

## HIGH CONFIDENCE OPTICAL CONFIRMATION OF HIGH SIGNAL-TO-NOISE *Planck* CLUSTER CANDIDATES

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### ABSTRACT

We report on newly identified galaxy clusters from the high signal-to-noise ( $> 5\sigma$ ) end of the second all-sky *Planck* Sunyaev-Zel'dovich (SZ) catalog (PSZ2). The clusters are identified in deep, optical imaging from the Kitt Peak National Observatory 4m Mayall telescope taken between 2014 and 2017. Here we focus on the highest richness systems, and identify galaxy clusters through a combination of the maxBCG algorithm and visual image inspection. Galaxy clusters are considered to be confirmed if they are both rich and spatially coincident ( $\lesssim 5'$ ) with the reported PSZ2 position. Of the 85 fields containing unconfirmed PSZ2 candidates observed, we find 15 (17.6% of the observed sample) corresponding galaxy clusters ( $0.13 < z < 0.74$ ), 12 of which are previously unrecognized as counterparts. We discuss three possible scenarios – clusters are mostly at low- or high- $z$ , or are obscured by the Milky Way – which could lead to the low identification fraction, and determine that no single scenario can account for the low purity of rich galaxy clusters among the high signal-to-noise PSZ2 unconfirmed candidates.

### 1. INTRODUCTION

Galaxy clusters, especially massive clusters, are extraordinary objects that contain vital clues to the structure and evolution of the universe. The generally accepted  $\Lambda$ CDM cosmological model makes detailed predictions about the number and total mass distribution of galaxy clusters throughout the universe. These galaxy clusters, particularly at high redshift, play a crucial role in constraining large scale structure formation and evolution from measurements of the overall matter density and the amplitude of matter fluctuations (e.g., Evrard 1989; Henry & Arnaud 1991; Borgani et al. 2001; White et al. 1993a,b; Eke et al. 1996; Donahue et al. 1998), the dark energy equation of state (e.g., Henry 2004; Mantz et al. 2008; Vikhlinin et al. 2009), and the potential falsification of  $\Lambda$ CDM from the existence of extreme clusters (e.g., Mortonson et al. 2010; Harrison & Coles 2012; Harrison & Hotchkiss 2013; Waizmann et al. 2013).

Large-area sky surveys, both currently underway and planned, are identifying many tens of thousands of galaxy clusters for both detailed examinations of our cosmological models and as probes of fundamental physics. Clusters have been identified in numerous ways: as overdensities of galaxies in optical surveys (e.g., Abell 1958; Postman et al. 1996), as extended X-ray sources (e.g., Gioia et al. 1990; Ebeling et al. 1998; Boehringer et al. 2000), as clusters of mass in gravitational-weak-lensing surveys (e.g., Wittman et al. 2006), and most recently as “shadows” or “holes” in the Cosmic Microwave Background (CMB). Today, large number of galaxy clusters

are being identified in ground based, millimeter wave surveys conducted by the Atacama Cosmology Telescope (ACT; Swetz et al. 2011) and the South Pole Telescope (SPT; Carlstrom et al. 2011), among others. These surveys have identified hundreds of massive galaxy clusters up to redshifts of  $z \sim 1.4$  (e.g., Vanderlinde et al. 2010; Menanteau et al. 2010a; Marriage et al. 2011; Hasselfield et al. 2013; Bleem et al. 2015; Hilton et al. 2018). This detection approach exploits the cluster’s hot intracluster medium which imprints a telltale signature on the Cosmic Microwave Background (CMB) through the Sunyaev-Zel’dovich effect (SZ; Sunyaev & Zeldovich 1972) effect.

Deep, wide field photometric surveys such as the ongoing Hyper Suprime-Cam Survey (Aihara et al. 2018) and Dark Energy Survey (DES; The Dark Energy Survey Collaboration 2005), as well as future surveys like the Large Synoptic Survey Telescope (LSST; LSST Dark Energy Science Collaboration 2012), *Euclid*, and WFIRST will discover many thousands of additional galaxy clusters at redshifts to  $z = 1$  (e.g., Dark Energy Survey Collaboration et al. 2016) and beyond. While a powerful discovery method, photometric surveys suffer from cosmological surface brightness dimming that reduces their sensitivity at high redshift (e.g., Calvi et al. 2014).

Using the SZ effect to discover clusters of galaxies has the distinct advantage that the surface brightness of the SZ effect does not dim with increasing redshift. This allows homogeneous samples of massive clusters to be detected out to arbitrary distances. Now, *Planck* (Tauber et al. 2010; Planck Collaboration et al. 2011) has released an all-sky SZ sample (hereafter PSZ; Planck Collaboration et al. 2014, 2015a) that contains 1943 detections with 1330 confirmed clusters and another 613 (as of PSZ catalogs versions 2.1 and 1) unconfirmed cluster candidates. Clusters were initially confirmed by cross correlating with previous catalogs (see Section 4; Planck Collaboration et al. 2014). More recently, dedicated follow up of still-unconfirmed clusters has begun in earnest (e.g., Liu et al. 2015; Planck Collaboration et al. 2015b, 2016;

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van der Burg et al. 2016; Burenin 2017; Barrena et al. 2018; Amodeo et al. 2018; Streblyanska et al. 2018).

In this paper we report on our efforts to classify unconfirmed PSZ cluster candidates. This paper is organized as follows: sections 2 through 4 describe the design, observations, data reduction and calibration, and creation of derived data products. In Section 5, we present the main results of our observations, and discuss those results in Section 6. In Section 7, we summarize the key results and conclude.

Unless otherwise noted, throughout this paper, we use a concordance cosmological model ( $\Omega_\Lambda = 0.7$ ,  $\Omega_m = 0.3$ , and  $H_0 = 70 \text{ km s}^{-1}\text{Mpc}^{-1}$ ), assume a Chabrier initial mass function (Chabrier 2003), use AB magnitudes (Oke 1974) and quote uncertainties at the  $1\sigma$  level.

## 2. DESIGN

Our observational design is motivated by the release of the second, all-sky PSZ catalog<sup>5</sup> (hereafter PSZ2; Planck Collaboration et al. 2015a) which contains 559 unconfirmed SZ detections with signal-to-noise ratio (SNR)  $> 4.5$ . We posit that the vast majority of these must lie at  $z > 0.4$  because the *Planck* confirmation process (Planck Collaboration et al. 2014) mostly relied on existing catalogs which have a preference for low- $z$  clusters. Furthermore, the confirmed sample of the PSZ2 catalog has only a small fraction (3%) of  $z > 0.6$  clusters compared to that expected ( $\sim 20\%$ ) based on the theoretical halo mass function (e.g., Jenkins et al. 2001; Tinker et al. 2008) for mass limit of  $6 \times 10^{14} \text{ M}_\odot$ . Of particular interest to us is the search for the most massive clusters at high redshift, such as ACT-CL J0102-4915 (hereafter “El Gordo”), which weighs in at  $\sim 2 \times 10^{15} \text{ M}_\odot$  at a redshift of  $z = 0.870$  (Menanteau et al. 2012). The Tinker halo mass function suggests as many as four clusters as massive as this at  $z > 0.6$  in the full sky area covered by the *Planck* PSZ catalog (83.7% of the sky). If other clusters as massive as “El Gordo” exist, they are hiding as high-significance candidates within the objects in this *all-sky* catalog. In Section 6 we examine this argument more carefully.

The core of our observational design relies on the use of optical imaging to confirm the SZ detections as real clusters and provide photometric redshifts using the multi-color information. This design is based on the previous success with the ACT cluster confirmation process using 4-m class telescopes. Although *Planck*s larger beam size (compared to both ACT and SPT) makes it more sensitive to clusters at lower redshifts (due to their larger projected area on the sky), among the confirmed clusters in the recently released all-sky *Planck* SZ catalog are the two highest significance high-redshift SZ detections from ACT (as well as several other ACT and SPT clusters).

Our strategy for this project is to use the Kitt Peak National Observatory (KPNO) Mayall-4m telescope as the first and fundamental step to confirm the highest significance detections in the PSZ2 catalog that are visible across the entire northern sky. Optical imaging should be sufficient to confirm nearly all of the candidates. However, for the highest redshift candidates, near-IR imaging

will be necessary. Those candidates with some evidence for a high- $z$  brightest cluster galaxy (BCG) should be targeted with near-IR observations to confirm the presence of the BCG and to establish a red sequence of cluster members.

Following closely the procedure used for ACT follow-up (e.g., Menanteau et al. 2013), targets are prioritized by SZ SNR. We choose to initially report on targets with PSZ2 SNR  $> 5$  as the statistical reliability of PSZ2 cluster candidates should be quite high: according to the *Planck* team  $\sim 90\%$  of candidates at SNR  $> 5$  are expected to be “real” clusters (see Figure 11; Planck Collaboration et al. 2015a).

