

Galaxy overdensities around 3C radio galaxies and quasars at $1 < z < 2.5$ revealed by *Spitzer* 3.6/4.5 μm and Pan-STARRS

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Luminous radio sources are thought to lie in galaxy clusters or proto-clusters. The complete sample of 64 high-redshift 3C sources at $1 < z < 2.5$ has been mapped with the *Spitzer Space Telescope*. The IRAC 3.6 and 4.5 μm 5σ detection limit of 4 μJy (22.4 AB mag) allows us to search for the brightest candidate cluster member galaxies associated with the 3C sources. To remove the contamination of foreground stars and galaxies along the lines of sight toward the 3C sources, we apply color cuts: the removed sources satisfy either the IRAC1/2 cut $[3.6] - [4.5] < -0.3$ or the Pan-STARRS/IRAC cut $i - [4.5] < 0.5$ if detected by Pan-STARRS. For both selection methods, about half of the 3C radio sources show significant overdensities ($> 3\sigma$) within $30''$ (~ 250 kpc) projected distance from the radio source compared to the surrounding galaxy densities measured in the 50–120'' annulus. The Pan-STARRS/IRAC cut reveals higher average overdensities than the IRAC1/2 cut and also a decline of overdensities at $z > 1.4$. To infer the nature of the cluster members, we rerun the analysis using a stronger IRAC1/2 cut $[3.6] - [4.5] < -0.1$, which removes $1 < z < 1.4$ passive ellipticals but not star-forming galaxies. For the strong cut, the overdensities, on average, completely disappear at $1 < z < 1.4$. We therefore suggest that the 4.5 μm detected cluster member galaxies are mainly passive ellipticals.

KEYWORDS

high-redshift – clusters of galaxies – catalogs – surveys

1 | INTRODUCTION

High-redshift ($z > 1$) radio galaxies (RGs) belong to the most massive host galaxies in the universe (e.g., Seymour et al. 2007 and references therein) and are consequently suspected to reside in galaxy proto-clusters or clusters (Miley & De Breuck 2008). To confirm this idea, however, it is necessary to identify possible companion galaxies at the redshifts of the RGs, in the presence of contamination from numerous stars and foreground galaxies. Background galaxies, unless gravitationally lensed, become fainter on average with increasing distance and therefore are expected to provide a relatively minor contamination. Previous studies have found galaxy overdensities around distant active galactic nuclei (AGN), but the results are far from definitive.

Multiband imaging and photometric redshift estimation are efficient ways to find candidate cluster member galaxies. In order to yield reliable outcomes, photo- z techniques generally require five or more photometric measurements, and ideally these should encompass a strong and ubiquitous feature in the spectral energy distribution (SED), for example, the 4,000 Å Balmer break. If fewer SED data points are available, however, broadband color cuts are a widely used alternative for selecting high-redshift sources as done by, for example, Huang et al. (2004).

The SEDs of nearly all galaxies show a peak at 1–2 μm in the rest frame, making near-infrared (NIR) observations very useful for photo- z estimates; for a detailed discussion we refer the reader to Galametz et al. (2012). Pioneering K- and J-band imaging of high- z 3C sources indicated a mean galaxy

overdensity but with a large field-to-field scatter (Best 2000; Best et al. 2003). These results were obtained with relatively small area coverage, limited to 50'' field of view (FoV), only about the expected cluster size at $z = 1$, thus making the estimation of the nearby foreground (and background) uncertain. Furthermore, at redshifts above 1, the SED peak shifts out of the K band, and observations at longer wavelengths are advantageous for source detection.

Such observations and studies have been performed for the sample of 72 RGs at $1 < z < 5.2$, hereafter referred to as the *Spitzer*-HzRG sample (Galametz et al. 2012; Seymour et al. 2007) and an extension to 387 radio-loud AGNs at $1 < z < 3.2$, hereafter referred to as the CARLA sample (Wylezalek et al. 2013). For these, the environment has been studied with observations at 3.6 and 4.5 μm using the IRAC instrument (Fazio et al. 2004) onboard the *Spitzer Space Telescope* (Werner et al. 2004). About half of the RGs and quasars in these samples show an overdensity of *Spitzer*/IRAC-detected galaxies, both compared to blank fields and in terms of a surface density rising toward the position of the AGN (Galametz et al. 2012; Hatch et al. 2014; Wylezalek et al. 2013). However, the other half shows only little evidence for associated clusters. The studies successfully used an IRAC color cut $[3.6] - [4.5] > -0.1$ (AB mag), following Huang et al. (2004), to identify $z > 1.3$ candidate cluster member galaxies.

Falder et al. (2010) employed an efficient strategy based on IRAC 3.6 μm one-filter-only observations of 173 AGN at $z \sim 1$ to reveal an excess of massive galaxies within 300 kpc of their targets compared to the field. The excess is more pronounced for radio-loud AGN. Notably, Falder et al. (2010) did not use any color information to reject foreground sources.

A more elaborate study by Haas et al. (2009) of 3C 270.1 at $z = 1.54$ involves *Spitzer*/IRAC observations in combination with deep z - and y -band imaging (~ 26 AB mag) with the 6.5-m MMT at Mt. Hopkins (Brown et al. 2008; McLeod et al. 2006). This strategy, which brackets the Balmer break at the expected cluster redshift, is relatively insensitive to photometric errors in the IRAC bands, which easily may exceed 10%. Fitting zy +IRAC photometry with two simple galaxy templates (elliptical and ULIRG) revealed a central overdensity of intrinsically red $z \approx 1.54$ galaxies around the radio source. This technique therefore shows significant promise for identifying candidate cluster member galaxies, but the need to collect the required deep optical imaging has so far impeded a systematic investigation of this kind for large galaxy samples.

The 3C sample contains 64 RGs and quasars at $1 < z < 2.5$ (Spinrad et al. 1985). They all have been observed with *Spitzer*/IRAC (3.6–8 μm) and MIPS (24 μm) with a nearly 100% detection rate (Podigachoski et al. 2015). While six 3C sources are contained in the *Spitzer*-HzRG sample (mentioned above), most of the high- z 3C environments have not been investigated. In addition, the high- z 3C sample has been mapped with the *Herschel Space Observatory* with a detection rate of over 50% (Podigachoski et al. 2015), in contrast to the $\sim 20\%$ *Herschel* detection rate of the *Spitzer*-HzRG

sample (Drouart et al. 2014). The high *Herschel* detection rate makes the 3C sample particularly interesting for an environment study over the whole near-, mid-, and far-infrared wavelength range. Such a study will allow one also to explore a possible connection between the environment and the black hole- and star-forming (SF) activity of the radio-loud AGNs and their host galaxies.

The advent of the Pan-STARRS *grizy* data release (Chambers et al. 2016; Magnier et al. 2016) offers a unique opportunity for a joint *Spitzer*–Pan-STARRS study of the high- z 3C environments. While the depth of Pan-STARRS (with a completeness limit of about $i = 21.2$ AB mag, see Section 2 below) might be too shallow to detect candidate cluster member galaxies, the Pan-STARRS data nonetheless help in rejecting many or even most of the foreground sources.

We here do not distinguish between clusters, proto-clusters, and galaxy groups; rather we simply search for galaxy overdensities. We examine the environment of 3C radio sources as seen in the near- and mid-infrared bands provided by *Spitzer*/IRAC+MIPS, supplemented in the visible by Pan-STARRS (PSO). The rest of the paper is organized as follows. Section 2 describes the sample and data, including the matched *Spitzer*–Pan-STARRS source catalog and the correction for the foreground galactic extinction. Section 3 shows example SEDs. Color cuts for redshifted galaxy templates are described in Section 4. Section 5 reports of two approaches to finding galaxy overdensities in the high- z 3C environments. A summary is presented in Section 6. Throughout this work we adopt a standard Λ CDM cosmology ($H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.73$, and $\Omega_m = 0.27$ (Spergel et al. 2007)). All magnitudes are AB, where zero mag corresponds to 3631 Jy.

2 | DATA

Figure 1 shows IRAC2 and Pan-STARRS *i*-band images of a crowded and a sparsely populated field. Only 5% of the 3C sources are that much crowded like 3C 418. About 60% of the sample has intermediately crowded fields, and 35% of the 3C sources lie in sparse fields like 3C 437. Figure 1 illustrates that our images are rather shallow and that most sources are well isolated, with the advantage that source confusion and deblending plays a minor role. It also indicates that the PSF (point spread function) differences (see Table 2) between the filters do not pose a real challenge for the matching. This conclusion is further supported by the fact that, in the final catalog of 50,000 IRAC sources, only about 15% of the IRAC sources have a double or multiple Pan-STARRS match.

2.1 | *Spitzer*/IRAC+MIPS

The sample of 64 3C sources at spectroscopic redshifts $1 < z < 2.5$ is listed in Table 1. All sources were mapped by the *Spitzer Space Telescope* during the cryogenic mission as part of several guaranteed time programs led by IRAC PI Giovanni

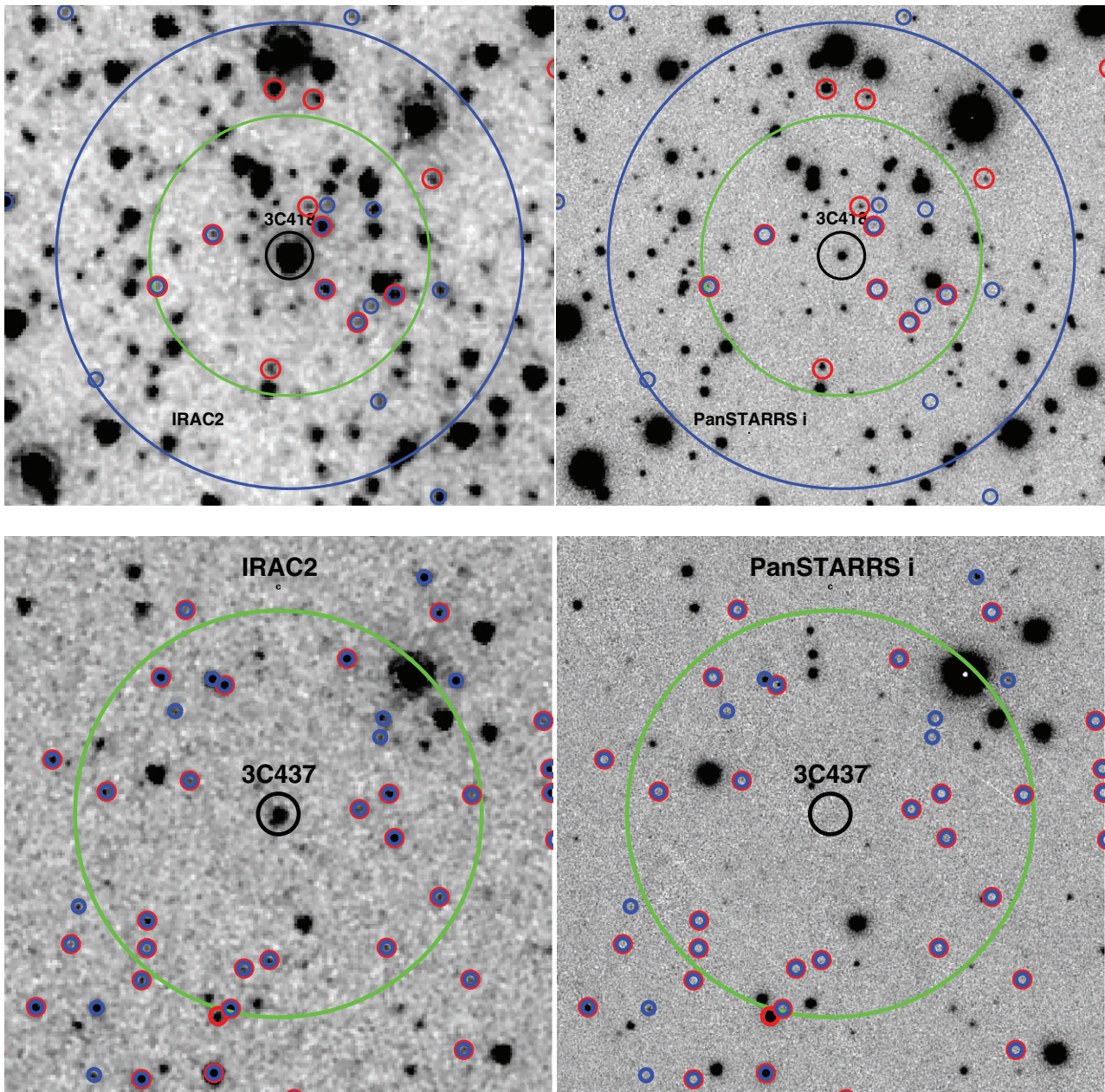


FIGURE 1 Images of the most crowded field (top: quasar 3C 418) and a sparsely populated field (bottom, RG 3C 437). The left panels are IRAC2 at $4.5\ \mu\text{m}$, the right panels are Pan-STARRS i -band. The black circles of $5''$ radius mark the 3C sources. The large circles (green/blue) have a radius of $30''$ and $50''$, respectively. The small circles mark the candidate cluster member galaxies found in Section 5 with the Pan-STARRS cut (blue, $1.''5$) and the IRAC cut (red, $2''$ radius)

