Passive galaxies as tracers of cluster environments at $z \lesssim 2$

V. Strazzullo, Emanuele Daddi, R. Gobat, B. Garilli, M. Mignoli, F. Valentino, M. Onodera, A. Renzini, Alessandro Cimatti, A. Finoguenov, et al.

To cite this version:

V. Strazzullo, Emanuele Daddi, R. Gobat, B. Garilli, M. Mignoli, et al.. Passive galaxies as tracers of cluster environments at $z \lesssim 2$. Astronomy and Astrophysics - A&A, 2015, 576, pp.L6. 10.1051/0004-6361/201425038. cea-01300539

HAL Id: cea-01300539
https://cea.hal.science/cea-01300539
Submitted on 11 Apr 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Passive galaxies as tracers of cluster environments at $z \sim 2$

V. Strazzullo$^{1,2}$, E. Daddi$^1$, R. Gobat$^1$, B. Garilli$^3$, M. Mignoli$^4$, F. Valentino$^1$, M. Onodera$^5$, A. Renzini$^6$, A. Cimatti$^7$, A. Finoguenov$^8$, N. Arimoto$^9$, M. Cappellari$^{10}$, C. M. Carollo$^5$, C. Feruglio$^{11}$, E. Le Floc’h$^1$, S. J. Lilly$^3$, D. Maccagni$^3$, H. J. McCracken$^{12}$, M. Moresco$^7$, L. Pozzetti$^4$, and G. Zamorani$^4$

1 Irfu/Service d’Astrophysique, CEA Saclay, Orme des Merisiers, 91191 Gif-sur-Yvette, France  
2 Department of Physics, Ludwig-Maximilians-Universität, Scheinerstr. 1, 81679 München, Germany  
e-mail: vstrazz@usz.lmu.de  
3 INAF–IASF, via Bassini 15, 20133 Milano, Italy  
4 INAF–Osservatorio Astronomico di Bologna, via Ranzani 1, 40127 Bologna, Italy  
5 Institute for Astronomy, ETH Zürich, Wolfgang-Pauli-strasse 27, 8093 Zürich, Switzerland  
6 INAF-Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5, 35122 Padova, Italy  
7 Dipartimento di Fisica e Astronomia, Università di Bologna, Viale Berti Pichat 6/2, 30127 Bologna, Italy  
8 Department of Physics, University of Helsinki, Gustaf Hallström katu 2a, 0014 Helsinki, Finland  
9 National Astronomical Observatory of Japan, Subaru Telescope, 650 North Aohoku Place, Hilo, HI 96720, USA  
10 Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK  
11 IRAM–Institut de Radioastronomie Millimétrique, 300 rue de la Piscine, 38406 Saint-Martin-d’Hères, France  
12 Institut d’Astrophysique de Paris, UMR 7095 CNRS, Université Pierre et Marie Curie, 75005 Paris, France

Received 22 September 2014 / Accepted 17 January 2015

ABSTRACT

Even 10 billion years ago, the cores of the first galaxy clusters are often found to host a characteristic population of massive galaxies with already suppressed star formation. Here we search for distant cluster candidates at $z \sim 2$ using massive passive galaxies as tracers. With a sample of ~40 spectroscopically confirmed passive galaxies at $1 < z < 2.1$, we tuned photometric redshifts of several thousand passive sources in the 2 sq. deg. COSMOS field. This allowed us to map their density in redshift slices, probing the large-scale structure in the COSMOS field as traced by passive sources. We report here on the three strongest passive galaxy overdensities that we identify in the range $1.5 < z < 2.5$. While the actual nature of these concentrations still needs to be confirmed, we discuss their identification procedure and the arguments supporting them as candidate galaxy clusters (probably in the mid-$10^{14} M_{\odot}$ range).