### 2.1. Observations

All observations were conducted with the KPNO Mayall telescope. The optical observations were made with the MOSAIC camera mounted at the prime focus. Two detector packages were used for the observations. The earlier MOSAIC1.1 instrument consisted of eight  $2048 \times 4096$  SITe CCDs, arranged  $2 \times 4$ , separated by a gap  $\sim 50$  pixels wide with a pixel scale of  $0''.26 \text{ pixel}^{-1}$ . MOSAIC1.1 was replaced with MOSAIC3, in mid-2015, and consists of four new  $4k \times 4k$ , 15 micron pixel, 500-micron thick LBNL deep-depletion CCDs. Because the only change from MOSAIC1.1 to MOSAIC3 are the CCDs and controllers, both versions have a  $36' \times 36'$  field-of-view.

The optical observing strategy consists of targeted *griz* observations of individual candidates with total exposure times of 360 s, 360 s, 1100 s and 1100 s (assuming dark conditions). The final exposures consist of four dithered positions with individual exposures of 90 s for the *gr*-bands or 275 s for the *iz*-bands. These exposure times are designed to ensure the unambiguous detection of the faint galaxies in the red cluster sequence up to  $z \sim 1.0$  and of brightest cluster galaxies (BCGs) to higher redshifts. The choice of filters in our program is driven by the need to segregate early-type galaxies in the cluster through their colors (or photometric redshifts) by sampling blue-ward and red-ward of the 4000Å break over a broad range of redshifts.

## 3. DATA REDUCTION AND CALIBRATION

Standard image reductions including subtraction of dark frames, flat fielding, sky-subtraction, and bad pixel masking were performed by the National Optical Astronomy Observatory virtual observatory (VO) using the MOSAIC (Valdes & Swaters 2007) science pipelines. The resultant FITS files consist of fully reduced images with either all single exposure CCDs mosaicked into a single image extension (as in the case of Mosaic1.1) or as a multi-extension FITS file with each single exposure CCD occupying a separate extension.

We then mosaic each separate exposure into a master mosaic as described in the following section.

### 3.1. Mosaicking

Combined mosaics are created with SWARP (version 2.38.0; Bertin et al. 2002). We create three distinct types of mosaics. The individual dither frames are stacked and then median combined to produce the final completed science mosaic. A “detection” is created by combining

<sup>5</sup> [http://szcluster-db.ias.u-psud.fr/sitools/client-user/SZCLUSTER\\_DATABASE/project-index.html](http://szcluster-db.ias.u-psud.fr/sitools/client-user/SZCLUSTER_DATABASE/project-index.html)

select science mosaics into a “chi2” image using a combination of the *i*- and *z*-band, when both are available and of sufficient quality, or the *i*-band when only one is present. Finally, we create a set of mosaics to produce the three color image used for cluster finding. We median combine the *griz* science mosaics into a “blue” (*g*-band), “green” (*r*-band), and “red” (*iz*-band) mosaic. All final mosaics have a pixel scale of  $0.^{\prime\prime}25$  pixel $^{-1}$ . The final exposure time is calculated as the median exposure time of the combined images, and similarly the final air mass is median of the individual air masses.

### 3.2. Source Extraction and Photometry

For source extraction and photometry estimation we use Source Extractor<sup>6</sup> (hereafter SExtractor; version 2.19.5; Bertin & Arnouts 1996) run in dual image mode with the “chi2” detection image as the detection image. See Section 3.1.

### 3.3. Astrometric Calibration

Each of the final science mosaics produced in the previous section is first astrometrically aligned with *Gaia* (Brown et al. 2016) Data Release 1 (Prusti et al. 2016) using SCAMP (Bertin 2006) as a part of PHOTOMETRYPipeline<sup>7</sup> (PP; Mommert 2017).

Sources are extracted from the mosaics with a SNR of at least ten and with a minimum area of at least 12 pixels. The extracted sources are then matched to the *Gaia* data and a new astrometric solution is calculated. Matching all science images to the *Gaia* world coordinate system ensures that we have a common alignment across all observing runs. Because the initial astrometric solution from the VO is quite accurate, the resultant corrections are much less than  $1.^{\prime\prime}$ .

### 3.4. Photometric Calibration

After the mosaics have been astrometrically aligned, we use PP to produce a photometric solution. PP calculates a photometric zero-point in each of our observed bands by comparing field stars located throughout the science mosaic to known photometry from large-area sky surveys. Because our sources are spread across the entire northern sky, and because we prefer to minimize the number of differences between photometric solutions we are limited to two optical surveys. We first seek photometric data from the *Sloan Digital Sky Survey* (SDSS; York et al. 2000) Data Release 13 (DR13; Albareti et al. 2017). When our target does not lie within the SDSS footprint we utilize the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS; Chambers et al. 2016) Data Release 1 (hereafter PS1; Flewelling et al. 2016). Both surveys provide accurate *griz* magnitudes and large on-line queriable databases for rapid automated calibration.

Sources are extracted from the combined mosaics with a  $3.^{\prime\prime}$  (12 pixel) diameter aperture; stars with a SNR  $\geq 10$  are matched to a survey catalog and a photometric zero-point is determined. We use at least 50% of the available stars (with accurate catalog photometry) to derive the zero-point resulting in zero-points calculated from

approximately 10–500 stars and with typical uncertainties of 0.05 mag for the *gri*-bands and 0.16 mag for the *z*-band.

## 4. ANALYSIS

### 4.1. Photometric Redshifts

We determine photometric redshifts (photo- $z$ ) from the four-band optical imaging catalogs using the Bayesian Photometric Redshifts (BPZ; Benítez 2000; Coe et al. 2006) code following the same procedure as in Menanteau et al. (2009).

We assess the effectiveness of our photo- $z$  estimates by comparing with the available spectroscopic redshifts (spec- $z$ ) from the SDSS. We use three diagnostics to gauge photo- $z$  accuracy. First, we report the full scatter between the photo- $z$  and spec- $z$ , defined as:

$$\sigma_f = \text{RMS}[\delta z / (1 + z_{\text{spec}})] \quad (1)$$

where  $\delta z = z_{\text{spec}} - z_{\text{phot}}$ . Second, we report the normalized median absolute deviation (NMAD; Ilbert et al. 2009; Dahmen et al. 2013; Molino et al. 2017), given as

$$\sigma_{\text{NMAD}} = 1.48 \times \text{median}\left(\frac{|\delta z|}{1 + z_{\text{spec}}}\right). \quad (2)$$

which provides an estimate of the scatter resistant to catastrophic outliers. Finally, the catastrophic outlier fraction (OLF) where we define a catastrophic outlier (following Molino et al. 2017) as,

$$\eta = \frac{|\delta z|}{(1 + z_{\text{spec}})} > 5 \times \sigma_{\text{NMAD}}. \quad (3)$$

Figure 1 shows the photo- $z$  performance as a function of the true spectroscopic redshift. Because we are primarily concerned with identifying clusters containing early-type galaxies, we show only galaxies classified E/S0 by BPZ. We find  $\sigma_f = 0.067$ ,  $\sigma_{\text{NMAD}} = 0.048$ , and an outlier fraction,  $\eta = 0.9\%$ .

### 4.2. Cluster Finding

In this section, we briefly describe the algorithms and methods use to select the galaxy clusters from the multi-wavelength optical imaging. We follow the methods described in detail in Menanteau et al. (2009, 2010a) and direct the reader there for an in depth description and discussion of the methods. In short, we adopt a hybrid approach where we first manually identify (by eye) potential cluster BCGs and then use the maxBCG algorithm (Koester et al. 2007) to identify cluster members.

We first create a three-color image using STIFF (version 2.4.0; Bertin & Emmanuel 2011). The red, green, and blue channels are given by the corresponding combined mosaics described in Section 3.1. We then visually inspect an area of roughly  $10' \times 10'$  centered on the position of each unconfirmed PSZ detection. Potential BCGs are selected manually, and are identified by their characteristic colors and accompanying member galaxies.

Once a potential BCG is selected, the maxBCG algorithm selects nearby galaxies, within  $|z_{\text{BCG}} - z| < 0.05$  and 0.5 Mpc projected radius, which BPZ has classified as either E or E/S0 galaxies. These photo- $z$ ’s of the galaxies are combined using a 3- $\sigma$  median sigma-clipping algorithm to estimate the cluster’s mean redshift,  $z_{\text{cl}}$ .