Fazio and described in more detail by Seymour et al. (2007) and Haas et al. (2008). In brief, the observations include the four IRAC bands (3.6 , 4.5 , 5.8 , and $8.0\ \mu\text{m}$), yielding three fields with roughly $4.5' \times 4.5'$ FoV. The central field was covered with all four filters, and the two flanking fields were each observed in two filters, with one about $6.5'$ to the “left” in 3.6 and $5.8\ \mu\text{m}$ and the other to the “right” in 4.5 and $8.0\ \mu\text{m}$. In addition, $24\ \mu\text{m}$ imaging of the central field covering about $5' \times 5'$ FoV was also obtained using the MIPS instrument (Rieke et al. 2004). The total exposure times were $4 \times 30\ \text{s}$ for each IRAC band and $10 \times 10\ \text{s}$ for the MIPS images. Eight 3C sources contained in the *Spitzer*-HzRG program (3C 065, 3C 239, 3C 257, 3C 266, 3C 294, 3C 356, 3C 368, 3C 470)

were observed at similar depths but covering a larger area. Photometry of the 3C sources themselves has already been reported by Seymour et al. (2007) for 8 sources and by Haas et al. (2008) for the remaining 56 sources. Podigachoski et al. (2015) published the *Spitzer* (and *Herschel*) photometry.

For the present study, we used the *Spitzer* Enhanced Imaging Products (SEIP)¹ to identify all sources in the IRAC+MIPS mosaics and carry out photometry. In each band, mosaic maps were created for sky areas covered by at least four dithered images. The pixel size of the provided IRAC maps is $0.''6$ (half the native IRAC pixel size)

¹ <http://irsa.ipac.caltech.edu/data/SPITZER/Enhanced/SEIP/overview.html>

TABLE 1 3C sample at $1 < z < 2.5$ from Spinrad et al. (1985)

Name	RA (J2000)	Dec (J2000)	Type ^a	Redshift	Name	RA (J2000)	Dec (J2000)	Type ^a	Redshift
3C 002	00h06m22.6s	−00d04m25s	Q	1.037	3C 250	11h08m52.1s	+25d00m55s	G	1.260
3C 009	00h20m25.3s	+15d40m53s	Q	2.009	3C 252	11h11m33.1s	+35d40m42s	G	1.100
3C 013	00h34m14.5s	+39d24m17s	G	1.351	3C 255	11h19m25.2s	−03d02m52s	Q	1.355
3C 014	00h36m06.5s	+18d37m59s	Q	1.469	3C 256	11h20m43.0s	+23d27m55s	G	1.819
3C 036	01h17m59.5s	+45d36m22s	G	1.301	3C 257	11h23m09.2s	+05d30m19s	G	2.474
3C 043	01h29m59.8s	+23d38m20s	Q	1.459	3C 266	11h45m43.4s	+49d46m08s	G	1.275
3C 065	02h23m43.2s	+40d00m52s	G	1.176	3C 267	11h49m56.5s	+12d47m19s	G	1.140
3C 068.1	02h32m28.9s	+34d23m47s	Q	1.238	3C 268.4	12h09m13.6s	+43d39m21s	Q	1.397
3C 068.2	02h34m23.8s	+31d34m17s	G	1.575	3C 270.1	12h20m33.9s	+33d43m12s	Q	1.532
3C 119	04h32m36.5s	+41d38m28s	G	1.023	3C 280.1	13h00m33.3s	+40d09m08s	Q	1.671
3C 124	04h41m59.1s	+01d21m02s	G	1.083	3C 287	13h30m37.7s	+25d09m11s	Q	1.055
3C 173	07h02m17.6s	+37d57m20s	G	1.035	3C 294	14h06m44.0s	+34d11m25s	G	1.779
3C 181	07h28m10.3s	+14d37m36s	Q	1.382	3C 297	14h17m24.0s	−04d00m48s	G	1.406
3C 186	07h44m17.4s	+37d53m17s	Q	1.067	3C 298	14h19m08.2s	+06d28m35s	Q	1.437
3C 190	08h01m33.5s	+14d14m42s	Q	1.195	3C 300.1	14h28m31.3s	−01d24m08s	G	1.159
3C 191	08h04m47.9s	+10d15m23s	Q	1.956	3C 305.1	14h47m09.5s	+76d56m22s	G	1.132
3C 194	08h10m03.6s	+42d28m04s	G	1.184	3C 318	15h20m05.4s	+20d16m06s	G	1.574
3C 204	08h37m44.9s	+65d13m35s	Q	1.112	3C 322	15h35m01.2s	+55d36m53s	G	1.681
3C 205	08h39m06.4s	+57d54m17s	Q	1.534	3C 325	15h49m58.6s	+62d41m21s	G	1.135
3C 208.0	08h53m08.8s	+13d52m55s	Q	1.110	3C 324	15h49m48.9s	+21d25m38s	G	1.206
3C 208.1	08h54m39.3s	+14d05m53s	G	1.020	3C 326.1	15h56m10.1s	+20d04m20s	G	1.825
3C 210	08h58m09.9s	+27d50m52s	G	1.169	3C 356	17h24m19.0s	+50d57m40s	G	1.079
3C 212	08h58m41.5s	+14d09m44s	Q	1.048	3C 368	18h05m06.3s	+11d01m33s	G	1.131
3C 220.2	09h30m33.5s	+36d01m24s	Q	1.157	3C 418	20h38m37.0s	+51d19m13s	Q	1.686
3C 222	09h36m32.0s	+04d22m10s	G	1.339	3C 432	21h22m46.2s	+17d04m38s	Q	1.785
3C 225A	09h42m08.5s	+13d51m54s	G	1.565	3C 437	21h47m25.1s	+15d20m37s	G	1.480
3C 230	09h51m58.8s	−00d01m27s	G	1.487	3C 454.0	22h51m34.7s	+18d48m40s	Q	1.757
3C 238	10h11m00.4s	+06d24m40s	G	1.405	3C 454.1	22h50m32.9s	+71d29m19s	G	1.841
3C 239	10h11m45.4s	+46d28m20s	G	1.781	3C 469.1	23h55m23.3s	+79d55m20s	G	1.336
3C 241	10h21m54.5s	+21d59m30s	G	1.617	3C 470	23h58m35.3s	+44d04m39s	G	1.653
3C 245	10h42m44.6s	+12d03m31s	Q	1.028	4C 13.66	18h01m39.0s	+13d51m23s	G	1.450
3C 249	11h02m03.8s	−01d16m17s	Q	1.554	4C 16.49	17h34m42.6s	+16d00m31s	Q	1.880

^aType denotes quasar (Q) or radio galaxy (G), depending on whether or not broad emission lines have been identified in their spectra.

and for the MIPS 24 μ m it is 2.''45 (native MIPS 24 pixel size). We used the SEIP average maps (with artifacts having been removed by SEIP algorithms) because the background of the average maps is slightly smoother than that of the median maps.

2.2 | *Spitzer* source extraction and photometry

SEIP provides source catalogs for 10σ detections with photometry in 3.''8 and 5.''8 diameter apertures, but we found by visual inspection that numerous visible sources are missing from the SEIP catalogs. We therefore performed new source identification and photometry using SExtractor² (Bertin & Arnouts 1996) in a manner similar to that described by Baronchelli et al. (2016) for

the *Spitzer*/IRAC+MIPS Extragalactic Survey (SIMES) but with several small modifications. We used a spacing of 128×128 pixels filtered with a 3-pixel top-hat kernel to model the backgrounds. This was necessary to account for extended sources ($\sim 5\%$) present in our maps. We used a pixel detection threshold of 2σ and a minimum number of six connected pixels above the background noise. We computed AUTO fluxes as done by Baronchelli et al.³

³AUTO fluxes are estimates of the total flux of a source in an elliptical aperture of semi-major axis (a) proportional to the Kron radius R_K of the object (Kron 1980). Setting the SExtractor parameter KronFact = 2.5, hence $a = 2.5R_K$ means—by definition of the Kron radius—that the AUTO flux contains more than 90% of the total galaxy flux. For apertures with $a < 3.5$ pixels (2.''1), the AUTO flux was computed within a circular aperture. AUTO fluxes account for the extent of each source, the elliptical shapes of the observed isophotes and the source's radial surface profile. For close double sources, AUTO flux performs a deblending and returns the Kron flux assuming isophotal symmetry.

² <http://www.astromatic.net/software/sextractor>

In a first step, we ran SExtractor on each IRAC image in single mode. We checked the positional accuracy of sources in the various IRAC bands in order to see how well the sources matched. The IRAC positions are generally good to less than $0.''2$, which means that position-matching to within $1''$ is appropriate, as also found by Ashby et al. (2013) for the Spitzer Extended Deep Survey. We checked for each IRAC image and each source the separation to the nearest neighbouring source. It turns out that, depending on the filter, between 10 and 20% of the sources have a neighbor closer than $6''$, many with even a $4''$ neighbor. This rules out the use of apertures larger than about $4''$ to avoid flux contamination by the neighbor. On the other hand, about 5% of the sources are more extended than $4''$ so that flux is lost when performing photometry with an aperture less than $4''$ diameter. Therefore all photometry given here refers to the AUTO fluxes that return the deblended Kron flux assuming isophotal symmetry.

In a second pair of steps, we ran SExtractor in dual mode using first the $4.5\mu\text{m}$ images and then the $3.6\mu\text{m}$ images as a reference. Using $4.5\mu\text{m}$ ($3.6\mu\text{m}$) as reference allows us to detect the sources in the central field and in the right (left) off-field, respectively. In general, the $4.5\mu\text{m}$ images (and the other longer wavelength images) are less affected by mux-bleeds from bright saturated stars compared to the $3.6\mu\text{m}$ images. Therefore we used as primary catalogs those based on the $4.5\mu\text{m}$ images (center fields and right off-fields) and added sources in the left off-fields from the $3.6\mu\text{m}$ -based catalogs.⁴ To get rid of false detections in the reference frames, we required that a source must be detected in single mode in at least one other filter (using a matching radius of $1''$). Finally, only sources with SExtractor detection flag ≤ 3 were accepted; this rejected saturated sources and uncertain sources near the map border.

To check on the uncertainties of the IRAC photometry, we compared our AUTO fluxes with the SEIP pipeline catalog photometry, which lists aperture-corrected total fluxes measured with circular apertures of $3.''8$ and $5.''8$ diameter. We used only sources that are compact (with Kron radius smaller than $6''$) and isolated (with a nearest neighbor more than $10''$ apart) and required that the $3.''8$ and $5.''8$ photometry agrees to better than 10%. Figure 2 shows the ratio of AUTO flux to total flux for the $5.''8$ aperture. For all bands, the average ratio of AUTO flux to total flux is ~ 0.9 , consistent with the Kron definition of the AUTO flux. The results are similar for the $3.''8$ aperture. These validation checks document, on average, the good photometric quality, and that any remaining filter-dependent PSF effects are remarkably well corrected for. Individual sources, however, may deviate considerably (about 30%). This calls for caution when our data are used for applying narrow IRAC1/2 color cuts, which may be sensitive

to photometric errors larger than 10% (as discussed further in Section 4).

For the MIPS $24\mu\text{m}$ images, we ran SExtractor in single-image mode only, using a global background of 32 pixels filtered with a 3-pixel top-hat kernel. To improve the detection and photometry and to reject uncertain sources at the map border, sources were accepted only if the coverage map indicated at least 6 exposures (maximum is 10 exposures).