Key words. galaxies: clusters: general – galaxies: high-redshift – large-scale structure of Universe

1. Introduction

Up to at least $z \sim 1$, passive galaxies with typically early-type morphology dominate the high-mass end of the galaxy population and are the best tracers of the highest density peaks in the large-scale structure. The evolution of passive galaxy populations at $z \lesssim 1$ – and in particular with respect to environmental effects – has also been explored in detail thanks to large spectroscopic campaigns (e.g., Kauffmann et al. 2004; Bernardi et al. 2006; Gallazzi et al. 2006, 2014; van der Wel et al. 2008; Sánchez-Blázquez et al. 2009; Kovač et al. 2014; Valentiniuzzi et al. 2011; Muzzin et al. 2012). On the other hand, the spectroscopy of passive galaxies at $z > 1.5$ has been until recently very difficult. In spite of several investigations pushing spectroscopic confirmation and more detailed studies to higher redshifts (e.g., Cimatti et al. 2004, 2008; Daddi et al. 2005; Kriek et al. 2006, 2009; Onodera et al. 2012; van de Sande et al. 2011, 2013; Toft et al. 2012; Gobat et al. 2012, 2013; Brammer et al. 2012; Weiner 2012; Krogager et al. 2014; Newman et al. 2014; Belli et al. 2014), sizable spectroscopic samples are still rare, and studying $z > 1.5$ passive populations mainly relies on photometric samples (e.g., Wuyts et al. 2010; Bell et al. 2012; Ilbert et al. 2013; Muzzin et al. 2013a; Cassata et al. 2013). These studies show that the number density of passive galaxies rapidly falls beyond $z > 1$, so that by $z \sim 2$ passive sources are no longer the dominant population, even among massive galaxies. However, the observed evolution of massive cluster galaxies up to $z \sim 1$ (and also theoretical models, e.g., De Lucia et al. 2006) typically suggests early ($z \approx 2$–3) formation epochs for their stellar populations (e.g., Mei et al. 2009; Mancone et al. 2010; Strazzullo et al. 2010). We might thus expect that the surge in passive galaxies around ten billion years ago occurred differently in different environments.

Several recent studies have claimed to find evidence of significant star formation even in central cluster regions at $z \gtrsim 1.5$ (e.g., Hilton et al. 2010; Tran et al. 2010; Hayashi et al. 2010; Santos et al. 2011; Fassbender et al. 2011; Brodwin et al. 2013), suggesting that we indeed are approaching the formation epoch of massive cluster galaxies. However, it is also noticeable that massive passive galaxies are often found, even in such most distant clusters, although in many cases sharing their environment with galaxies in a still active formation phase (e.g., Kurk et al. 2009; Papovich et al. 2010; Gobat et al. 2011, 2013; Tanaka et al. 2013; Spitler et al. 2012; Strazzullo et al. 2013; Newman et al. 2014; Andreon et al. 2014). This may suggest that, even at a cosmic time when star formation rate density is at its peak (e.g., Madau & Dickinson 2014) and star formation is
still active in a considerable fraction of massive galaxies (e.g., Ilbert et al. 2013; Muzzin et al. 2013a), the densest cores of most evolved cluster progenitors already host a typically small but characteristic population of massive quiescent galaxies. For this reason, overdensities of passive sources might be considered as possible signposts to clusters up at least to $z \sim 2$.

2. Photometric redshift estimation for high-redshift passive galaxies in the COSMOS field

Using one of the first sizable samples of $z \gtrsim 1.4$ passive galaxies in the COSMOS field for calibration, in Onodera et al. (2012; hereafter O12) we could estimate more accurate photometric redshifts (photo-$z$s, $z_{\text{phot}}$) for high-redshift passive sources. We have now assembled a new, independent sample of passive galaxies in COSMOS with redshifts measured through UV features using VLT/VIMOS spectroscopy. We targeted 29 $I_{\text{AB}} < 25$ galaxies selected as passive BzKs (“pBzKs”, Daddi et al. 2004, plus 624 $\mu$m-detected pBzKs) from the McCracken et al. (2010; hereafter M10) catalog. A redshift was measured for 34 of the 35 targets, with a robust estimate for 29 sources. The observations, analysis, and a full redshift list will be presented in Gobat et al. (in prep.). Here we focus on a subsample of 42 spectroscopically confirmed pBzKs, selected in the range $1.3 < z_{\text{spec}} < 2.1$ and with restframe $UVJ$ colors (Williams et al. 2009) consistent with passive populations (15 and 27 galaxies from the O12 and VIMOS samples, respectively, including 324 $\mu$m-detected sources as noted below). Figure 1 shows the performance on this sample of our photo-$z$s, estimated with EAzY (Brammer et al. 2008) and calibrated as in O12. The normalized median absolute deviation (NMAD) of $\Delta z/(1 + z)$ is 2.5% on the full sample, or 1.8% excluding galaxies with less reliable $z_{\text{spec}}$ (Fig. 1), with no catastrophic outliers (thus $<2.5%$ for this sample). All results presented here are based on the photometric catalog by M10.$^1$