<sup>6</sup> <https://github.com/astromatic/sextarator>

<sup>7</sup> <https://github.com/mommert/photometrystipline>

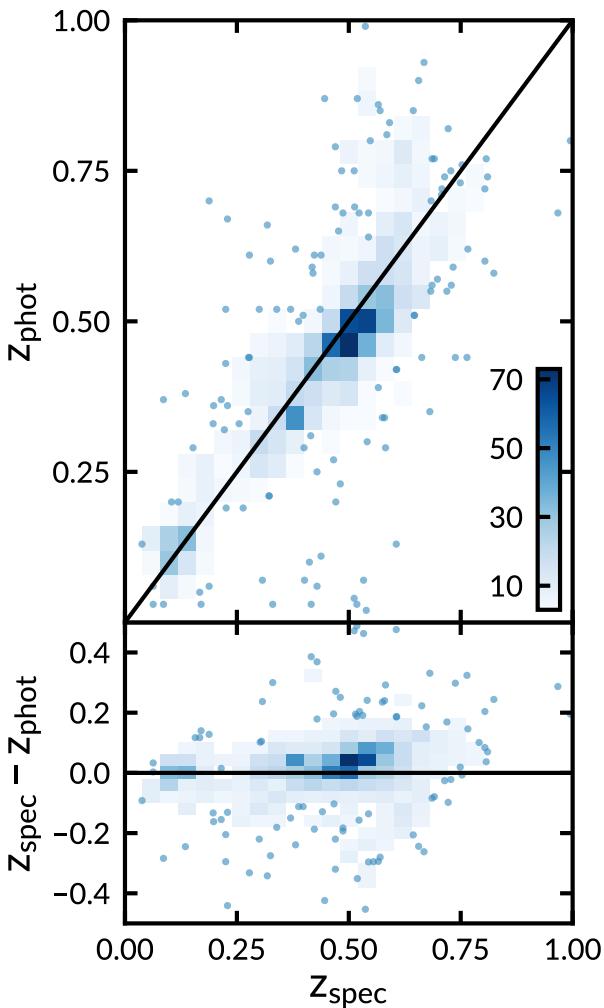


FIG. 1.— Comparison between photometric and spectroscopic redshifts for 1588 elliptical galaxies with spectroscopic redshifts from the SDSS. *Top:* The photometric redshifts are those reported by BPZ with a custom empirical prior on galaxy brightness for the photometric redshifts. *Bottom:* The difference between the spectroscopic and photometric redshifts,  $z_{\text{spec}} - z_{\text{phot}}$ , as a function of spectroscopic redshift. In both panels the shading scales (darker is greater) with the density of points where bins with fewer than three points are shown as single points. The solid black line shows the 1:1 relation.

The potential member galaxies are iterated over until the number of cluster members converges. We use this cluster redshift measurement and the member selection criteria given previously to estimate the number of cluster members within 1 Mpc which we define as the richness (e.g., Abel 1958) of the cluster,  $\text{Ngal}$ .

We correct the  $\text{Ngal}$  estimate by subtracting a statistical background of galaxies. We first estimate the number of background ellipticals by selecting galaxies within an annulus ( $4 \text{ Mpc} < r < 9 \text{ Mpc}$ ) around each cluster's position. We include galaxies with  $\delta z = 0.05$  and similar colors as those galaxies assumed to belong to the cluster. The number of background galaxies is scaled by the ratio of areas ( $1/\sqrt{65} = 1.54 \times 10^{-2}$ ) and then subtracted from the number of cluster members to provide a corrected  $\text{Ngal}$ ,  $\text{Ngal}_c$ , which we then use to compute other important quantities. In practice the corrected number

of galaxies is between 15% and 20% lower than the uncorrected number (Menanteau et al. 2010a). We report  $\text{Ngal}_c$  for the remainder of this work.

#### 4.3. Recovery of the Brightest Cluster Galaxies

We have designed our observations to detect BCGs to  $z \sim 1.5$ . To quantify the actual depths of our images, we perform two distinct tests. First, we perform a Monte Carlo simulation by injecting artificial, elliptical galaxies into the science imaging and computing their recovery fractions. Second, we fit a power-law model to the bright side of each field's differential number count curve and identify the magnitude,  $m$ , at which the observed differential,  $dN/dm$ , falls below the extrapolated power-law fit by a specified amount.

The Monte Carlo simulation broadly follows the procedure given in Menanteau et al. (2010b). We create the artificial elliptical galaxies with the MODELING package, part of ASTROPY (The Astropy Collaboration et al. 2013). The synthetic galaxies are created to have de Vaucouleurs (de Vaucouleurs 1948) profiles and surface brightnesses corresponding to their magnitude and assumed sizes. We inject the artificial galaxies into our science images with similar noise characteristics as their real counterparts.

We generate ten rounds each spreading one hundred elliptical galaxies randomly across our science imaging. Galaxies are placed at different random positions, from round to round, to suppress abnormally boosted recovery fractions due to source confusion. The artificial galaxies have total fluxes corresponding to apparent magnitudes between 20 mag  $< i <$  25 mag with 0.2 mag spacing. We report the 80%  $i$ -band limit for each field, which is the magnitude where 80% of the simulated galaxies are recovered.

The second method to estimate the limiting magnitudes of our observations uses the calibrated SExtractor catalogs (see Section 3.2). We bin the objects identified by SExtractor as galaxies in 0.5 mag wide bins from  $15 < i < 30$ . We identify the peak of the differential number counts function ( $dN/dm$  vs.  $m$ ) in log space and fit a power-law model to the five magnitude bins on the bright side of the peak. The 80% completeness limit is defined as the magnitude bin at which the observed counts are 80% of the value from the extrapolated power-law.

The completeness limits reported by each method are consistent and provide an important check on one another as they are wholly independent estimates of the limiting  $i$ -band magnitude in each of our fields. We choose to focus on the limiting magnitudes reported by the number counts based method as it is less prone to errors from very bright stars or diffuse emission from the Milky Way also present in some fields.

With a limiting magnitude reported for each field, we are able to estimate the redshift to which we could reliably identify massive galaxy clusters. We compare the completeness limits of our observations to the expected (i.e., known) apparent magnitudes of galaxies in clusters as a function of redshift. We define the expected apparent  $i$ -band magnitude of a galaxy following the population of red galaxies defined by Blanton et al. (2003). The  $0.4L_*$ ,  $L_*$ , and  $4L_*$  galaxies (representing faint members to bright BCGs) are composed of stars formed in a burst at  $z = 5$ , with solar metallicity (Bruzual & Char-

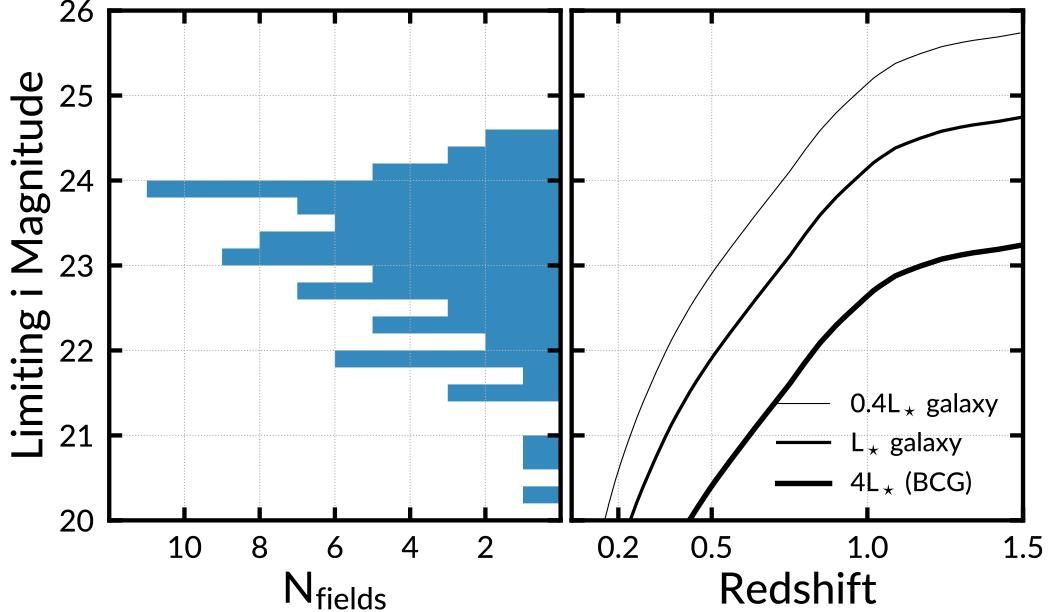


FIG. 2.— *Left:* Histogram of the  $i$ -band magnitude corresponding to 80% completeness in galaxy recovery. When 80% completeness is not achieved we show the limiting magnitude with the highest completeness. *Right:* Observed  $i$ -band magnitudes of  $L^*$ ,  $0.4L^*$ , and  $4L^*$  (BCG) early-type galaxies as a function of redshift. We define an  $L^*$  galaxy following Blanton et al. (2003) as a population of red galaxies at  $z = 0.1$  and allow it to evolve passively. The left and right panels can be combined to estimate the limiting redshift to which we could identify galaxy clusters.

lot 2003), and allowed to evolve passively,  $\tau = 1.0$  Gyr. We show the expected  $i$ -band apparent magnitude as a function of redshift for each galaxy in the right panel of Figure 2.