We estimated the sensitivity and completeness limits via number count histograms of sources detected with at least 5σ (Figure 3). As detection limit we did not simply take the faintest detected source; rather we allowed for 2% faint outliers, thus 98% of the sources are brighter than the detection limit. The values are listed in Table 2. Both detection and completeness limits agree within 0.2 mag for all 64 central fields.⁵

2.3 | Pan-STARRS

Pan-STARRS has imaged the entire northern sky in the five bands, namely g , r , i , z , and y , and created catalogs from the image data⁶ (Chambers et al. 2016; Flewelling et al. 2016). We retrieved the Pan-STARRS images (with a pixel scale of $0.''25$) and source catalogs for all 64 high- z 3C fields from the Mikulski Archive for Space Telescopes (MAST) at the Space Telescope Science Institute web page.⁷ From the source catalogs we extracted sources within $12'$ of the 3C position and used the Kron photometry (Magnier et al. 2016).

2.4 | Cross-matched catalog

We found systematic positional offsets, median $\sim 0.''2$, between IRAC and Pan-STARRS sources.⁸ Therefore, for each 3C field we performed two iterations of the matching: in the first iteration we determined the median offset between IRAC and Pan-STARRS using a matching radius of $1.''2$; in the second we matched the offset-corrected positions using a matching radius of $1''$. Among all sources finally matching within $1''$, 96% match within $0.''75$ and 87% within $0.''5$. On average, about 15% of the IRAC sources have a double or multiple PSO counterpart. These sources are flagged and not used in the overdensity analysis. For matching the MIPS24 and IRAC sources, we used a radius of $2''$.⁹

⁵Both detection and completeness limits are about 0.5–0.7 mag brighter for the IRAC off-fields. This is because we required that a source must be detected in single mode in at least two filters, and that the available second filter in the off-fields (5.8 and $8\mu\text{m}$, respectively) is less sensitive than the 3.6 and $4.5\mu\text{m}$ bands.

⁶ <https://panstarrs.stsci.edu/>

⁷ <https://archive.stsci.edu/panstarrs/>

⁸The net position offset is consistent with the offset between 2MASS and Pan-STARRS, see Magnier et al. (2016). IRAC positions are tied to 2MASS.

⁹Increasing the $2''$ MIPS24 – IRAC matching radius to $3''$ did not increase the number of unique matches.

⁴While both the left and the right off-fields will not be used in the environment analysis in Section 5, they are cataloged here as well for future use.

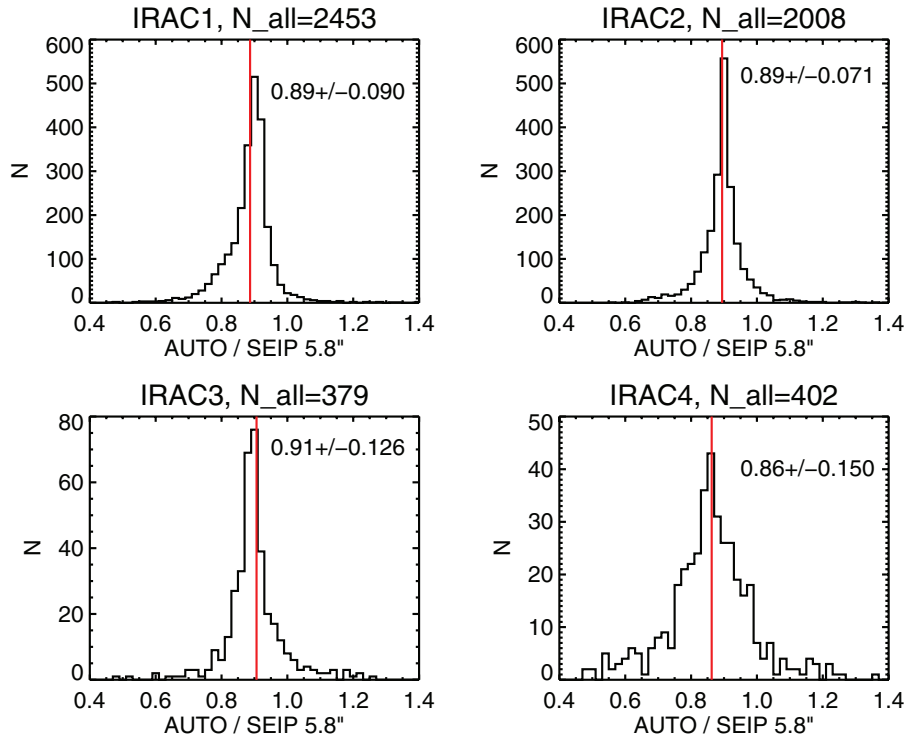


FIGURE 2 Ratio of our AUTO flux to total 5.8'' aperture flux of the SEIP catalog. Only compact, isolated sources enter the histograms. The vertical red line marks the average. Average and 1σ are as labeled

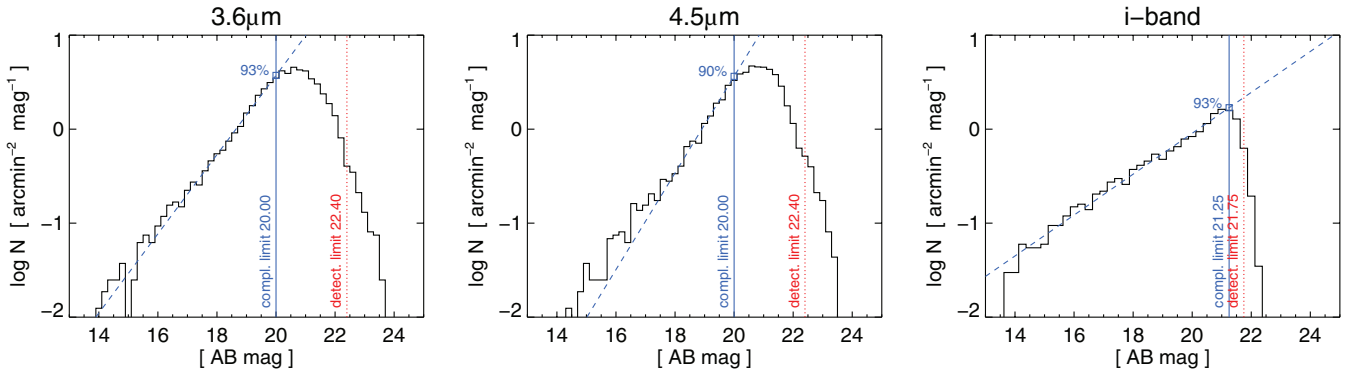


FIGURE 3 Number counts within $2'$ radius around all 3C sources in the three filters 3.6 μm , 4.5 μm , and i used for the galaxy overdensity search. The detection limit (red dotted line) is the magnitude at which 98% of the sources are brighter. The blue dashed line shows a linear fit. The completeness limit (blue solid line) and the completeness fraction ($\sim 90\%$) are estimated relative to the extrapolation of the linear fit (blue square)

The final *Spitzer* source catalog, supplemented by Pan-STARRS photometry, contains about 50,000 sources. About 20,000 sources are detected with both *Spitzer* and Pan-STARRS, and the remaining 30,000 sources only with *Spitzer*.¹⁰ About 27,000 sources are located in the IRAC central fields and detected in both IRAC 3.6- and 4.5 μm bands (on average 20 sources per square arcmin); 10,000 of these 27,000 sources are detected also with Pan-STARRS. In the IRAC off-fields, the detection rate is lower because only two IRAC filters were observed; we required sources to be detected in both filters in order to exclude spurious sources.

Among those sources of the present *Spitzer*–Pan-STARRS catalog detected at both 3.6 and 4.5 μm , the Pan-STARRS detection rate in the g , r , i , z , and y bands is 24, 33, 40, 37, and 29%, respectively. The i band has the highest detection rate, and only $\sim 4\%$ of the i -band non-detections were detected in any of the other four Pan-STARRS bands. Following the same procedure used for the *Spitzer* bands, we determined the Pan-STARRS detection and completeness limits via histograms for those sources in the *Spitzer*–Pan-STARRS catalog (Figure 3, Table 2).

We did not apply a correction for PSF differences between the filters. We consistently used Kron photometry for both Pan-STARRS and *Spitzer* data. We expect any bias to be small compared to the photometric uncertainty of the faint IRAC sources (10–30%).

¹⁰There are also 200,000 Pan-STARRS sources not detected by *Spitzer*. Those are of no interest for present purposes.

TABLE 2 5σ detection limits and completeness limits in AB mag for each filter as determined from histograms such as shown in Figure 3

Filter	Wavelength (μm)	Detect.	Compl. ($\sim 90\%$)	PSF FWHM (arcsec)
PSO <i>g</i>	0.481	22.2	21.7	~ 1.1
PSO <i>r</i>	0.617	22.0	21.5	~ 1.1
PSO <i>i</i>	0.752	21.7	21.2	~ 1.1
PSO <i>z</i>	0.866	21.2	20.5	~ 1.1
PSO <i>y</i>	0.962	20.5	19.7	~ 1.1
IRAC 1	3.6	22.4	20.0	1.66
IRAC 2	4.5	22.4	20.0	1.72
IRAC 3	5.8	20.8	19.4	1.88
IRAC 4	8.0	20.8	19.6	1.98
MIPS 1	24.0	18.5	17.3	~ 5.9

Note. Zero mag corresponds to 3631 Jy. The last column lists the PSF FWHM. For Pan-STARRS, median values from Magnier et al. (2016) are given. FWHM = full-width at half-maximum; PSF = point spread function.

The catalog was created with the main aim to detect as many real $4.5\ \mu\text{m}$ sources as possible. At the faint end (below $20\ \mu\text{Jy}$), the photometric uncertainties may become large; even for nominal 5σ detected sources, the real uncertainties may exceed 20%, in particular for the other IRAC bands (see Figure 2). Any photometric errors will smear out the color contrasts needed and thus will lower the detection of galaxy overdensities. Nevertheless, the search for galaxy overdensities turns out to be successful (Section 4). Thereby, the galaxy overdensities are based on typically a dozen galaxies, the brightest cluster members. While this search only uses the 3.6- and $4.5\ \mu\text{m}$ data of the central 3C fields (and the corresponding *i*-band data), for future purposes we have created the catalog also for the other filters and the off-fields. The catalog can be obtained from the authors on request.

For the rest of the paper, we removed some extreme sources from the catalog: (a) We removed bright sources ($\sim 1\%$) having $F(4.5\ \mu\text{m}) > 1,000\ \mu\text{Jy}$ (16.4 AB mag), about 3.5 mag brighter than an L^* galaxy at $z > 1$ (Wylezalek et al. 2014). (b) We also removed extended sources ($\sim 15\%$) where the IRAC Kron semimajor axis is larger than $3.''8$. At $z > 1$, a galaxy of this size has a diameter of about 60 kpc and we do not expect it to be more extended. The size cut also removes IRAC double sources that have not properly been deblended. (c) Finally, we removed all IRAC sources with a double or multiple PSO counterpart, to avoid color mismatch. We do not expect that this source removal creates galaxy overdensities.

2.5 | Foreground galactic extinction

The 3C sample is selected at a low radio frequency of 178 MHz (Spinrad et al. 1985). At this frequency, any foreground galactic extinction is negligible. Therefore, the 3C sources are found also at low galactic latitude, where foreground galactic extinction may become relevant at optical wavelengths. Table 3 lists the galactic coordinates as well as

the foreground galactic extinction in those three bands used for the galaxy overdensity search (*i*, IRAC1 and IRAC2).

Among the 64 sources, 6 sources lie close ($\lesssim 15^\circ$) to the galactic plane. These are 3C 119, 3C 368, 3C 418, 3C 454.1, 3C 469.1, and 4C 13.66. While their foreground galactic extinction is negligible in the IRAC bands, in the *i* band it is substantial with values in the range $0.25 < A_i < 1.8$. For most of the remaining 3C sources, the *i*-band foreground galactic extinction is small with respect to the *i* – [4.5] color uncertainties.

For the rest of the paper, in particular for the galaxy overdensity search, *all sources are corrected for foreground galactic extinction* using the values of Table 3. If a source is actually a star in the Milky Way, then its extinction may be lower so that the correction makes it too blue, but a star shall be removed anyway by the color cuts applied.

