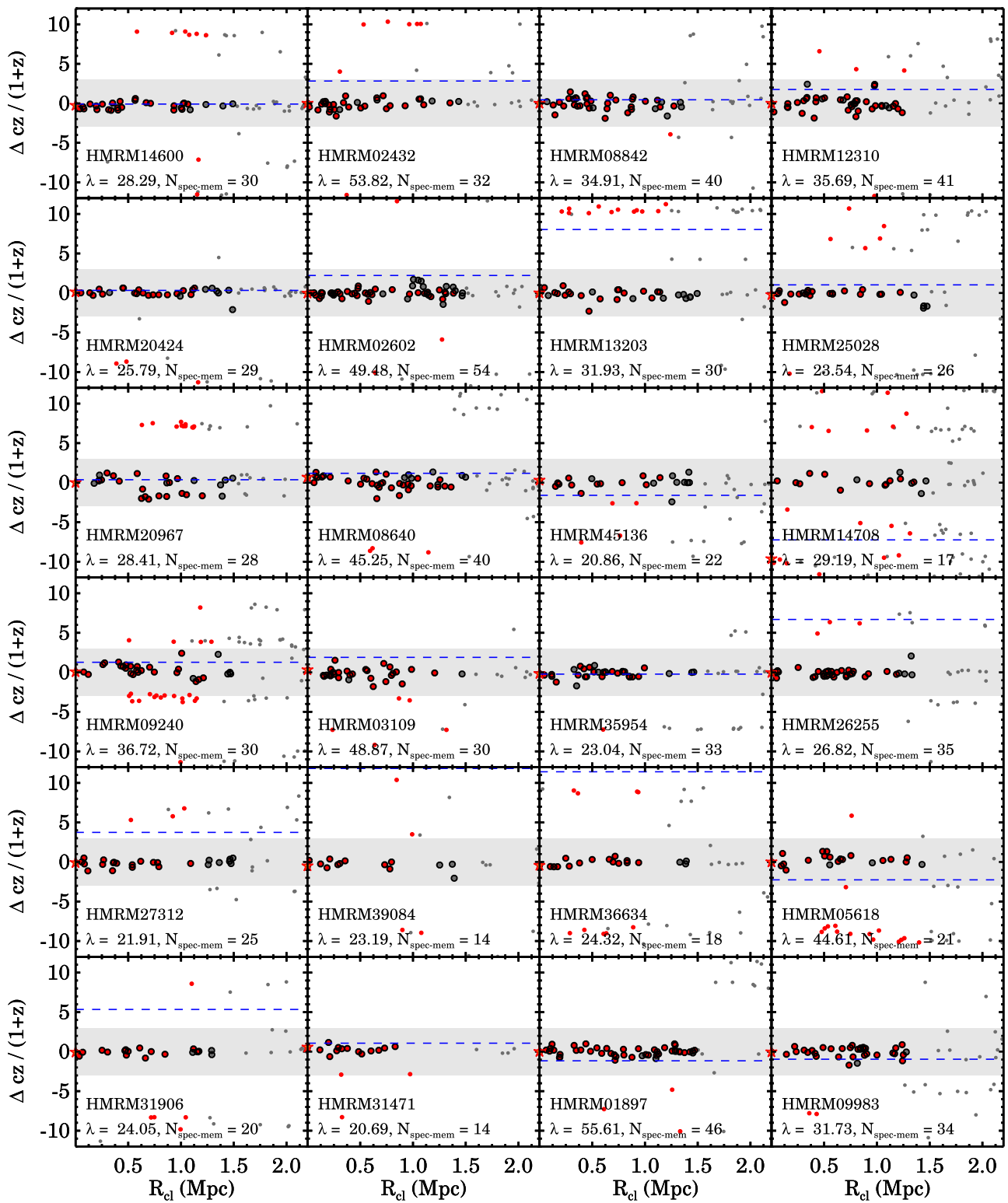


Figure 15. (Continued.)