## 5. RESULTS

Here, we report the high confidence clusters identified as a result of our cluster finding. A high confidence result consists of a clear BCG and many accompanying satellite galaxies (high richness). For the 85 fields observed, we identify 15 high confidence clusters (see Figures 3–6) and discuss each in detail below.

In the following subsections, we compare our results with previously known sources by querying the NASA/IPAC Extragalactic Database (NED)<sup>8</sup> and the SIMBAD (Set of Identifications, Measurements, and Bibliography for Astronomical Data) astronomical database<sup>9</sup> (Wenger et al. 2000). We include sources from the NRAO (National Radio Astronomy Observatory) VLA (Very Large Array) Sky Survey (NVSS; Condon et al. 1998), the Röntgensatellit (ROSAT) All-Sky Survey Bright Source Catalog (RASS-BSC; Voges et al. 1999), the ROSAT All-Sky Faint Source Catalog (RASS-FSC; Voges et al. 2000), and the SDSS. We make note of confident associations of X-ray and radio sources with the BCG or other clusters members within 5' of the reported BCG pointing (within 10' for the three low redshift clusters).

### 5.1. PSZ2 G029.66-47.63

This is a rich cluster at  $z_{\text{cl}} = 0.34 \pm 0.03$  with 130 members, approximately 5' to the northwest of the *Planck* position. The X-ray source 1RXS J214531.1–214339 is coincident with the BCG. Our data show another, slightly less rich, system (with  $z_{\text{cl}} = 0.33 \pm 0.04$  and 76 members) within 0.5' of the *Planck* position. Both systems likely contribute to the *Planck* SZ signal. This is the richest cluster in our sample.

### 5.2. PSZ2 G043.44-41.27

This is the second richest cluster we have found; the system is at  $z_{\text{cl}} = 0.41 \pm 0.03$  with 116 members. There are two plausible BCGs with nearly the same photo- $z$ ; the one we select is slightly brighter in the  $i$ -band, yields a slightly higher number of cluster members, and is positionally coincident with the X-ray source 1RXS J213644.4–101904. The other bright galaxy is at  $\alpha=21:36:38.6$ ,  $\delta=-10:18:35.7$ , some 1.3' to the west. This galaxy is associated with a bright radio source (NVSS J213638–101836) with a flux density of  $107.8 \pm 3.3$  mJy at 1.4 GHz that has been classified as a symmetric double (Douglas et al. 1996).

### 5.3. PSZ2 G084.62–15.86

This cluster was previously confirmed by the *Planck* team, where they quote a spectroscopic cluster redshift (from two members) of  $z_{\text{spec}} = 0.364$  (Planck Collaboration et al. 2016). This system has at least three bright member galaxies within 2' of the *Planck* position that are plausible BCG candidates. Among these we chose the brightest one in the  $i$ -band (which is about an arcminute south of the *Planck* team's chosen BCG) and recovered the cluster at  $z_{\text{photo}} = 0.27 \pm 0.10$  with 18 members. The *Planck* team's selected BCG is associated with a radio

<sup>8</sup> <https://ned.ipac.caltech.edu/>

<sup>9</sup> <http://simbad.u-strasbg.fr/simbad/>

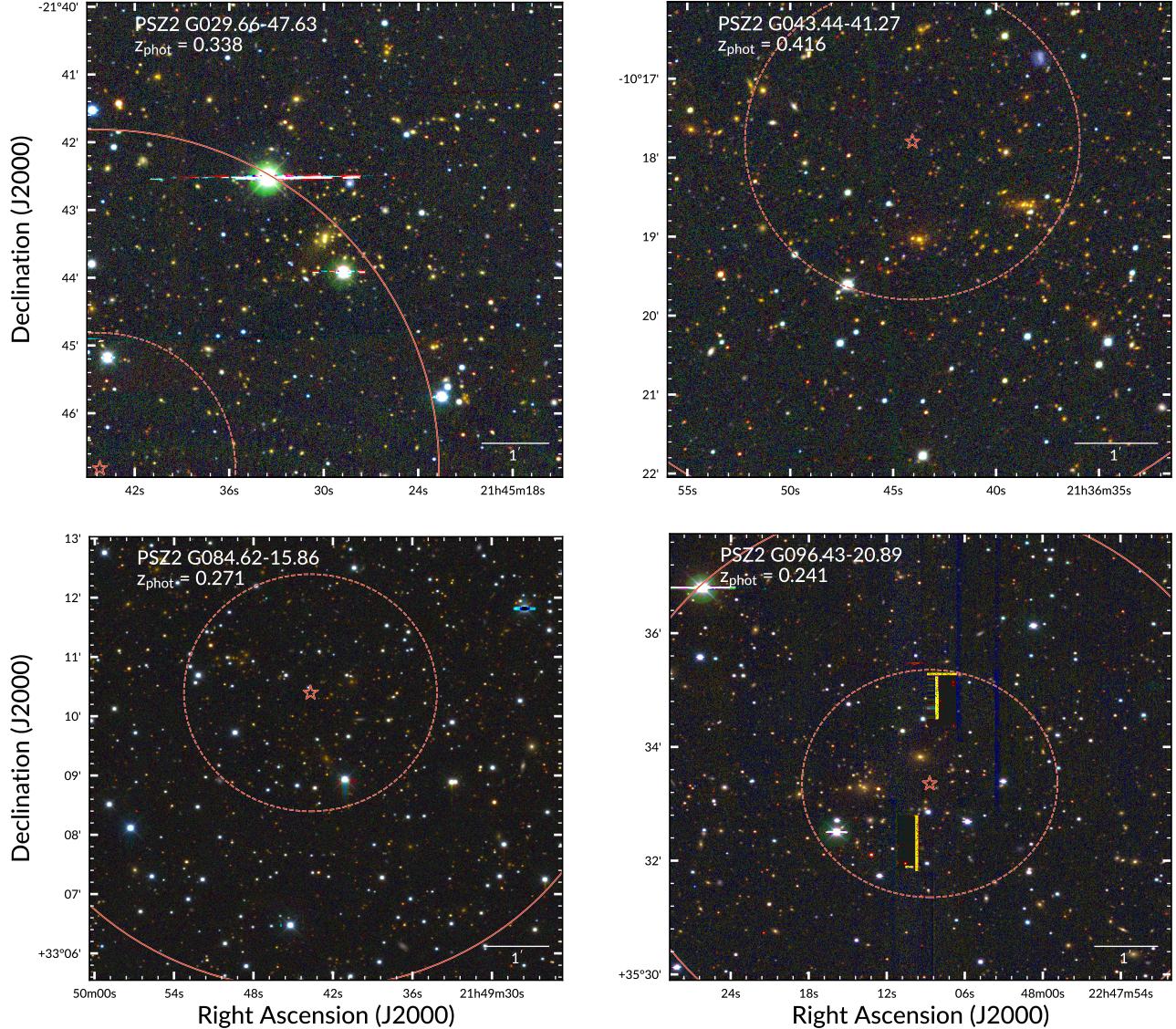


FIG. 3.— RGB (*irg*) color images for four PSZ clusters optically confirmed using our optical imaging. Each panel is centered on the cluster’s BCG and has a width of 1 Mpc at the corresponding cluster’s redshift. The horizontal bar in the lower right of each panel shows the scale of the panel, where north is up and east is to the left. The location of the PSZ detection is denoted by a red star. The dashed and solid, concentric, red circles are 2' and 5' in radius respectively.

source (NVSS J214940+331031) with a flux density of  $19.7 \pm 0.8$  mJy at 1.4 GHz.

#### 5.4. PSZ2 G096.43-20.89

The BCG of this cluster is only 0.5' from the *Planck* position. The cluster’s redshift is  $z_{\text{cl}} = 0.24 \pm 0.04$  with 54 members. An X-ray source (1RXS J224806.6+353230) is 1.44' away from the BCG position. This cluster appears to extend more toward the southwest quadrant in the direction of a catalogued Zwicky cluster (ZwCl 2245.6+3516; Zwicky & Kowal 1968).

#### 5.5. PSZ2 G098.38+77.22

This is the highest redshift cluster in the sample at  $z_{\text{cl}} = 0.78 \pm 0.05$  with 58 members; it is 5.8' away from the *Planck* position. About 2' east of our chosen BCG there is a luminous ( $i \sim 20$  mag), red galaxy (SDSS

J131814.99+383055.8) with a spectroscopic redshift of  $z = 0.726$ . This galaxy has similar colors to the cluster BCG and may be part of the system.