3 | SED EXAMPLES

Figure 4 depicts the SEDs of eight typical galaxies in the field of the quasar 3C 002 along with three galaxy SED templates. The three templates were chosen to embrace the range of candidate cluster member galaxies: NGC 6946 is a relatively blue SF spiral galaxy with moderate FIR luminosity ($L_{\text{FIR}} < 10^{11} L_\odot$); Arp 220 is an archetypal ultraluminous infrared galaxy (ULIRG); and NGC 221 is an old elliptical with marginal post-SF signatures. The template SEDs were taken from the NASA Extragalactic Database (NED).¹¹

The important features of each Figure 4 example, respectively, are as follows:

- Bright, about a factor of 5 above the IRAC completeness limits ($36\ \mu\text{Jy}$). The Pan-STARRS *-Spitzer* color is $i - [4.5] \ll 0$ AB mag. This source is a foreground elliptical at photometric redshift $z_p = 0.57$.
- Pan-STARRS *i* similarly bright as *Spitzer*, $i - [4.5] \sim 0$. This source is a foreground elliptical at $z_p = 0.6$.
- Pan-STARRS slightly fainter than *Spitzer*, Pan-STARRS SED very red, only detected in the *r*, *i*, and *z* bands, $i - [4.5] \sim 0$. A foreground elliptical at $z_p = 0.7$ fits best.
- Pan-STARRS much fainter than *Spitzer*, only detected in the *r* and *i* bands, $i - [4.5] \sim 2$. The SED may belong to an SF galaxy type between the NGC 6946 and Arp 220 templates at $z = 1.037$ of 3C 002.
- Not detected in Pan-STARRS; detected in only two IRAC bands. $[3.6] - [4.5] \sim -0.09$. Each template fits well at the redshift of 3C 002, but the non-detection at *i* may reject a blue SF galaxy at $z = 1.037$.
- Not detected in Pan-STARRS; detected in only two IRAC bands. $[3.6] - [4.5] \sim 0.44$. Potentially a background ($z > 3$) galaxy with intrinsically red color.

¹¹ <http://ned.ipac.caltech.edu/>

TABLE 3 Galactic coordinates of the 3C sample and foreground galactic extinction at the i band and IRAC1 and IRAC2 (in magnitudes) taken from NED, based on Schlafly & Finkbeiner (2011)

Name	Longitude	Latitude	i	IRAC1	IRAC2	Name	Longitude	Latitude	i	IRAC1	IRAC2
3C 002	99.2804	−60.8588	0.078	0.008	0.007	3C 250	212.3735	66.9100	0.028	0.003	0.002
3C 009	112.0466	−46.5331	0.089	0.009	0.008	3C 252	184.8085	67.1171	0.035	0.004	0.003
3C 013	119.3154	−23.3473	0.086	0.009	0.008	3C 255	263.0142	52.5427	0.092	0.010	0.008
3C 014	117.8728	−44.0881	0.112	0.012	0.010	3C 256	218.0286	69.2001	0.029	0.003	0.003
3C 036	127.7840	−17.0153	0.110	0.012	0.010	3C 257	254.8015	59.8493	0.063	0.007	0.006
3C 043	134.2174	−38.3866	0.152	0.016	0.013	3C 266	147.6420	64.0886	0.031	0.003	0.003
3C 065	141.4979	−19.5069	0.084	0.009	0.007	3C 267	254.8051	69.6831	0.058	0.006	0.005
3C 068.1	145.6014	−23.9886	0.116	0.012	0.010	3C 268.4	147.4838	71.4045	0.024	0.002	0.002
3C 068.2	147.3258	−26.3775	0.230	0.024	0.020	3C 270.1	166.3069	80.6393	0.021	0.002	0.002
3C 119	160.9652	−4.3423	0.952	0.100	0.083	3C 280.1	115.2599	76.8402	0.028	0.003	0.002
3C 124	195.5094	−27.7441	0.206	0.022	0.018	3C 287	22.4661	80.9884	0.019	0.002	0.002
3C 173	178.9788	18.2911	0.177	0.019	0.015	3C 294	61.1329	72.3714	0.024	0.003	0.002
3C 181	203.7542	14.6299	0.107	0.011	0.009	3C 297	339.9002	52.5772	0.091	0.010	0.008
3C 186	181.7870	26.1410	0.085	0.009	0.007	3C 298	352.1592	60.6666	0.050	0.005	0.004
3C 190	207.6235	21.8410	0.052	0.006	0.005	3C 300.1	346.1491	53.1231	0.084	0.009	0.007
3C 191	211.8721	20.9011	0.038	0.004	0.003	3C 305.1	114.9214	38.3324	0.050	0.005	0.004
3C 194	177.8578	31.9170	0.083	0.009	0.007	3C 318	29.6412	55.4156	0.107	0.011	0.009
3C 204	150.3443	35.5122	0.134	0.014	0.012	3C 322	88.5228	49.1338	0.023	0.002	0.002
3C 205	159.2604	36.8964	0.133	0.014	0.012	3C 324	34.9362	49.1595	0.079	0.008	0.007
3C 208	213.6616	33.1581	0.057	0.006	0.005	3C 325	96.2666	44.0857	0.023	0.002	0.002
3C 208.1	213.5991	33.5803	0.051	0.005	0.004	3C 326.1	33.6858	47.3295	0.086	0.009	0.007
3C 210	197.7630	38.7775	0.052	0.005	0.005	3C 356	77.9218	34.2051	0.054	0.006	0.005
3C 212	213.9971	34.5042	0.069	0.007	0.006	3C 368	37.7076	15.2246	0.250	0.026	0.022
3C 220.2	188.1127	46.7802	0.026	0.003	0.002	3C 418	88.8081	6.0405	1.784	0.187	0.155
3C 222	230.1417	38.3249	0.077	0.008	0.007	3C 432	67.9354	−22.8248	0.152	0.016	0.013
3C 225	219.8665	44.0246	0.092	0.010	0.008	3C 437	70.8753	−28.3921	0.151	0.016	0.013
3C 230	237.5733	39.0949	0.128	0.013	0.011	3C 454.0	87.3528	−35.6483	0.098	0.010	0.009
3C 238	234.0453	46.6644	0.037	0.004	0.003	3C 454.1	113.5670	10.8496	0.689	0.072	0.060
3C 239	170.4717	53.1961	0.015	0.002	0.001	3C 469.1	120.3877	17.3280	0.383	0.040	0.033
3C 241	213.2053	55.7394	0.045	0.005	0.004	3C 470	113.0052	−17.7716	0.181	0.019	0.016
3C 245	233.1245	56.3004	0.042	0.004	0.004	4C 13.66	40.0101	17.1849	0.295	0.031	0.026
3C 249	255.6952	51.2821	0.071	0.007	0.006	4C 16.49	39.3069	24.0067	0.125	0.013	0.011

Note. NED = NASA Extragalactic Database.

- g. Not detected in Pan-STARRS, but detected in three IRAC bands, $[3.6] - [4.5] \sim 0.3$, and in MIPS. Best fitted by a background ULIRG at $z_p = 1.5$. This is consistent with the detection on *Herschel* PACS and SPIRE maps (Westhues et al. in prep.). The Pan-STARRS non-detection rejects a blue SF galaxy at $z \sim 1.0$.
- h. The quasar 3C 002, detected in all bands with a power-law-rising infrared SED typical for type-1 AGN. $[3.6] - [4.5] \sim 0.3$, $i - [4.5] \sim 2$.

The SED examples demonstrate that the combination of Pan-STARRS and *Spitzer* constrains the redshifts of galaxies, both for Pan-STARRS detections and non-detections.

4 | COLOR CUTS

To make the search for candidate cluster member galaxies in the high- z 3C environments more sensitive, color cuts have

to be defined. Ideally, such cuts should remove as many foreground stars and galaxies as possible but none or as few as possible of the candidate cluster member galaxies. In practice, for data with uncertainties in the color, a compromise has to be chosen. Figure 5 shows the color as a function of redshift for the three templates introduced in the previous section. We here consider two colors: (a) the IRAC1/2 color $[3.6] - [4.5]$, and (b) the Pan-STARRS–IRAC color $i - [4.5]$. The pure IRAC color $[3.6] - [4.5]$ has successfully been applied to other datasets, for example, Wylezalek et al. (2013). The combination of IRAC and optical colors has also been applied in the past on other datasets to remove foreground sources and to identify candidate high- z galaxies and clusters, for example, by Eisenhardt et al. (2004, 2008) and Falder et al. (2011) with optical data from the NOAO and INT, respectively.

IRAC1/2: For $z \lesssim 1$, the three templates (with added uncertainties) populate the color range $-0.4 < [3.6] - [4.5] < 0.1$.

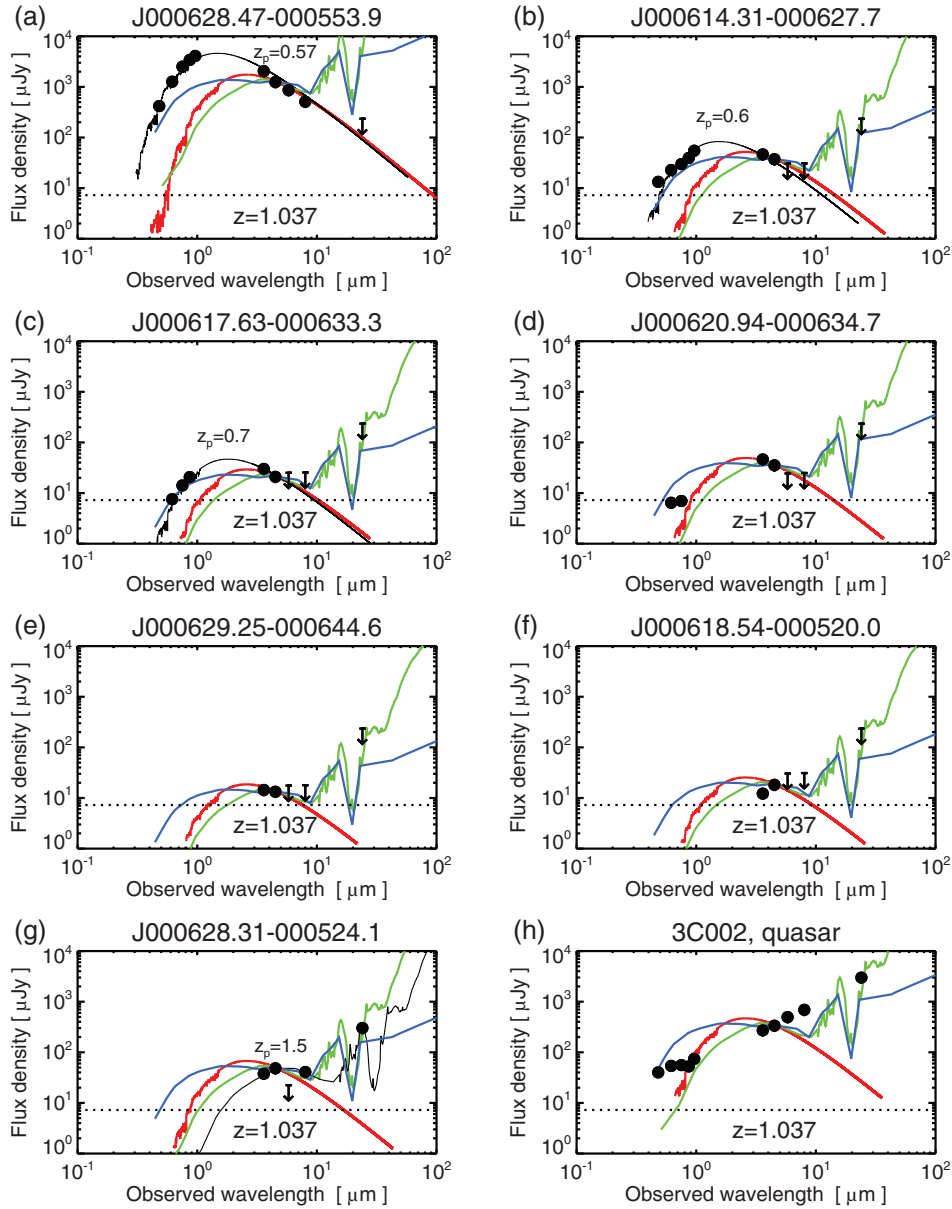


FIGURE 4 Eight example SEDs of galaxies in the field of the quasar 3C 002. The SEDs shown are typical for the entire sample. Black dots denote detections, black arrows denote the 3σ upper limits, and error bars are smaller than the symbol size. The dotted horizontal line marks the Pan-STARRS i -band detection limit (7.2 μJy). The first four examples (a)–(d) are detected with both *Spitzer* and Pan-STARRS and the next three examples (e)–(g) only with *Spitzer*. The last example (h) shows the quasar itself with a power-law SED, so that none of the galaxy template SEDs fits. The three colored solid lines illustrate galaxy templates shifted to the redshift $z = 1.037$ of 3C 002: red = elliptical (NGC 221), green = ultraluminous infrared galaxy (ULIRG, Arp 220), blue = star-forming spiral galaxy (NGC 6946). For panels (a), (b), and (c), the black line shows the elliptical template at the best fitted photometric redshift z_p . For panel (g), a background ULIRG at $z_p = 1.5$ fits the best

At $z \gtrsim 1$, $[3.6] - [4.5] > -0.1$ selects blue SF galaxies and ULIRGs and presumably any SF galaxy. It appears most efficient to exclude foreground ULIRGs at $0.1 < z < 1$ and SF at $0.1 < z < 0.5$. For comparison, based on synthetic galaxy models by Bruzual & Charlot (2003), Wylezalek et al. (2013, see their fig. 3) used this same color cut to select essentially all types of galaxies at $z \gtrsim 1.3$. However, this color cut excludes also ellipticals at $z < 1.5$, that is, the redshift of most of the 3C sources. Therefore, we will here use the color cut $[3.6] - [4.5] > -0.3$, which excludes many but not all $z < 1$ galaxies. It also excludes stars all having $[3.6] - [4.5] \sim -0.5$ (~ 0 Vega mag).