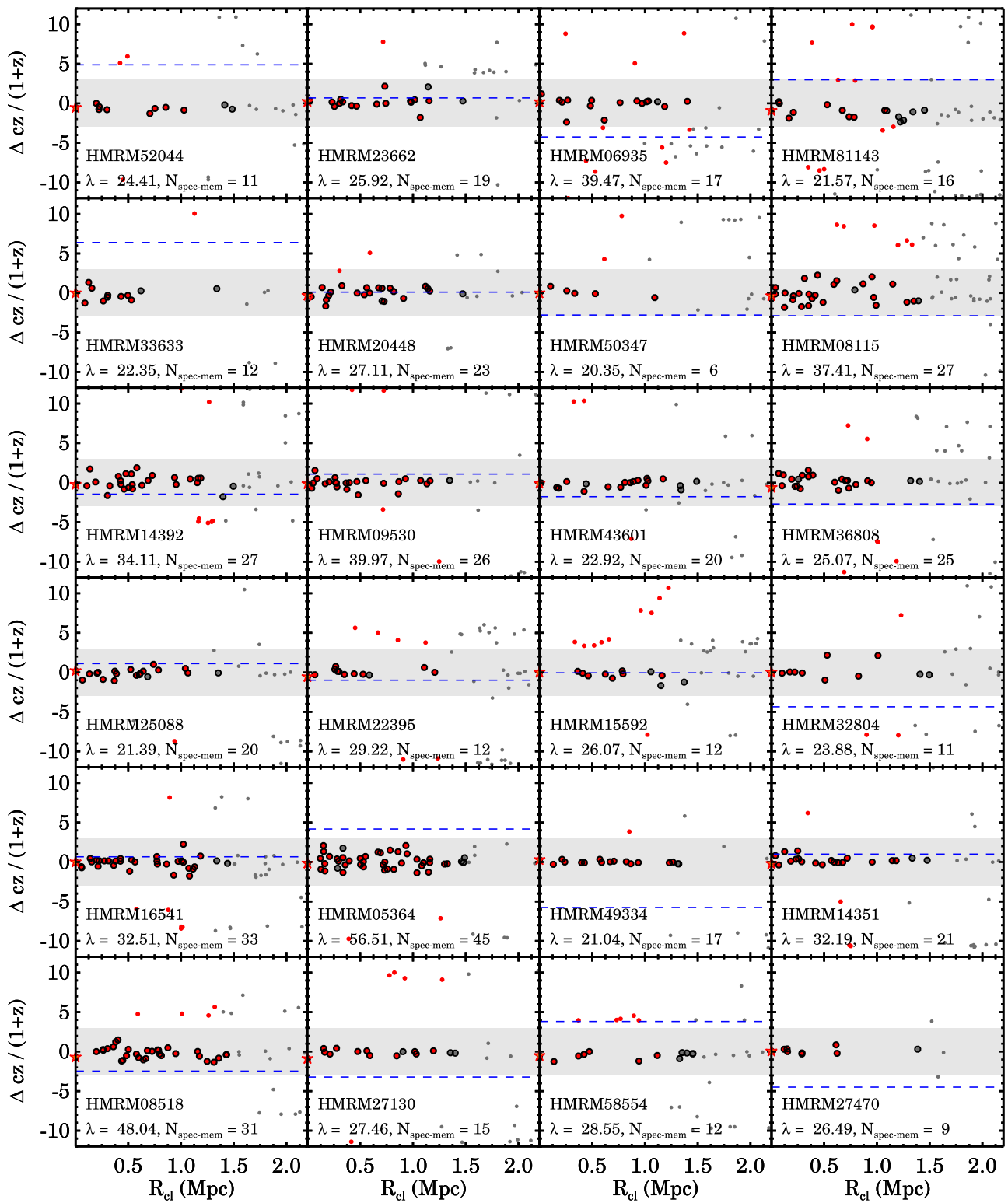


Figure 15. (Continued.)