#### 5.6. PSZ2 G106.11+24.11

PSZ2 G106.11+24.11 is a low redshift system at  $z_{\text{cl}} = 0.14 \pm 0.06$ . The BCG is a large galaxy close to the *Planck* position. There are 27 members after correcting for background galaxies. This object was identified as an X-ray cluster (RXC J1921.3+7433) based on its extent in the RASS (Bohringer et al. 2000), although these authors did not publish a redshift. Using their flux value and our photometric redshift, we estimate the cluster’s X-ray luminosity in the 0.1–2.4 keV band to be  $L_X \sim 2.6 \times 10^{44}$  erg s $^{-1}$ . This luminosity value is broadly consistent with those of other confirmed *Planck* clusters at this redshift range (Planck Collaboration et al. 2015b).

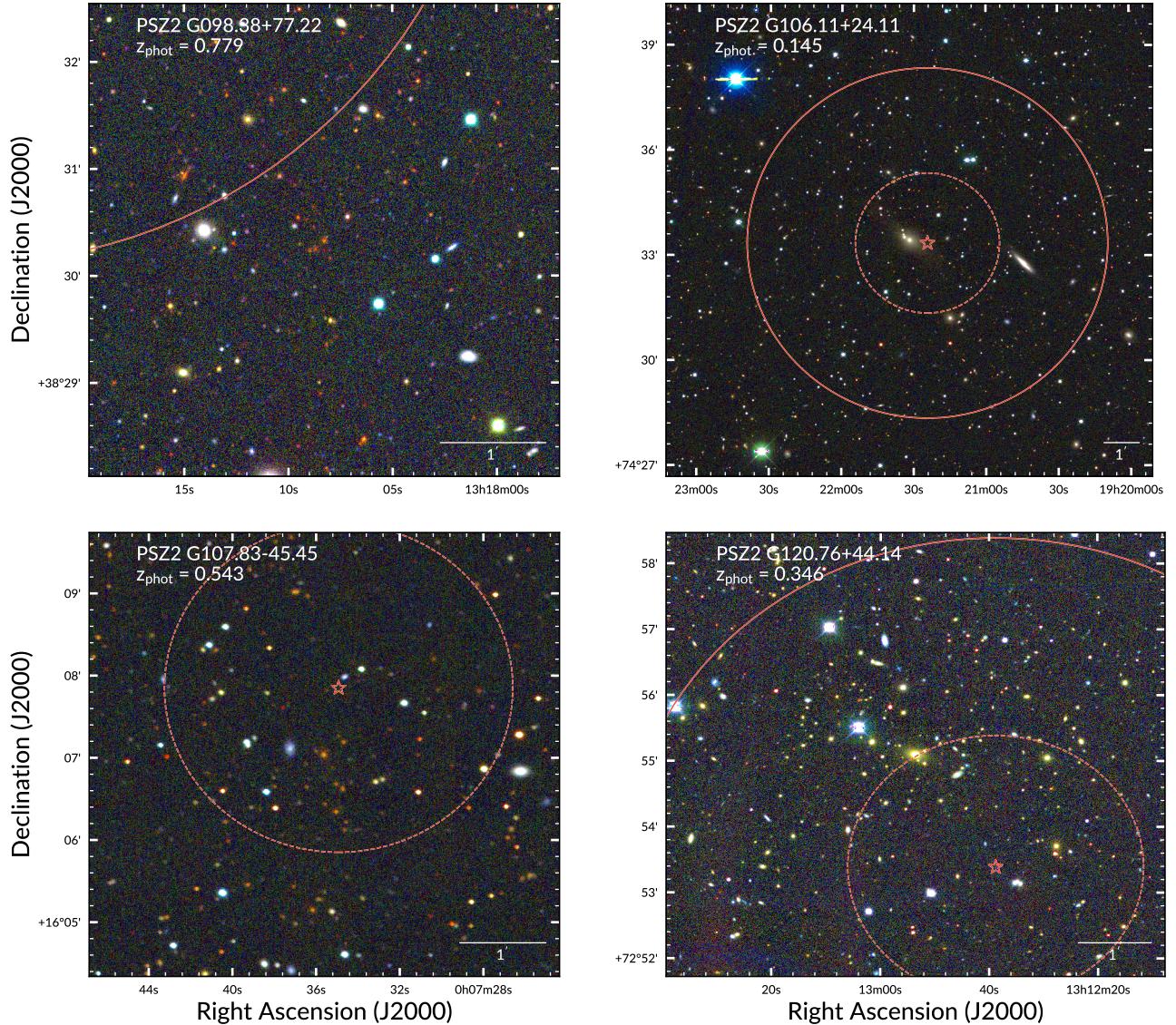


FIG. 4.— Same as Figure 3.

### 5.7. PSZ2 G107.83-45.45

This cluster at  $z_{\text{cl}} = 0.54 \pm 0.05$  has 30 members. The BCG (SDSS J000735.62+160701.8) as well as another member (SDSS J000736.15+160508.9) have spectroscopic redshifts from the SDSS of  $z = 0.5673$  and  $z = 0.5667$ , respectively. There are 4 other galaxies with SDSS spectroscopic redshifts (0.5649, 0.5661, 0.5655, and 0.5625) within  $7'$  (2.7 Mpc) of the BCG.

### 5.8. PSZ2 G120.76+44.14

The BCG we select yields an estimated redshift for the cluster of  $z_{\text{cl}} = 0.35 \pm 0.03$  with 92 members; this galaxy has a published spectroscopic redshift of  $z = 0.2959$  (Huchra et al. 1990). We associate the cluster with Abell 1705 and the RASS X-ray source 1RXS J131252.0+725514.

Approximately  $2.6'$  south of the PSZ2 position, there is a luminous red galaxy with a gravitationally lensed arc that is the BCG of a rich system catalogued as WL 1312.5+7252 with a photometric redshift of 0.55 (Dahle

et al. 2003). This galaxy is also a radio source (NVSS J131230+725051) with a flux density of  $3.5 \pm 0.5$  mJy (1.4 GHz). Our analysis also yields a rich cluster with this BCG ( $\alpha=13:12:30.9$ ,  $\delta=+72:50:54.2$ ) with  $N_{\text{gal}} = 89$  at  $z = 0.59 \pm 0.05$ . Given the similar optical richnesses of these two systems it is likely that both contribute to the *Planck* SZ signal.

### 5.9. PSZ2 G125.55+32.72

There are two plausible BCGs in this cluster; the one we select yields a redshift of  $z_{\text{cl}} = 0.21 \pm 0.06$  and 32 members. The other BCG ( $\alpha=11:25:46.8$ ,  $\delta=+83:55:04.4$ ) is about 0.14 mag fainter in the *i*-band and, using it for cluster finding, results on a cluster at  $z_{\text{cl}} = 0.20 \pm 0.03$  with 31 members. These two plausible BCGs are separated by  $\sim 4'$ . Both BCGs are radio sources: the northern galaxy (corresponding to our selected BCG) is catalogued as NVSS J112535+835858 with a 1.4 GHz flux density of  $10.2 \pm 0.9$  mJy; the southern one corresponds to NVSS J112550+835508 with a flux density at