PSO-IRAC: The color $i - [4.5]$ shows a steep redshift dependence for elliptical and red SF galaxies (ULIRGs), rising between $z = 1$ and $z = 2.5$ from $i - [4.5] \sim 3$ to $i - [4.5] \sim 6$. For blue SF galaxies, the color rises more slowly from $i - [4.5] \sim 0.5$ to $i - [4.5] \sim 2.5$. To exclude $z < 1$ foreground galaxies, a color cut $i - [4.5] > 2$ appears efficient, but it will also exclude blue SF galaxies at $1 < z < 2$. Therefore, we will here use the softer color cut $i - [4.5] > 0.5$, which again should be reliable at the expense of letting through some $z < 1$ galaxies. This cut also excludes most stars ($i - [4.5] \sim 0.5$ AB mag corresponds to $R_J - [4.5] \sim 3.5$ Vega mag).

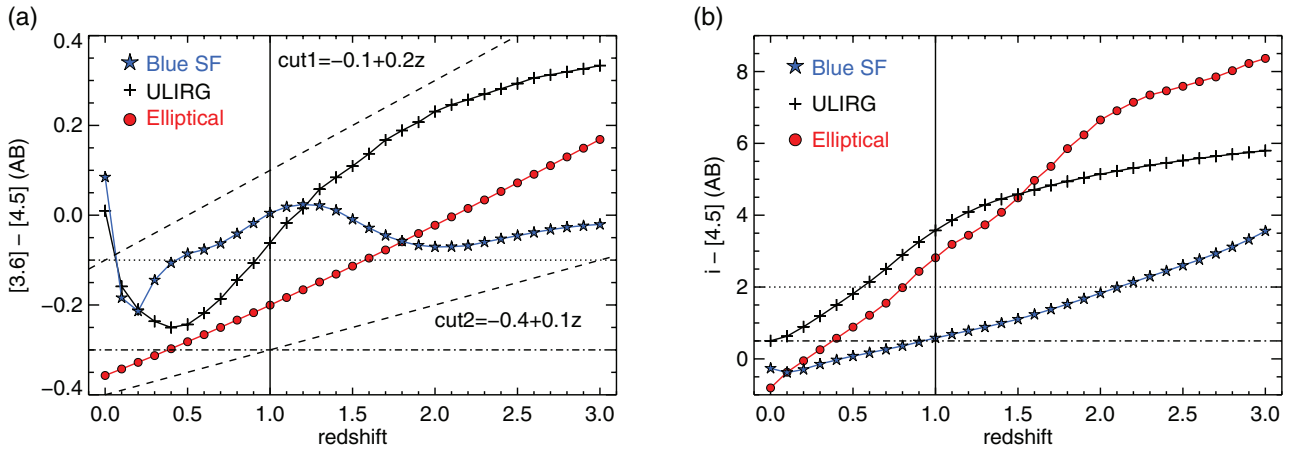


FIGURE 5 Color $[3.6] - [4.5]$ (left) and $i - [4.5]$ (right) versus redshift for three templates: elliptical (NGC 221), ultraluminous infrared galaxy (ULIRG, Arp 220), blue star-forming spiral galaxy (Blue SF, NGC 6946). The black dotted, dash-dotted, and solid lines mark color and redshift cuts discussed in Section 4. The long-dashed slopes in panel (a) embrace a redshift-dependent color range between cut1 and cut2

The main difference between the IRAC1/2 and PSO–IRAC color cuts is that the IRAC1/2 color requires high photometric accuracy while the range of the PSO–IRAC colors is so large that even a color uncertainty of 0.3 mag plays a minor role. Also, at $1 < z < 1.4$ the galaxy types close to the color cuts differ, being passive ellipticals for the IRAC cut but blue SF galaxies for the PSO–IRAC cut.

To further justify the choice of the color cuts, we consider color–color diagrams of our data, taking into account also the i -band upper limits. Figure 6 shows an example representative for the entire sample. The striking features of the color–color diagrams are as follows:

1. The removal of foreground stars and galaxies is essential to reveal candidate cluster member galaxies. The foreground sources are bluer than both the IRAC1/2 and the PSO–IRAC color cuts.
2. Each of the color cuts removes about 70% of the i -band detections. A stricter IRAC color cut $[3.6] - [4.5] > -0.1$ or a stricter PSO–IRAC color cut $i - [4.5] > 2$ would remove nearly all i -band detections. However, the i -band non-detections remain potential cluster member galaxies because of the lower limit nature of their color.
3. Both color cuts $[3.6] - [4.5] > -0.3$ and $i - [4.5] > 0.5$ select also high- z AGN, as indicated by the 3C source itself.
4. For about half of our sources, the uncertainty of the IRAC1/2 color exceeds 0.1 mag. This is large relative to the IRAC color range. The relatively large uncertainty of the IRAC1/2 color makes it likely that a stricter IRAC1/2 color cut will reject also candidate cluster member galaxies. On the other hand, for all sources, the uncertainty of the PSO–IRAC color is small enough (< 0.3 mag) to be negligible at the PSO–IRAC color range of several mag.
5. On average, only about 40% of the sources have an i -band detection and hence a measured PSO–IRAC color; the remaining 60% of the sources with i -band upper limits have only a lower limit for PSO–IRAC color.

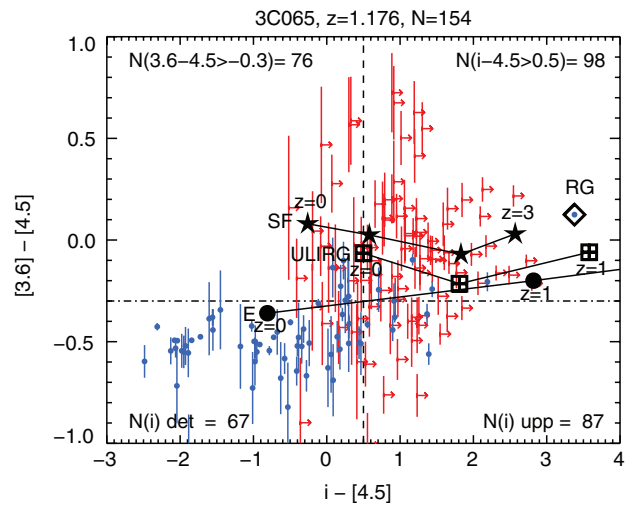


FIGURE 6 Color-color diagram $[3.6] - [4.5]$ versus $i - [4.5]$ of the 3C 065 field typical of the entire sample. Only sources with $F(4.5) > 4 \mu\text{Jy}$ and located within $120''$ angular separation from the 3C source are plotted. Blue dots and red arrows with vertical error bars distinguish between i -band detected and undetected sources, respectively. The lower limits in $i - [4.5]$ assume $i = 21.7$ AB mag (Table 2). The redshift-dependent positions of the three templates (SF, ULIRG and Elliptical) are shown, as well as the position of the 3C AGN itself (diamond, RG). Note that stars lie around $[3.6] - [4.5] = -0.5$ (Vega color ~ 0). The vertical dashed and horizontal dashed-dotted lines mark the adopted color cuts. The number of sources is given for the i -band detections, non-detections, and for both cuts

6. On average, the IRAC1/2 and PSO–IRAC color cuts reject 45% and 30% of the sources, respectively.

We have tested several color cuts on the present 3C data, that is, including redshift-dependent and redshift-independent ones, using colors based on other Pan-STARRS filters and a criterion accepting only the i -band upper limits as candidate cluster member galaxies. These tests led us to the redshift-independent color cuts either $[3.6] - [4.5] > -0.3$ or $i - [4.5] > 0.5$ plus all i -band non-detections. For the present purpose, sources satisfying either of these cuts are considered high- z candidate galaxies.

5 | GALAXY OVERDENSITIES

5.1 | Radial surface density profiles

For each 3C source¹² we determined the radial surface density of galaxies satisfying the color cuts of Section 4. These galaxies are considered candidate cluster members. We applied two methods to identify the candidate cluster member galaxies:

1. The IRAC color selection $[3.6] - [4.5] > -0.3$ AB mag.
2. The PSO-IRAC criterion introduced here:
 $i - [4.5] > 0.5$ AB mag plus all i -band non-detections.

For both methods we applied a flux cut requiring $F4.5 > 4 \mu\text{Jy}$ (22.4 AB mag). For comparison, from the clustering analysis of the CARLA sample Wylezalek et al. (2014) found that the $4.5 \mu\text{m}$ magnitude of an L^* galaxy in the redshift range $1.3 < z < 3.1$ is about 20 AB mag. Figure 7 depicts the radial surface density profiles of candidate cluster member galaxies for three 3C fields with a clear central overdensity.

For either selection criterion, the radial surface density of candidate cluster member galaxies varies from field to field. For each 3C field we determined the central radial surface density (D_{cent}) within $30''$ and the mean surrounding density (D_{surr}) between $50''$ and $120''$ and the uncertainty of the mean (U_{surr}).¹³ Using $\text{Exc} = D_{\text{cent}} - D_{\text{surr}}$, we define overdensity as the excess (Exc) of the central radial density above the mean surrounding density. We consider the overdensity as significant if Exc lies above the mean surrounding density by 3 times the uncertainty, that is if $\text{Exc} > D_{\text{cent}} - (D_{\text{surr}} + 3 \times U_{\text{surr}})$. The numbers of candidates in each radial bin are listed for both color selection methods in Table 4. Table 5 list the central and average surrounding surface densities.

About 50% of the 3C sources show an overdensity of candidate cluster member galaxies within the central $30''$ (and 20% of them even within 30 – $50''$); the remaining $\sim 50\%$ do not. While the examples of Figure 7 exhibit a clear central galaxy overdensity, Figure 8 shows examples with less pronounced or no overdensity. Inspection of the IRAC maps confirms that in those cases with no overdensity, there are, in fact, very few sources near the radio source. The surrounding density varies considerably between the 3C fields, and within a field (outside of the central area) the distribution of candidate cluster member galaxies is not homogeneous (“cosmic variance”). Despite the variations, both color selection methods yield remarkably consistent overdensity results: if for a given 3C

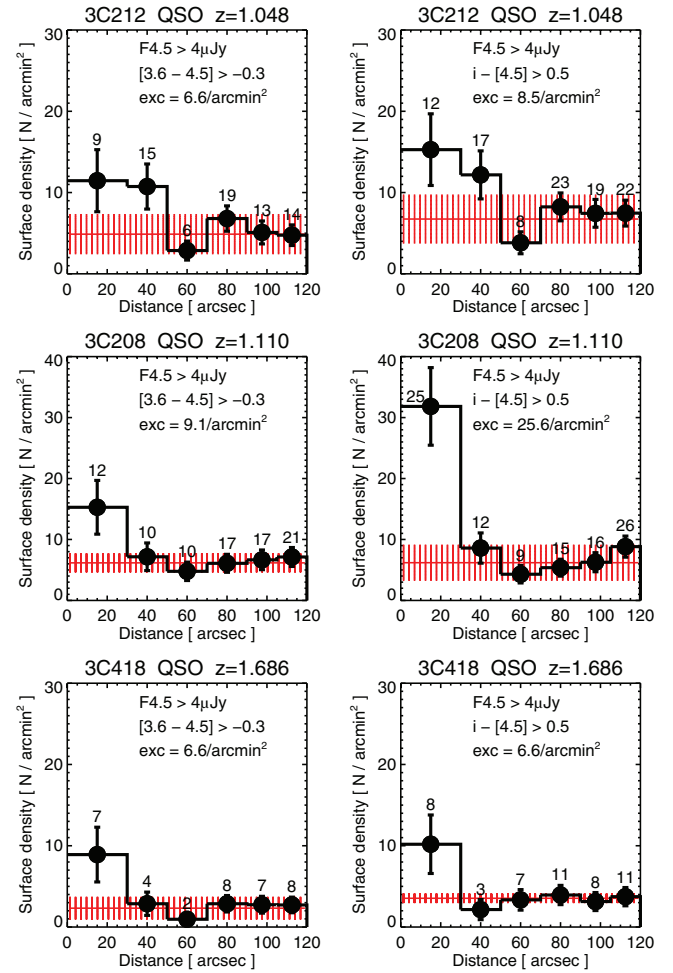


FIGURE 7 Radial surface density of candidate cluster member galaxies for three 3C fields with a clear central overdensity. The candidate cluster member galaxies were selected with (a) the IRAC color cut $[3.6] - [4.5] > -0.3$ AB mag (left column) or (b) the Pan-STARRS-IRAC criterion (right column). The bin radii are 30, 50, 70, 90, 105, and $120''$. The first ($30''$) corresponds to about 250 kpc projected separation for all redshifts of this work. Numbers show the number of candidates in each radial bin. Error bars show Poisson uncertainty in each bin. The red shaded areas mark the $\pm 3\sigma$ range around the mean surrounding density (red solid line), determined from the four outermost annuli at 50 – $120''$. The excess density as labeled gives the density inside $30''$ above the mean surrounding density. The 3C source is not counted in the radial density plots. The examples are typical for those 3Cs with a clear central overdensity

field one method finds a central overdensity, then mostly the other method does as well (Table 5).