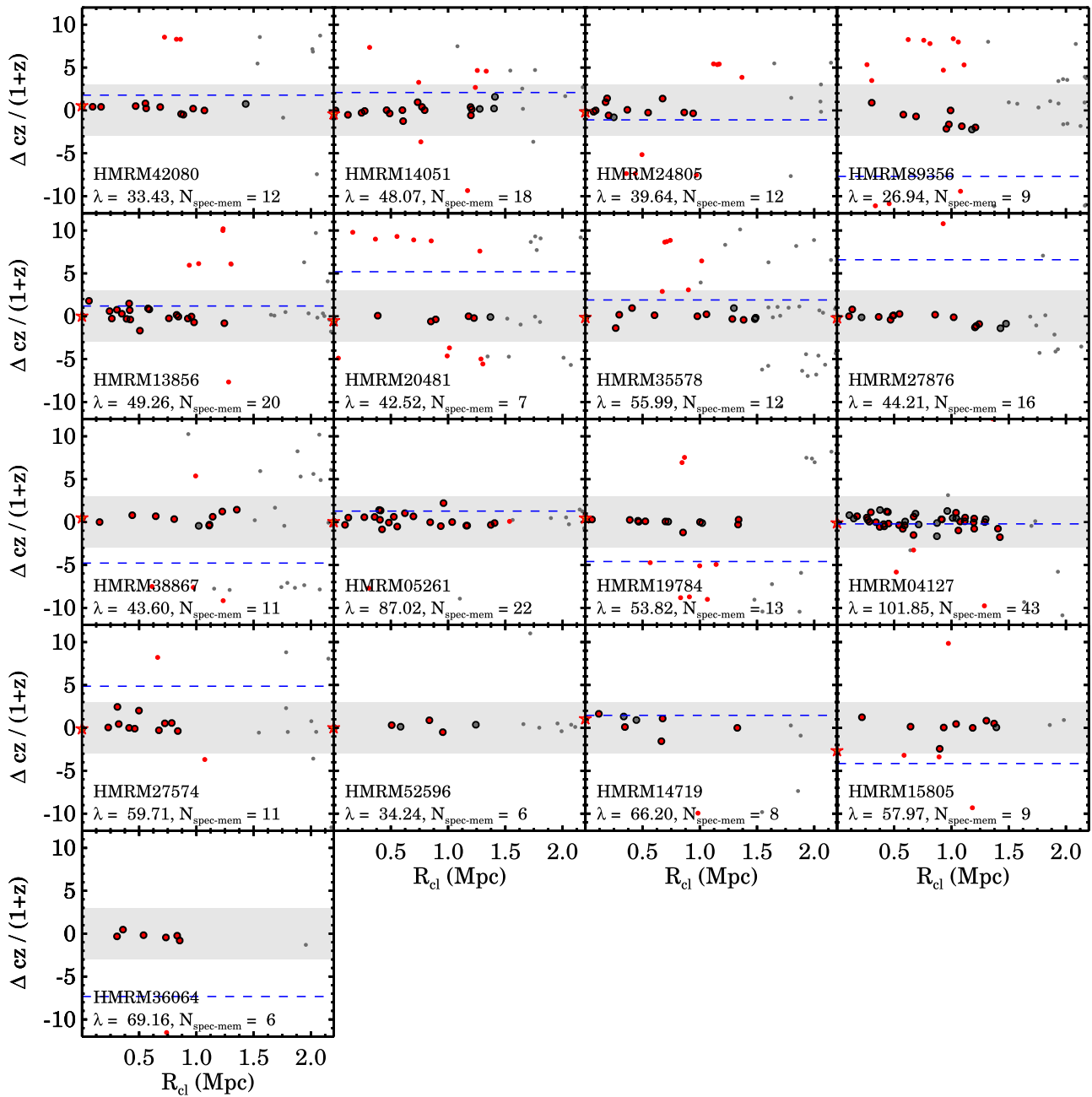


Figure 15. (Continued.)

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