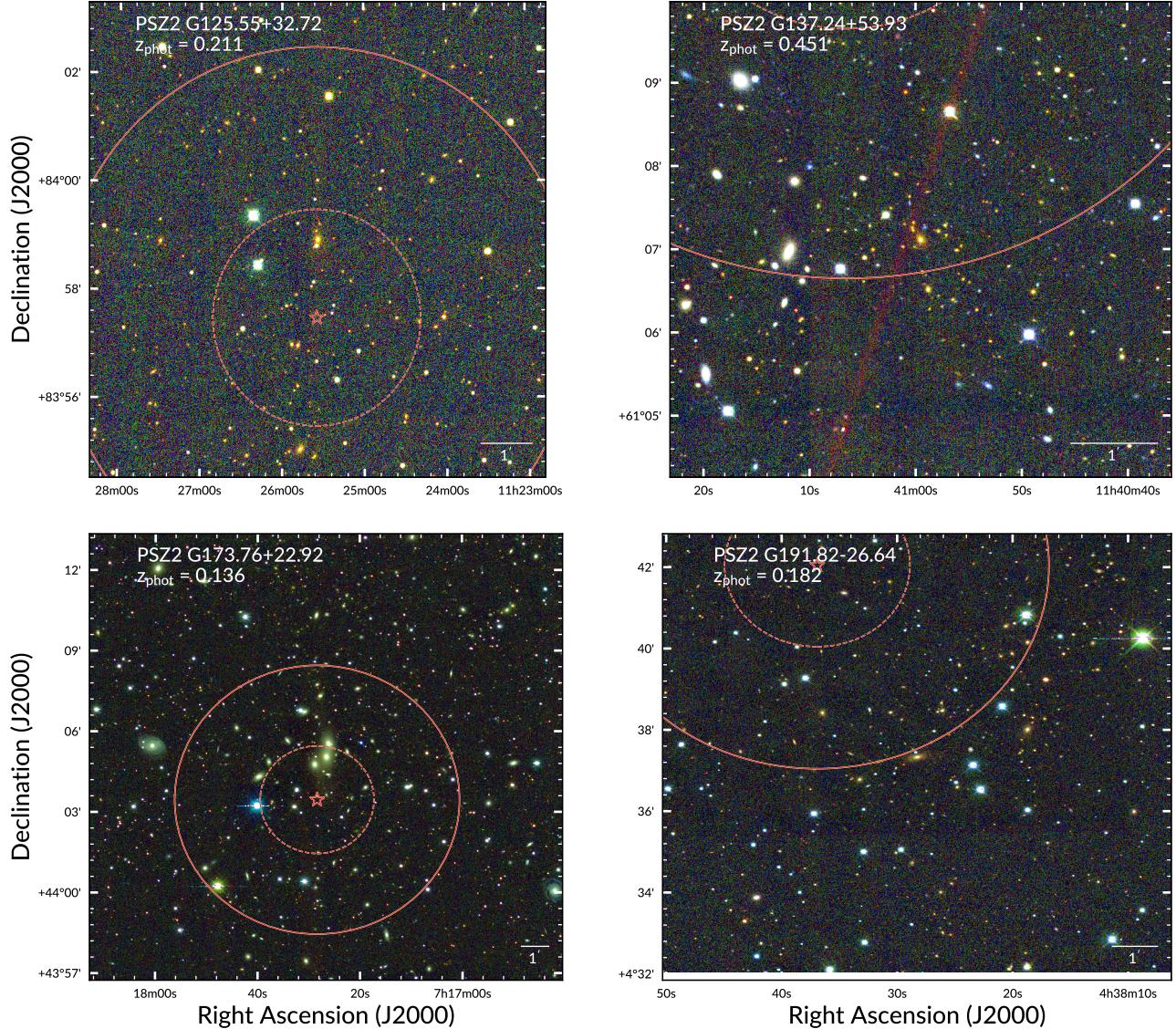


FIG. 5.— Same as Figure 3.

the same frequency of  $3.6 \pm 0.6$  mJy. The southern galaxy is about  $1'$  away from the RASS X-ray source 1RXS J112547.3+835559. Both systems should contribute to the *Planck* SZ signal and the quoted richness in Table 1 is almost surely an underestimate of the richness of the combined system.

#### 5.10. PSZ2 G137.24+53.93

Here we find a cluster at  $z_{\text{cl}} = 0.45 \pm 0.06$  with 40 members. The BCG is a radio source (NVSS J114059+610658) with a flux density of  $10.2 \pm 0.9$  mJy (1.4 GHz) and has a spectroscopic redshift from the SDSS of  $z = 0.4770$ . Another cluster member also has a concordant SDSS spectroscopic redshift of  $z = 0.4697$ . The cluster has been cataloged as WHL J114058.8+610631 with a similar photometric redshift.

#### 5.11. PSZ2 G173.76+22.92

This low redshift system, which we find at  $z_{\text{cl}} = 0.14 \pm 0.04$ , has a very interesting BCG. It is catalogued in

NED as B3 0713+441 and has a spectroscopic redshift of  $z = 0.0652$  (Bauer et al. 2000). It is associated with the RASS X-ray source 1RXS J071726.9+440557 as well as a bright radio source (NVSS J071726+440504) with a flux density of  $220.4 \pm 7.6$  mJy (at 1.4 GHz). Higher resolution images from Faint Images of the Radio Sky at Twenty-centimeters (FIRST; Becker et al. 1995) reveal that this radio source is double lobed. Some  $6'$  to the east is a catalogued Seyfert 1 galaxy (2MASX J07180060+4405271) with a spectroscopic redshift of  $z = 0.0614$  (Michel & Huchra 1988) and a 1.4 GHz radio flux of  $50.8 \pm 1.6$  mJy (NVSS J071800+440527).

#### 5.12. PSZ2 G191.82-26.64

This is another low redshift cluster at  $z_{\text{cl}} = 0.18 \pm 0.06$  with 24 members. Two cluster members are associated with radio sources: NVSS J043836+043824 and NVSS J043818+043802 with 1.4 GHz flux densities of  $24.8 \pm 1.2$  mJy and  $22.7 \pm 1.5$  mJy, respectively.

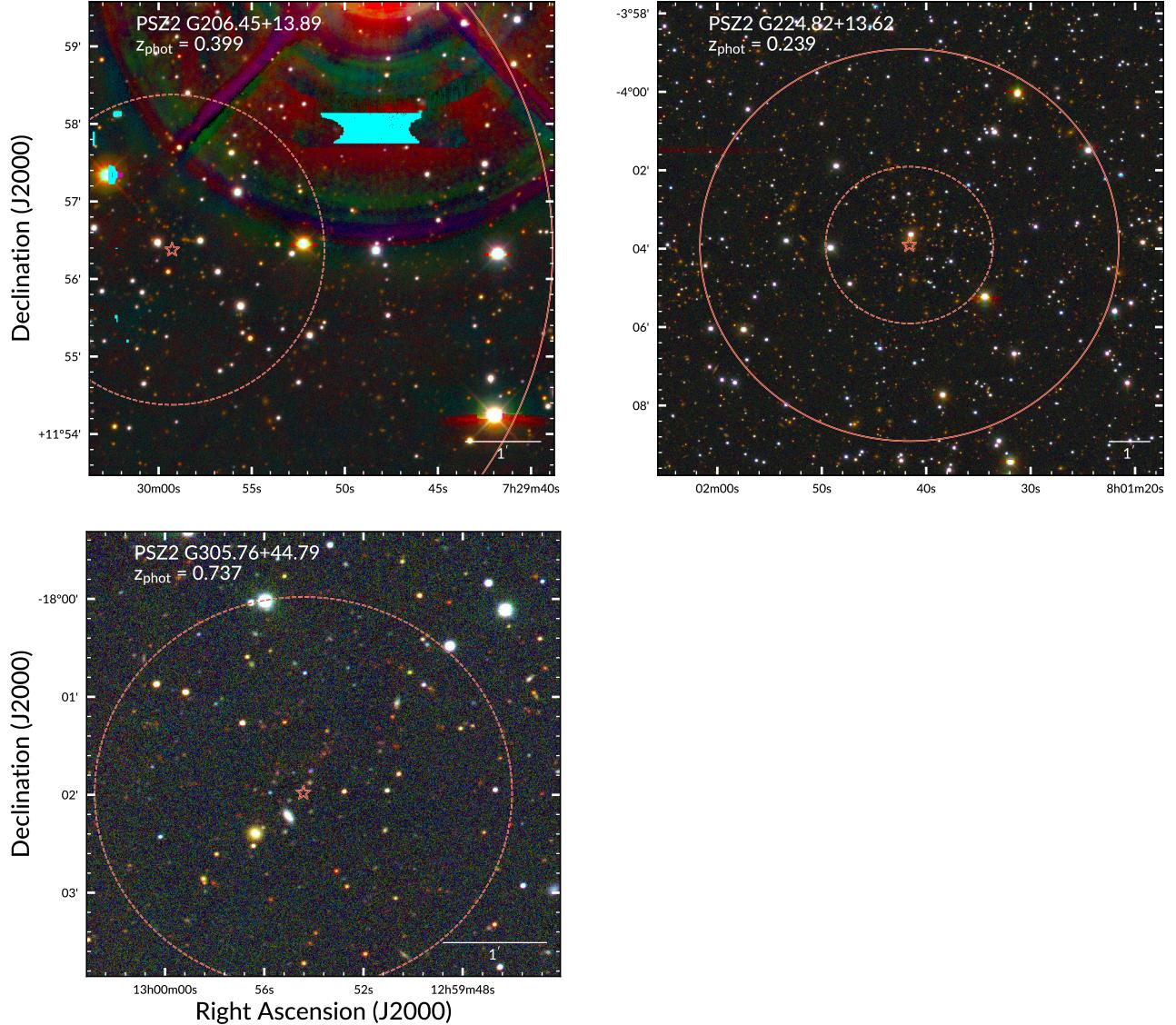


FIG. 6.— Same as Figure 3.