5.2 | Statistics of the overdensities

Figure 9 shows the distribution of the central $30''$ overdensities (i.e., positive and negative excess) over the 50 – $120''$ surrounding as measured by both the IRAC1/2 and the PSO-IRAC color cuts for the 61 3C fields used. Both color cuts yield, on average, an overdensity with values for average and standard deviation of 2.2 ± 3.5 (IRAC1/2) and 4.4 ± 4.9 (PSO-IRAC). The uncertainties of the mean ($\sigma/\sqrt{61}$) are 0.45 and 0.63, respectively, and show that the means are $> 5\sigma$

¹²Three 3C sources are excluded from the analysis here: 3C 239 has a poor S/N on the IRAC $4.5 \mu\text{m}$ map, and both 3C 294 and 3C 470 are contaminated by a bright nearby star preventing the detection of candidate cluster member galaxies out to $15''$ radius. Furthermore, 3C 294 lies less than $2'$ from the IRAC map border, preventing the proper determination of the surrounding density.

¹³We did not use the IRAC off fields to determine the surrounding because these fields were observed in two IRAC bands only hence have brighter completeness and detection limits than the central field observed in four IRAC bands.

TABLE 4 Number of candidate cluster member galaxies per radial bin for the color selections: IRAC1/2 [3.6]–[4.5] > −0.3 (columns N1–N6), PSO–IRAC (columns M1–M6), strong IRAC1/2 [3.6]–[4.5] > −0.1 (columns K1–K6)

Name	N1	N2	N3	N4	N5	N6	M1	M2	M3	M4	M5	M6	K1	K2	K3	K4	K5	K6
3C 002	9	7	14	15	16	14	12	11	17	19	21	18	4	5	11	10	12	8
3C 009	11	18	26	19	34	27	12	22	32	24	39	36	9	14	23	16	26	20
3C 013	8	6	11	23	18	13	9	8	11	30	21	19	5	3	7	12	8	6
3C 014	4	11	11	12	11	14	4	14	22	17	21	16	3	9	9	6	9	9
3C 036	8	12	13	21	14	17	9	12	13	25	24	22	5	7	8	11	5	10
3C 043	8	6	6	6	11	14	8	5	9	13	12	20	6	6	5	4	9	13
3C 065	6	9	12	15	11	22	11	13	18	20	13	24	5	5	8	9	4	13
3C 068.1	4	19	12	15	16	19	6	23	20	22	21	27	1	11	4	7	6	12
3C 068.2	7	6	9	11	13	15	13	9	17	19	24	26	5	1	7	5	7	9
3C 119	5	11	10	12	15	12	9	11	14	21	25	15	2	6	6	4	7	4
3C 124	11	5	19	17	23	22	15	12	19	26	27	30	3	4	13	11	12	13
3C 173	2	7	12	15	13	20	6	11	14	22	14	22	2	3	7	8	9	10
3C 181	8	9	12	16	22	11	9	12	20	22	27	18	6	5	8	9	11	5
3C 186	3	10	8	9	9	13	5	14	12	11	11	16	2	6	4	6	8	5
3C 190	7	3	21	18	17	20	10	7	26	23	22	24	4	1	14	12	13	10
3C 191	6	5	13	13	17	20	9	7	12	16	22	21	4	5	7	5	12	13
3C 194	4	11	15	25	21	22	9	12	16	25	24	25	2	7	7	14	12	14
3C 204	11	12	23	16	27	25	16	16	31	21	34	25	1	5	11	11	13	14
3C 205	5	11	14	13	15	18	10	16	19	22	21	17	4	7	9	12	6	11
3C 208.1	7	14	10	29	15	24	9	14	18	36	19	27	6	9	7	22	10	16
3C 208	12	10	10	17	17	21	25	12	10	15	17	26	7	5	5	11	11	15
3C 210	9	12	28	36	27	27	26	16	41	46	31	41	2	5	13	20	17	13
3C 212	9	15	7	19	13	14	13	17	9	23	19	22	3	10	5	13	8	8
3C 220.2	8	13	15	14	13	18	11	14	17	14	14	25	5	7	11	11	9	15
3C 222	7	4	5	17	12	15	12	6	8	22	15	15	5	4	2	13	7	12
3C 225A	3	7	5	25	22	14	3	7	6	27	24	18	2	3	4	12	10	11
3C 230	5	11	7	12	10	14	7	11	9	17	19	18	1	6	4	6	5	10
3C 238	9	9	5	13	15	12	11	11	5	19	17	19	4	4	2	6	11	9
3C 241	11	13	13	25	18	23	12	14	15	32	21	24	8	8	10	14	10	15
3C 245	8	11	18	25	21	19	13	11	24	32	28	33	3	7	12	19	13	11
3C 249	9	4	5	16	15	16	10	6	10	22	19	15	5	3	3	12	7	12
3C 250	9	8	13	15	7	20	11	10	15	17	13	22	4	7	6	10	5	13
3C 252	2	12	14	18	16	26	8	15	19	21	20	32	0	7	10	8	13	20
3C 255	5	14	14	19	23	34	11	19	15	27	26	43	2	10	8	10	16	26
3C 256	5	21	13	25	28	29	10	24	21	35	37	46	2	13	7	13	17	12
3C 257	4	1	9	12	15	12	5	6	9	15	16	20	3	1	7	8	10	9
3C 266	2	6	15	13	18	12	4	8	17	21	24	26	1	4	12	8	10	8
3C 267	10	14	20	31	24	17	14	15	25	37	29	25	5	9	14	26	18	14
3C 268.4	4	9	9	10	11	15	7	9	16	11	19	25	2	6	6	7	3	9
3C 270.1	7	16	17	17	15	18	8	20	21	26	20	29	4	13	9	11	10	13
3C 280.1	8	13	20	19	17	15	9	17	21	21	21	20	7	8	14	14	12	8
3C 287	8	11	14	15	24	24	9	13	18	25	28	31	4	8	9	14	15	13
3C 297	4	11	14	14	13	24	4	12	15	18	16	30	3	8	13	12	10	14
3C 298	3	6	16	17	19	14	5	10	17	19	27	16	3	4	7	6	12	7
3C 300.1	6	10	20	20	23	33	14	19	26	22	25	39	2	5	10	10	13	26
3C 305.1	5	7	17	14	16	28	6	12	24	19	21	35	2	4	11	13	8	15
3C 318	6	5	16	18	16	17	5	9	18	21	17	20	5	3	14	14	13	10
3C 322	10	21	16	15	11	20	12	23	19	19	17	23	7	13	11	8	8	15
3C 324	12	13	19	32	32	33	17	18	22	34	42	38	3	5	12	24	18	18
3C 325	10	6	17	22	18	19	14	12	22	38	29	26	2	5	7	11	11	13
3C 326.1	11	8	24	24	16	18	13	11	26	31	16	21	8	4	19	13	10	10
3C 356	3	8	18	9	15	25	7	6	21	10	16	22	1	3	12	3	13	16
3C 368	4	8	3	14	3	20	4	8	7	12	7	18	4	2	1	6	1	13

TABLE 4 Continued

Name	N1	N2	N3	N4	N5	N6	M1	M2	M3	M4	M5	M6	K1	K2	K3	K4	K5	K6
3C 418	10	5	3	8	9	10	14	9	10	22	16	22	4	0	0	3	2	4
3C 432	5	9	10	16	13	13	5	9	11	21	18	15	1	5	6	6	5	11
3C 437	4	12	11	13	13	16	5	15	15	14	17	20	3	10	9	9	7	9
3C 454.1	10	6	9	11	18	9	9	8	12	14	21	12	3	4	6	9	10	4
3C 454	5	4	12	11	13	10	6	9	13	15	18	17	3	1	8	9	11	8
3C 469.1	7	9	20	23	20	27	16	17	21	41	25	36	3	6	14	15	13	18
4C 13.66	8	5	13	18	22	8	7	8	19	23	19	20	4	4	7	8	7	2
4C 16.49	4	12	12	30	28	30	13	13	17	31	31	39	3	5	7	12	13	19

Note. The six bin radii are 30'', 50'', 70'', 90'', 105'', and 120''. The six bin areas are 0.785, 1.396, 2.094, 2.793, 2.553, and 2.945 arcmin².

above zero. However, the distributions are broad and include zero, indicating that some 3C fields have an overdensity and others do not, consistent with the findings shown in Figures 7 and 8.

To further check the statistical significance of the mean central overdensities, we consider the cumulative surface density distributions as shown in Figure 10. For both color cuts, the cumulative distribution of the central bin diverges continuously from the cumulative average surrounding. For both color cuts, the two-sided KS test gives an extremely low probability that the measured central and surrounding distributions are drawn from the same intrinsic populations. The probabilities of finding such large deviations are $10^{-4.7}$ (IRAC) and $10^{-6.8}$ (PSO-IRAC). This provides clear statistical evidence for the average central overdensities. As already indicated by Figure 9, the PSO-IRAC selection method reaches a higher significance for overdensities than the IRAC1/2 selection.

The surrounding counts shown in Figure 10 ought to be linearly rising with increasing X , which is the index of the 3C sources sorted by redshift. The surrounding galaxies do not care whether there is a 3C source nearby or what its redshift is.¹⁴ In fact, the surrounding counts of the PSO-IRAC selection follow a linear relation, while the cumulative central counts of the PSO-IRAC selection show a clear deviation from the linear fit, that is, a trend of a decline of overdensities with increasing redshift. On the other hand, both surrounding and central counts of the IRAC selection show a good linear relation with X , and any deviation is marginal.

To demonstrate the redshift trends more clearly, Figure 11 shows the cumulative overdensities, that is, the central 30'' surface densities after subtraction of the mean surrounding surface densities. For the IRAC color selection, the cumulative overdensity linearly increases with increasing index of the 3C sources except for a small bump at $50 < X < 55$, that is, at $z \sim 1.7$. The overall linear increase does not indicate a significant redshift dependency except at $z \sim 1.7$, where the rest-frame 1.6 μ m SED bump shifts into the IRAC2 band,

both increasing the 4.5 μ m flux and making the IRAC1/2 color particularly red and thus the detection of $z \sim 1.7$ candidate cluster member galaxies most efficient, even in case of IRAC1/2 color errors. On the other hand, for the PSO-IRAC selection, the cumulative overdensity shows a change in slope, first being steep until $X = 35$, that is, $z \sim 1.4$, and then at $z > 1.4$ the increase becoming, on average, shallower until $X = 61$ ($z \sim 2.5$) but again with a small bump at $z \sim 1.7$. (This bump is possibly due to increased 4.5 μ m flux, as mentioned above.) Comparison with Figure 10 shows that the change of the cumulative overdensity is mainly caused by the central surface density rather than by the surrounding density. This argues for a z -dependent decline of the measured overdensities above $z \sim 1.4$; we discuss that further below.