### 5.13. PSZ2 G206.45+13.89

We find a cluster at  $z_{\text{cl}} = 0.39 \pm 0.05$  with 73 cluster members. A bright star ( $V = 4.5$  mag; Høg et al. 2000) lies only  $\sim 4.9'$  away from the reported BCG, which prevents accurate photo- $z$  estimates for a significant fraction of the projected area of the cluster. This cluster has been previously confirmed in Barrena et al. (2018) as a rich cluster with a spectroscopic redshift of  $z_{\text{spec}} = 0.406$  from 45 members. We confirm the presence of a possible gravitationally-lensed arc  $\sim 13''$  northeast of the BCG.

### 5.14. PSZ2 G224.82+13.62

The BCG of this system is partially obscured by a nearby star and was not fully deblended in our catalogs. Still we are able to find a rich cluster at  $z_{\text{cl}} = 0.23 \pm 0.05$  with 38 members. An interesting aspect of this cluster is that it is positionally coincident with an unidentified X-ray source (2E 0759.2–0355) from the *Einstein Observatory* (Harris et al. 1990). This cluster was confirmed by Barrena et al. (2018) with a spectroscopic redshift of

$z_{\text{spec}} = 0.274$  from 28 members.

### 5.15. PSZ2 G305.76+44.79

Finally, PSZ2 G305.76+44.79 is our second highest redshift cluster at  $z_{\text{cl}} = 0.74 \pm 0.08$  with 48 members. The BCG is associated with radio source PMN J1259 – 1801 with a 1.4 GHz flux density of  $42.2 \pm 1.4$  mJy from the NVSS.

## 6. DISCUSSION

In this section, we discuss the results given in the previous section as a whole, and frame those results in the context of the broader PSZ sample.

### 6.1. Overview of Sample

Of the 85 cluster candidates observed as part of our program, we confirm 15 clusters, 12 of which were previously unrecognized as associations with *Planck* candidates. The clusters span the redshift range  $0.13 < z <$

TABLE 1

SUMMARY OF CLUSTER CONFIRMATION: COLUMN 1: THE PSZ2 CLUSTER NAME; COLUMN 2: PSZ2 SIGNAL-TO-NOISE RATIO; COLUMN 3: PSZ1 ID NUMBER; COLUMN 4: BCG RIGHT ASCENSION IN J2000; COLUMN 5: BCG DECLINATION IN J2000; COLUMN 6: BCG SEPARATION FROM PSZ POSITION IN ARCMINUTES; COLUMN 7: CLUSTER PHOTOMETRIC REDSHIFT WITH  $1-\sigma$  UNCERTAINTY; COLUMN 8: CORRECTED NUMBER OF MEMBER GALAXIES; COLUMN 9: NEW CONFIRMATION?

Cluster (1)	SNR (2)	PSZ1 ID (3)	$\alpha$ (J2000) (4)	$\delta$ (J2000) (5)	Sep. ('') (6)	$z_{\text{cl}}$ (7)	$N_{\text{gal},c}$ (8)	New (9)
PSZ2 G029.66 – 47.63	5.74	...	21 : 45 : 29.940	-21 : 43 : 26.29	4.73	$0.34 \pm 0.03$	130	✓
PSZ2 G043.44 – 41.27	5.55	...	21 : 36 : 43.728	-10 : 19 : 02.15	1.24	$0.42 \pm 0.04$	116	✓
PSZ2 G084.62 – 15.86	6.01	284	21 : 49 : 42.524	+33 : 09 : 17.29	1.14	$0.27 \pm 0.10$	18	
PSZ2 G096.43 – 20.89	5.81	...	22 : 48 : 09.402	+35 : 33 : 49.45	0.49	$0.24 \pm 0.04$	54	✓
PSZ2 G098.38 + 77.22	5.51	346	13 : 18 : 08.274	+38 : 30 : 20.10	5.84	$0.78 \pm 0.05$	58	✓
PSZ2 G106.11 + 24.11	5.70	...	19 : 21 : 31.852	+74 : 33 : 27.17	0.51	$0.14 \pm 0.06$	27	✓
PSZ2 G107.83 – 45.45	7.09	...	00 : 07 : 35.605	+16 : 07 : 02.39	0.83	$0.54 \pm 0.05$	30	✓
PSZ2 G120.76 + 44.14	5.59	...	13 : 12 : 53.537	+72 : 55 : 06.05	2.02	$0.35 \pm 0.03$	92	✓
PSZ2 G125.55 + 32.72	6.49	...	11 : 25 : 34.008	+83 : 58 : 55.75	1.44	$0.21 \pm 0.06$	32	✓
PSZ2 G137.24 + 53.93	7.87	...	11 : 40 : 59.525	+61 : 07 : 07.07	4.61	$0.45 \pm 0.06$	40	✓
PSZ2 G173.76 + 22.92	5.80	...	07 : 17 : 26.636	+44 : 05 : 02.97	1.62	$0.14 \pm 0.04$	117	✓
PSZ2 G191.82 – 26.64	6.17	646	04 : 38 : 28.283	+04 : 37 : 19.91	5.18	$0.18 \pm 0.06$	24	✓
PSZ2 G206.45 + 13.89	5.90	682	07 : 29 : 51.234	+11 : 56 : 31.31	1.97	$0.40 \pm 0.05$	73	
PSZ2 G224.82 + 13.62	5.51	752	08 : 01 : 41.492	-04 : 03 : 44.48	0.17	$0.24 \pm 0.04$	38	
PSZ2 G305.76 + 44.79	5.72	1070	12 : 59 : 53.612	-18 : 01 : 35.05	0.44	$0.74 \pm 0.08$	48	✓

0.74 with mean redshift  $< z > = 0.36$ . Seven of the clusters have published spectroscopic redshifts from other observations (see Section 5 for details). The scatter between our reported photo- $z$ 's and the reported spec- $z$ 's, using Equation 1, is  $\sigma_f = 0.036$  indicating that our clusters' photometric redshifts are accurate.

As part of the confirmation process we limited our cluster search to objects within  $\sim 5'$  of the reported PSZ position. The mean separation between our reported BCGs and the PSZ position is  $2'15$  with 68% of BCGs within  $2'$  of the quoted PSZ position. We find that our spatial distribution of clusters is roughly consistent with other follow up observations of PSZ cluster candidates (e.g., Barrena et al. 2018).

A number of clusters have noteworthy properties. We find that roughly 1/3 of the confirmed sample appear to contain multiple BCGs, or are part of multi-cluster systems. Seven of the 15 clusters have BCGs or other cluster members that host radio sources.

## 6.2. Implications for Full PSZ Sample

Using our galaxy cluster identification scheme described in Section 4.3, we fail to identify an optical counterpart to 70 PSZ cluster candidates. Because our observations are limited to candidates with  $\text{SNR} > 5-\sigma$ , we would expect at most one failed detection. Here we discuss four possible scenarios that could contribute to this low purity.

The first possibility is that clusters in our sample were missed because they are at low- $z$ . The initial design of our survey uses a  $10' \times 10'$  search window centered on the PSZ position. Low- $z$  clusters could appear as an isolated elliptical galaxy or a small number of galaxies and thus might not be classified as clusters. In follow up inspection of the full-sized mosaics, approximately 1 degree $^2$ , reveals no such low- $z$  structures.

To investigate this low- $z$  hypothesis quantitatively, we compute the expected fraction of galaxy clusters as a function of redshift from the cluster mass function of Tinker et al. (2008). The cluster mass sensitivity of *Planck* varies with redshift (see Figure 27, Planck Collaboration et al. 2015a). To capture this variability, we draw

random samples (with replacement) from the confirmed PSZ2 clusters. Because each cluster is previously confirmed, the PSZ2 catalog provides an  $M_{500c}$  estimate of the total mass. The bottom panel of Figure 7 shows the cluster mass as a function of redshift, where the gray lines are individual samples and the orange solid and dashed curves are the median and 68% limits respectively. The top panel of Figure 7 shows the expected cumulative distribution of galaxy clusters as a function of redshift.

From these numerical simulations we can see that a low fraction ( $< 5\%$ ) of all clusters detectable by *Planck* are expected to reside at redshifts less than 0.1. Of the 85 fields observed, we expect approximately four clusters to lie at such low redshifts. This is consistent with the three low- $z$  clusters we recover during the course of our analysis. Thus it is very unlikely that we have missed a significant number of low redshift clusters.

The second possibility posits that many of the clusters in our sample lie at redshifts beyond our optical detection limits. The median limiting  $i$ -band magnitude of our survey is 23.2 mag, corresponding to a limiting redshift of  $z = 0.75$  for an  $L_*$  galaxy (see Figure 2).

From the predicted number of PSZ clusters as a function of redshift (Fig. 7), we expect  $\sim 3\%$  of the sample to lie at  $z > 0.7$ . Out of the 1943 total *Planck* SZ detections, our simulated redshift distribution predicts that there should be 58 clusters at high- $z$  (if all *Planck* SZ detections are real clusters). There are only 12, currently confirmed, clusters at  $z > 0.7$  in PSZ2, only five of which are above  $z = 0.8$ . So there should be 46 high- $z$  clusters among the unconfirmed sample of 613, or approximately 7%. Applying this percentage to the 85 fields we observed, suggests that we should have found six high- $z$  clusters. We have only found two, each of which lies close to the redshift limit of our optical search.

Thus while high- $z$  systems were expected to be missed by this (optical only) survey, high- $z$  clusters alone cannot account for the high number of still unconfirmed clusters. We expect further follow up observations with deep infrared imaging will be required to either confirm or place additional limits on putative high- $z$  clusters.

The third possibility is that the vast majority of clus-

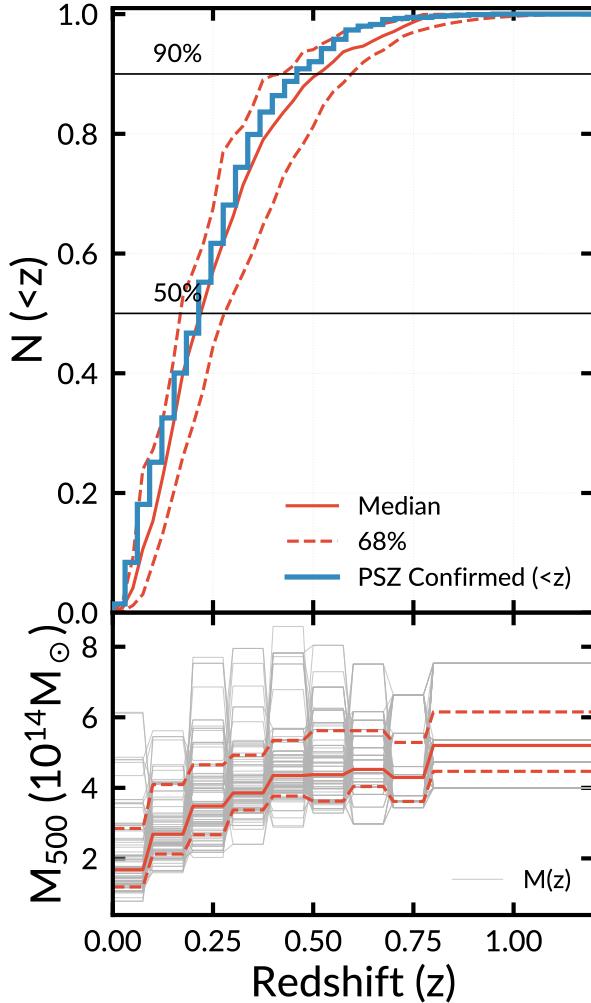


FIG. 7.— Top: The predicted number of clusters as a function of redshift and normalized to unity from the mass function of Tinker et al. (2008). At each redshift the lower mass limit is given by the mass in the bottom panel at the corresponding redshift. The blue PSZ Confirmed curve shows the normalized, cumulative number of confirmed clusters as a function of redshift. For reference we show the 50% and 90% fractional completeness levels. Bottom: Cluster mass as a function of redshift. Redshift bins are the same as Planck Collaboration et al. (2015a) Figure 27. In each panel the solid and dashed orange lines show the median and region enclosing 68% of the data respectively.

ters are obscured by the Milky Way. It is possible that the underlying cause for failed cluster identification is confusion from source crowding in our images. If a cluster lies behind a dense foreground of Milky Way sources, then it could be difficult to visually identify the cluster. To estimate the object surface density in our fields, we sum the number of objects reported by SExtractor and divide by the sky-area of the image. Figure 8 allows us to explore the possibility that we fail to confirm a cluster in the majority of fields because of foreground contamination. The left panel shows the surface density of objects in the search area as a function of the limiting *i*-band magnitude (see also the left panel of Figure 2). The right panel shows the number of observed fields with the corresponding object density. In both panels, the fields where we do not identify a cluster are shown in blue, and

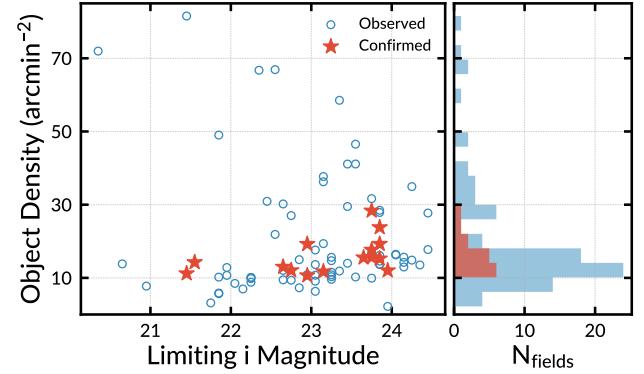


FIG. 8.— Right: Object Density in units of number per arcmin<sup>-2</sup> as a function of the 80% *i*-band limiting magnitude taken from Figure 2. Fields where no cluster is identified are given by blue circles and fields with confirmed clusters are shown by orange stars. Left: Histogram of the object surface density of observed fields.

the fields with successfully identified clusters are shown in orange.

Our identified clusters fall in a relatively narrow range of object densities, 10 – 30 objects arcmin<sup>-2</sup>. Roughly two thirds of our fields fall within this range. Of the 31 fields outside the range, 15 fields have higher densities. If all 15 fields contain an obscured cluster we could still not account for the vast majority of fields where we did not identify a cluster, 51 fields or ∼ 60% of our observed sample.

Perhaps more interesting are the sixteen fields where the object surface density is lower than the range where we made successful identifications. These are fields where it should be relatively easy to identify a massive cluster should it exist. Of course, the presence of a massive cluster could raise the object density above the lower identification threshold. These fields, especially the fields with deep optical limiting magnitudes are prime candidates for the potential high-*z* clusters lurking beyond the reach of our optical search.

The fourth possibility, and perhaps most plausible, is that the vast majority of cluster candidates in our sample are not true 5- $\sigma$  (or higher) detections. In other words, no optical counterpart to the PSZ detection exists. Previous works (e.g., Barrena et al. 2018) find a similar fraction of non-detections, and consider contamination from foreground radio sources as a possible culprit. As part of our NED search, we track NVSS radio sources within 5' of the reported PSZ position. We find approximately 75% of confirmed PSZ clusters have a NVSS radio source (39.6 mJy average flux) and unconfirmed PSZ candidates show slightly fewer sources with approximately 55% having a NVSS radio source (25.1 mJy average flux) within 5'. For the 85 cluster candidates observed in this work ∼ 70% of fields have at least one radio source (30.8 mJy average flux). Twelve of the 15 confirmed clusters (80%; 26.12 mJy average flux) have nearby radio sources. Based on these results, we find it unlikely that foreground radio contamination is a leading cause of the low purity of the unconfirmed PSZ sample.

## 7. SUMMARY

In this work, we report on our analysis of images targeting galaxy cluster candidates selected from the sec-

ond *Planck* all-sky galaxy cluster catalog (PSZ2) (Planck Collaboration et al. 2015a). We observe 85 candidates with SZ effect SNR > 5 over the course of seventeen nights spread over three years (2014–2017). We independently develop and utilize a pipeline to process the *griz* imaging taken with both the MOSAIC 1.1 and MOSAIC 3 imagers on the KPNO Mayall-4m telescope (see Section 3). We present the first results from the complete data set of 85 fields, 15 rich galaxy clusters of which 12 were previously unassociated with a *Planck* cluster.

After computing accurate photometric redshifts (see Section 4) we visually inspect each galaxy cluster candidate and adopt stringent confirmation criteria based on the richness and separation from the reported PSZ2 position.

The newly discovered clusters range in photometric redshift between  $0.13 < z < 0.74$ . The upper redshift limit is due to the depth of imaging restricting our ability to reliably detect  $L_*$  galaxies to  $z < 0.9$ . Ultimately, this prevents us from finding the most interesting rich clusters at very high redshifts; this will be addressed in a future follow-up study.

A large motivation for this work has come from the recent successes of other SZ follow-up programs (e.g., Bayliss et al. 2016; Sifón et al. 2016; Kirk et al. 2015). We present this sample of clusters to aid in the confirmation of the full PSZ cluster sample, and to potentially reveal clusters with interesting astrophysical properties. The PSZ cluster candidates which remain unconfirmed have the potential to be the most interesting.

In future work, we will present the properties of lower richness clusters and small groups of galaxies in addition to multi-wavelength studies using the clusters detected as part of this survey.

All source code used to conduct this analysis is available at <https://github.com/boada/planckClusters>. The raw and processed imaging along with final data products for the 15 clusters presented here are available upon request.

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