5.3 | Discussion

Both IRAC1/2 and PSO-IRAC color criteria reveal, on average, a central overdensity of candidate cluster member galaxies around the high- z 3C sources in all redshift bins. This result is consistent with expectations from other high- z AGN samples. Notably, the overdensities are better revealed by the PSO-IRAC color selection, which selects about a factor 1.4 more candidate cluster member galaxies than the IRAC color; this is evident from the numbers listed below the histograms (Figures 7 and 8) and from the cumulative density distributions (Figure 10). Evidently, for our 3C data the IRAC color selection not only rejects more sources but also some candidate cluster member galaxies. On the other hand, the PSO-IRAC color selection rejects fewer sources but appears to keep more true candidate cluster member galaxies. To explain this, we suggest that, besides the influence of photometric color uncertainties mentioned above, also the type of rejected galaxies plays a role: in case of color errors, the IRAC1/2 color cut affects primarily elliptical galaxies (lying close to the color cut in Figure 5, left), while the PSO-IRAC color cut affects primarily blue SF galaxies (Figure 5, right). If cluster galaxies in our IRAC flux-limited sample are predominantly ellipticals, then PSO-IRAC color errors will have little effect on the PSO-IRAC selection, but IRAC color errors may have a large effect. Therefore, we suggest that most of the

¹⁴An exception may occur if strong cluster lensing plays a role, but this topic is beyond the scope of the current study.

TABLE 5 Central and average surrounding surface densities per square arcmin

Name	30"	50"	Surr	Err	OD	30"	50"	Surr	Err	OD	30"	50"	Surr	Err	OD
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
3C 002	11.46	5.01	5.77	0.44	+	15.28	7.88	7.31	0.52	+	5.09	3.58	4.06	0.57	–
3C 009	14.01	12.89	10.43	1.50	–	15.28	15.76	12.76	1.60	–	11.46	10.03	8.42	1.28	–
3C 013	10.19	4.30	6.24	0.86	+	11.46	5.73	7.67	1.19	+	6.37	2.15	3.20	0.46	+
3C 014	5.09	7.88	4.65	0.23	–	5.09	10.03	7.44	1.05	–	3.82	6.45	3.26	0.45	–
3C 036	10.19	8.59	6.25	0.45	+	11.46	8.59	7.81	0.57	+	6.37	5.01	3.28	0.46	+
3C 043	10.19	4.30	3.52	0.61	+	10.19	3.58	4.99	0.63	+	7.64	4.30	2.94	0.65	+
3C 065	7.64	6.45	5.72	0.66	–	14.01	9.31	7.07	0.84	+	6.37	3.58	3.26	0.61	+
3C 068.1	5.09	13.61	5.96	0.25	–	7.64	16.47	8.51	0.50	–	1.27	7.88	2.71	0.47	–
3C 068.2	8.91	4.30	4.51	0.25	+	15.28	5.01	8.19	0.50	+	6.37	0.72	2.73	0.34	+
3C 119	6.37	7.88	4.47	0.52	+	11.46	6.45	5.68	1.06	+	2.55	4.30	2.10	0.41	–
3C 124	14.01	3.58	7.81	0.67	+	17.83	8.59	9.43	0.28	+	3.82	2.86	4.82	0.49	–
3C 173	2.55	4.30	5.66	0.41	–	7.64	7.88	6.70	0.44	–	2.55	2.15	3.28	0.14	–
3C 181	10.19	6.45	5.95	1.01	+	11.46	7.88	8.53	0.98	–	7.64	3.58	3.26	0.57	+
3C 186	3.82	7.16	3.54	0.19	–	6.37	10.03	4.85	0.43	+	2.55	4.30	2.22	0.32	–
3C 190	8.91	2.15	7.48	0.85	–	12.73	4.30	9.35	1.02	+	5.09	0.72	4.87	0.70	–
3C 191	7.64	3.58	6.08	0.49	+	11.46	5.01	6.77	0.73	+	5.09	3.58	3.56	0.66	–
3C 194	5.09	7.88	7.95	0.40	–	11.46	8.59	8.62	0.38	+	2.55	5.01	4.45	0.38	–
3C 204	14.01	7.88	8.86	1.22	+	20.37	11.46	10.94	1.85	+	1.27	3.58	4.76	0.29	–
3C 205	6.37	7.88	5.83	0.43	–	12.73	11.46	7.57	0.77	+	5.09	5.01	3.67	0.46	+
3C 208	15.28	7.16	6.16	0.51	+	31.83	8.59	6.19	0.97	+	8.91	3.58	3.93	0.57	+
3C 208.1	8.91	10.03	7.21	1.23	–	11.46	9.31	9.35	1.21	–	7.64	6.45	5.14	1.01	–
3C 210	11.46	8.59	11.59	1.03	–	33.10	11.46	15.22	1.57	+	2.55	3.58	6.11	0.60	–
3C 212	11.46	10.74	4.88	0.81	+	15.28	12.18	6.74	0.99	+	3.82	7.16	3.22	0.50	–
3C 220.2	10.19	8.59	5.84	0.51	+	14.01	9.31	6.78	0.89	+	6.37	5.01	4.45	0.43	+
3C 222	8.91	2.86	4.57	0.78	+	15.28	4.30	5.67	0.85	+	6.37	2.86	3.11	0.82	+
3C 225A	2.55	5.01	6.18	1.58	–	2.55	5.01	7.01	1.60	–	2.55	2.15	3.46	0.53	–
3C 230	5.09	7.88	4.08	0.30	+	7.64	7.88	5.90	0.65	–	1.27	4.30	2.35	0.35	–
3C 238	11.46	6.45	4.25	0.73	+	14.01	7.88	5.58	1.07	+	5.09	2.86	2.62	0.71	+
3C 241	14.01	9.31	7.51	0.58	+	15.28	10.03	8.75	0.94	+	10.19	5.73	4.70	0.27	+
3C 245	10.19	7.88	7.97	0.51	+	16.55	7.88	11.18	0.10	+	3.82	5.01	5.34	0.64	–
3C 249	11.46	2.86	4.86	0.83	+	12.73	4.30	6.21	0.74	+	6.37	2.15	3.14	0.66	+
3C 250	11.46	5.73	5.28	0.89	+	14.01	7.16	6.45	0.54	+	5.09	5.01	3.20	0.52	+
3C 252	2.55	8.59	7.06	0.60	–	10.19	10.74	8.82	0.76	–	0.00	5.01	4.88	0.80	–
3C 255	6.37	10.03	8.43	1.07	–	12.73	13.61	10.31	1.55	–	2.55	7.16	5.62	1.23	–
3C 256	6.37	15.04	8.99	1.02	–	12.73	17.19	13.17	1.16	–	2.55	9.31	4.68	0.71	–
3C 257	5.09	0.72	4.64	0.42	–	6.37	5.01	5.60	0.49	–	3.82	0.72	3.30	0.23	–
3C 266	2.55	4.30	5.74	0.80	–	5.09	5.73	8.20	0.64	–	1.27	2.86	3.81	0.69	–
3C 267	12.73	10.03	9.13	1.11	+	17.83	10.74	11.43	0.99	+	6.37	6.45	6.95	0.93	–
3C 268.4	5.09	6.45	4.32	0.31	–	8.91	6.45	6.88	1.01	–	2.55	4.30	2.40	0.42	–
3C 270.1	8.91	11.46	6.55	0.53	+	10.19	14.32	9.35	0.40	–	5.09	9.31	4.14	0.13	+
3C 280.1	10.19	9.31	7.03	0.93	+	10.19	12.18	8.23	0.64	+	8.91	5.73	4.78	0.81	+
3C 287	10.19	7.16	7.40	0.88	+	11.46	9.31	9.77	0.63	–	5.09	5.73	4.90	0.36	–
3C 297	5.09	7.88	6.23	0.75	–	5.09	8.59	7.40	0.93	–	3.82	5.73	4.79	0.50	–
3C 298	3.82	4.30	6.48	0.67	–	6.37	7.16	7.73	1.10	–	3.82	2.86	3.14	0.58	–
3C 300.1	7.64	6.45	9.01	0.84	–	17.83	12.89	10.66	1.12	+	2.55	3.58	5.57	1.13	–
3C 305.1	6.37	5.01	7.23	0.99	–	7.64	8.59	9.38	1.22	–	2.55	2.86	4.53	0.48	–
3C 318	7.64	3.58	6.53	0.40	–	5.09	6.45	7.30	0.44	–	6.37	2.15	5.05	0.67	–
3C 322	12.73	15.04	6.03	0.74	+	15.28	16.47	7.59	0.56	+	8.91	9.31	4.09	0.63	+
3C 324	15.28	9.31	11.07	0.73	+	21.65	12.89	13.01	1.25	+	3.82	3.58	6.87	0.64	–
3C 325	12.73	4.30	7.37	0.38	+	17.83	8.59	10.89	0.91	+	2.55	3.58	4.00	0.24	–
3C 326.1	14.01	5.73	8.01	1.30	+	16.55	7.88	8.84	1.48	+	10.19	2.86	5.26	1.30	+
3C 356	3.82	5.73	6.55	1.27	–	8.91	4.30	6.84	1.34	–	1.27	2.15	4.33	1.09	–

TABLE 5 Continued

Name	30"	50"	Surr	Err	OD	30"	50"	Surr	Err	OD	30"	50"	Surr	Err	OD
3C 368	5.09	5.73	3.60	1.38	–	5.09	5.73	3.58	0.95	–	5.09	1.43	1.86	0.94	+
3C 418	8.91	2.86	2.32	0.46	+	10.19	2.15	3.54	0.18	+	5.09	0.00	0.80	0.29	+
3C 432	6.37	6.45	5.00	0.28	+	6.37	6.45	6.14	0.56	–	1.27	3.58	2.68	0.40	–
3C 437	5.09	8.59	5.14	0.31	–	6.37	10.74	6.31	0.47	–	3.82	7.16	3.33	0.34	–
3C 454.1	11.46	4.30	4.49	0.77	+	10.19	5.01	5.11	0.79	+	3.82	2.86	2.84	0.54	–
3C 454	6.37	2.86	4.54	0.53	+	7.64	5.01	6.02	0.39	+	3.82	0.72	3.52	0.35	–
3C 469.1	8.91	6.45	8.70	0.40	–	20.37	11.46	11.75	1.04	+	3.82	4.30	5.82	0.36	–
4C 13.66	10.19	3.58	5.81	1.23	+	8.91	5.01	7.23	0.58	–	5.09	2.86	2.41	0.59	+
4C 16.49	5.09	8.59	9.19	1.32	–	16.55	9.31	10.97	1.02	+	3.82	3.58	4.80	0.66	–

Note. Columns 2–6 for the IRAC1/2 $[3.6] - [4.5] > -0.3$ cut; cols. 7–11 for the PSO–IRAC color selection; and cols. 12–16 for the strong IRAC1/2 $[3.6] - [4.5] > -0.1$ cut. Columns 2, 7, 12 in the central bin of 30" radius. Columns 3, 8, 13 in the 30–50" annulus. Columns Surr and Err give mean and error of the mean of the surrounding surface densities, calculated from the 50–120" annuli. Columns 6, 11, 12 indicate a significant central 30" overdensity above surrounding $+3\sigma$ (+), or not (–).

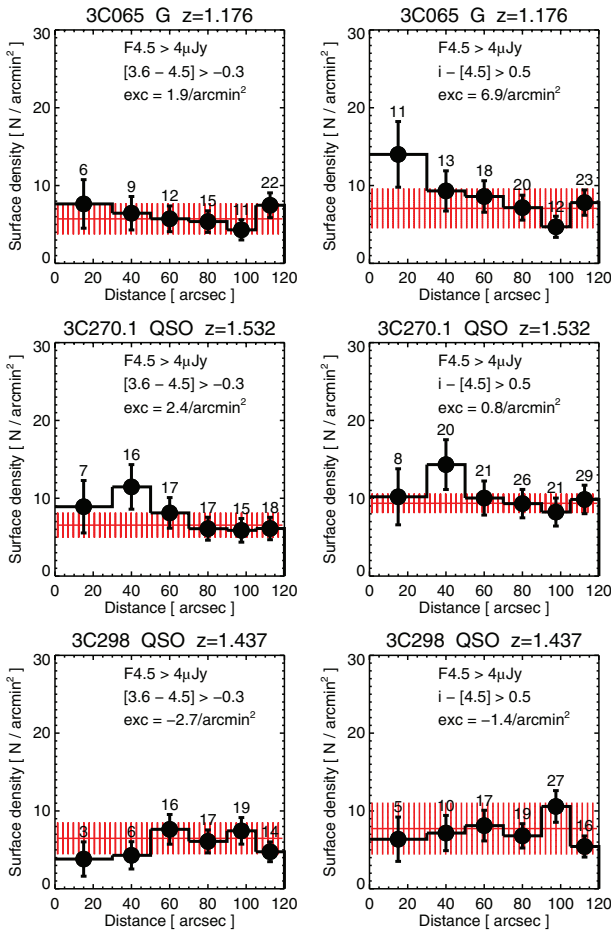


FIGURE 8 Same as Figure 7 but for 3C fields with less pronounced or no central overdensity

actual cluster member galaxies detected by IRAC are passive ellipticals rather than blue SF galaxies.

Further support for the passive nature of the cluster member galaxies comes from the following check: we repeated the overdensity analysis using a strong IRAC color cut $[3.6] - [4.5] > -0.1$, that is, 0.2 mag redder than for the “soft” IRAC color cut $[3.6] - [4.5] > -0.3$. The strong IRAC color cut should remove ellipticals at $z \lesssim 1.5$ (Figure 5, left). For

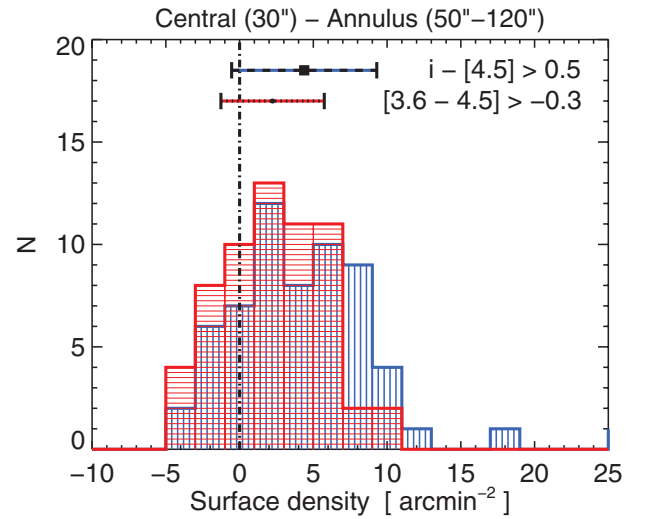


FIGURE 9 Distribution of the central overdensities, that is, central surface density minus surrounding surface density, for both color selections IRAC1/2 (red, dotted) and PSO–IRAC (blue, dashed). For both distributions the average with standard deviation are plotted above the histograms. The uncertainty of the mean is smaller than the size of the square. The vertical black dash-dotted line marks zero excess surface density

the strong IRAC color cut, in fact, the cumulative central and surrounding surface densities perfectly agree at $1 < z < 1.4$ (Figure 10). This is in contrast to the results for the soft IRAC color cut $[3.6] - [4.5] > -0.3$ used before. This strongly suggests that the cluster member galaxies at $1 < z < 1.6$ are passive ellipticals.

If most IRAC-detected cluster galaxies are in fact passive, this might also explain why two refinements of the IRAC1/2 color cut to select candidate cluster member galaxies failed to yield more significant overdensities. These refinements are, first, the combination of IRAC1/2 and PSO–IRAC color cuts and, second, a redshift-dependent IRAC1/2 color cut $(-0.4 + 0.1z < [3.6] - [4.5] < -0.1 + 0.2z)$ indicated in Figure 5. In both cases, the additional constraints may better reject foreground or surrounding galaxies but cannot recover the lost elliptical candidate cluster member galaxies.

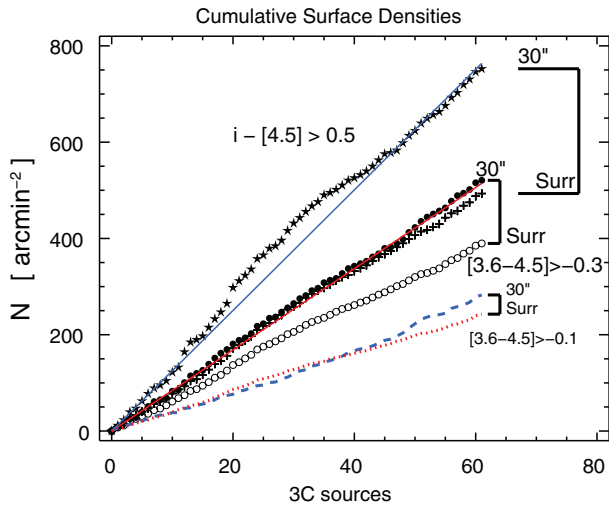


FIGURE 10 Cumulative surface densities of the central bin (30'' radius) and the mean surrounding for the IRAC color selection (filled and open circles, respectively) and the PSO-IRAC color selection (stars and crosses, respectively). The X-axis refers to the index of the 3C sources sorted by redshift, that is, $z \approx 1.0$ at $X = 1$, $z \approx 1.4$ at $X = 35$, $z \approx 1.6$ at $X = 45$, and $z \approx 2.5$ at $X = 61$. The blue and red solid lines show a linear fit through the PSO-IRAC central and surrounding distributions, respectively. For comparison, the blue dashed and red dotted lines with small labels show the results for a strong IRAC1/2 cut $[3.6]-[4.5] > -0.1$.

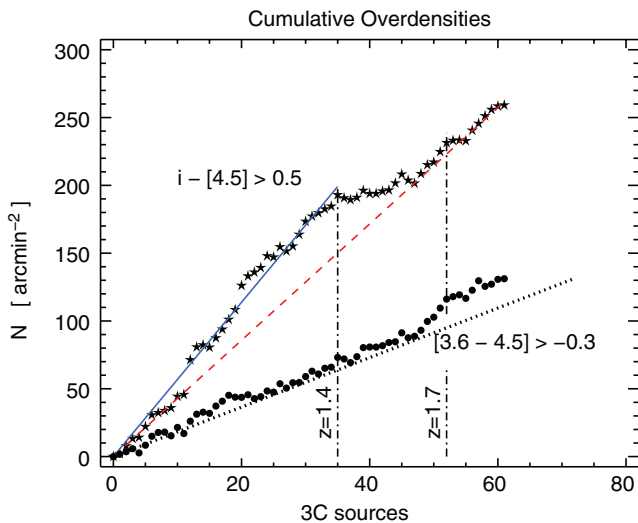


FIGURE 11 Cumulative overdensities for the IRAC color selection $[3.6]-[4.5] > -0.3$ (circles) and the PSO-IRAC color selection (stars). The overdensities are the central surface densities after subtraction of the mean surrounding (see Figure 10). The X-axis refers to the index of the 3C sources sorted by redshift. The vertical dash-dotted lines mark the X-position of 3C sources at $z = 1.4$ and $z = 1.7$. The dotted line shows the fit of the IRAC slope, whereby the range near $z = 1.7$ was excluded. The solid blue and dashed red lines embrace the range of the PSO-IRAC slopes.

Both the IRAC1/2 and PSO-IRAC color cuts reveal a central 30'' overdensity for about half of the 3C sources (33/61 for IRAC1/2 cut, 36/61 for PSO-IRAC cut, Table 5). An open issue is whether for the remaining 3C sources overdensity is absent or escaped detection by our methods. If there were two classes, with and without overdensity, one would expect that the overdensity distribution is bimodal, but this is not seen in

Figure 9. The failure to see a bimodal distribution could be due to the limited sensitivity of our methods and the low number statistics. Alternatively, an overdensity could be present in each 3C source but less concentrated (e.g., for proto-clusters), or there is a real spread in overdensities around the 3C sources as indicated by our visual inspection of the IRAC maps (see also the negative overdensity for 3C 298 in Figure 8).

Clues on the limited sensitivity of our methods may come from the individual case of 3C 270.1 at $z = 1.5$, where the PSO-IRAC color cut failed to reveal a central (30'') overdensity, the IRAC cut yields a marginal overdensity, and both cuts find an extended overdensity in the radial bin at 30'' and 50'' (Figure 8, Table 5). Both the elaborated IRAC environment study of 3C 270.1 with supplementary deep z - and y -band imaging (~ 26 AB mag) and photometric redshift determination from SED fitting of all sources in the field (Haas et al. 2009) and the IRAC1/2 counts-in-cells analysis of the 3C 270.1 field (Galametz et al. 2012) show an overdensity within 50'' and 60'' radius, respectively. This suggests that both the IRAC1/2 and PSO-IRAC color cuts are successful in revealing average overdensities but not sensitive enough to detect overdensities for each individual 3C source. Therefore, future investigations with improved methods and/or deeper data are needed.

For the PSO-IRAC selection of candidate cluster member galaxies, the cumulative central overdensity shows a redshift trend: the overdensity is largest at redshift $1.0 < z < 1.4$ and declines at $z > 1.4$ (Figure 11). Such a decline appears consistent with expectations from cosmic evolution models, for example, passive galaxy evolution, as discussed for the CARLA sample at $1.3 < z < 3.2$ by Wylezalek et al. (2014). For our 3C data, however, the redshift-dependent decline of the overdensity is not directly evident for the IRAC1/2 selection; the reason could be that, as mentioned above in case of color errors, the IRAC1/2 cut may reject elliptical cluster member galaxies at redshift $1.0 < z < 1.4$.

We examined the overdensities of the 27 quasars and 34 RGs separately (Table 1 lists the types Q and G). For quasars we find an overdensity with values for mean and uncertainty of the mean of 2.1 ± 0.6 (IRAC1/2) and 3.5 ± 0.7 (PSO-IRAC). For RGs, the corresponding values are 2.3 ± 0.7 (IRAC1/2) and 5.0 ± 1.0 (PSO-IRAC). Thus, for both selection criteria, the mean overdensities of quasars and RGs agree within the uncertainties, consistent with the unified model (Barthel 1989).

Our derivation of the central overdensities made the assumption that the 3C source is located in the center of a potential cluster or proto-cluster. While this assumption reveals the overdensities, visual inspection of the sky position of the candidate cluster members of the individual 3C sources indicates that, independent of redshift, in some cases the 3C source may be located at the cluster border. A future analysis of the individual 3C environments using density maps with Voronoi cells may provide further clues on the location of the 3C source within its cluster or proto-cluster.

6 | SUMMARY AND OUTLOOK

We explored the environment of the complete sample of 64 high-redshift 3C RGs and quasars as seen by the *Spitzer Space Telescope*, supplemented by Pan-STARRS (PSO).

IRAC color selection $[3.6]-[4.5] > -0.3$ AB mag and PSO-IRAC color selection $i - [4.5] > 0.5$ AB mag (plus all *i*-band non-detections) both reveal an average overdensity of galaxies within 250 kpc projected distance from $z > 1$ luminous radio sources. There is a clear field-to-field scatter in the overdensities of individual 3C environments; about half of the 3C sources show a significant (3σ) overdensity, and the other half do not. The origin of this difference has still to be explored.

The overdensities disappear at $1 < z < 1.4$ for a strong IRAC1/2 color selection $[3.6]-[4.5] > -0.1$, which removes passive elliptical galaxies at that redshift but not SF galaxies. Therefore we conclude that the cluster members are mainly passive elliptical galaxies.

The overdensities are more pronounced for the PSO-IRAC color selection than for the IRAC color selection. The IRAC color selection rejects about 40% more sources, but it appears to reject also candidate cluster member galaxies. While primarily elliptical galaxies lie close to the IRAC color cuts, the PSO-IRAC color cut primarily affects blue SF galaxies. The cuts are quite sensitive to IRAC color errors but relatively robust against PSO-IRAC color errors. We suggest that the combination of IRAC color errors and the prevalence of elliptical galaxies among the candidate cluster member galaxies explains why the IRAC color leads to lower overdensities than the PSO-IRAC color. Furthermore, the PSO-IRAC data indicate a decline of the average central overdensities with increasing redshift beyond $z \sim 1.4$, consistent with galaxy evolution models.

Future investigations may provide further clues on the diversity of the overdensities and the nature of the candidate cluster member galaxies. The *Herschel* far-infrared observations hold the key for dusty starburst galaxies in the high- z 3C environments (Westhues et al. in prep.). In addition, new *Hubble Space Telescope* images of a subsample of high- z 3Cs with about $2'$ FoV have been obtained (Hilbert et al. 2016). The *Spitzer*-PSO study here finds that the overdensities occur within about $30''$ radius around the 3C sources. Therefore the *HST* images might be large enough for a deep *HST/Spitzer* optical-infrared study of the overdensities (Ghaffari et al. in prep.). Also, the analysis of *Chandra* X-ray data, where available for the 3C sources, may reveal the extended hot X-ray gas characteristic of galaxy clusters (Wilkes et al. in prep.).

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