3. Passive galaxy overdensities at $z > 1.5$

Spectroscopic confirmation of large passive galaxy samples at high redshift is precluded for now, so we rely on passive candidates with photo-$z$s calibrated as above. We select a sample of $z > 1.5$ passive galaxies as follows: with an initial BzK selection on the M10 $K_{\text{AB}} < 23$ catalog, we take all pBzK galaxies, as well as galaxies formally classified as star-forming BzKs (“sBzKs”) but with $S/N < 5$ in the $B$- (and possibly $z$-) band. From this first selection, we retain all galaxies also having $UVJ$ passive colors (assuming their $z_{\text{phot}}$ as of Sect. 2). Sources detected at $24 \mu$m and satisfying the above criteria are retained, because of the possibility of AGN-powered $24 \mu$m flux. Sources with possibly contaminated IRAC photometry (as in the M10 catalog) were discarded (<10%). Figure 2 shows the stellar mass, $K$-band magnitude, and photo-$z$ distributions for the full retained sample of passive galaxies and for its subsample of pBzK sources.

The $K_{\text{AB}} < 23$ limit corresponds to 90% completeness for point-like sources, going down to ~22.5 for disk-like profiles (see M10). At $z \sim 2.5$, this translates in a mass completeness of $\log(M/M_\odot) \sim 10.8$–11 (−10.9 in the following, Salpeter 1955, IMF) for an unreddened SSP (Bruzual & Charlot 2003) of solar metallicity formed at $z = 5$. On the other hand, the combination of selection criteria adopted above is expected to result in a largely pure (in terms of contaminants) but not complete sample of massive ($\log(M/M_\odot) > 10.9$) passive galaxies. For this reason, we may be missing some overdensities or reducing their significance, which would affect the results presented here in a conservative way. The BzK selection and the depth of the M10 catalog effectively limit our sample at $z > 1.5$ and $z < 2.5$, respectively (Fig. 2, right). The full sample of $K_{\text{AB}} < 23$ passive galaxy candidates includes ~4500 sources. Of these, ~3500 are at $1.5 < z_{\text{phot}} < 2.5$ (~70% at $\log(M/M_\odot) > 10.9$, ~50% selected as pBzK, ~10% 24 $\mu$m-detected).

3.1. Identification of cluster candidates

We have built local density maps for the full COSMOS field in redshift slices, based on the catalog of passive galaxy candidates described above. In spite of the quoted ~2% photo-$z$ relative accuracy (by comparison with $z_{\text{spec}}$, Sect. 2), we need to consider that the spectroscopic sample is very biased toward brighter, lower redshift sources (Fig. 2), thus photo-$z$ performance on the bulk of our sample is likely to be significantly worse. We estimated a more realistic photo-$z$ accuracy as a function of magnitude, recalculating photo-$z$s on SEDs of well-fitted spectroscopic sources ($|\Delta z/(1 + z)| < 2.5\%$) dimmed to fainter magnitudes, randomly scattering fluxes in the different bands according to photometric errors in our catalog. This simulation indeed gives a photo-$z$ accuracy $<2.5%$ at $K_{\text{AB}} \leq 21$ (Sect. 2), but rising to ~3.5% (5%) at $K_{\text{AB}} \sim 22$ (22.5) and to more than 6% approaching our $K_{\text{AB}} \sim 23$ limit. These estimates are “model-independent” in the sense that they use observed (rather than synthetic) SEDs, but they still assume that SEDs of less massive and/or higher redshift sources in our sample behave similarly to those of the spectroscopic sources used as input in the simulation. For comparison, the formal 68% errors estimated in McCracken et al. (2013b) UltraVISTA catalog, in agreement with – and only marginally better than – photo-$z$s obtained by Muzzin et al. (2013b), as will be discussed in a forthcoming paper (Strazzullo et al., in prep.). Here we use the M10 catalog, which includes the southern part of the 2 sq. deg COSMOS field where one of our overdensities (Sect. 3.1) is found, which is not covered by the UltraVISTA survey (McCracken et al. 2012).

$^1$ An even better photo-$z$ accuracy (as low as 1.5%, with a marked improvement at $z \gtrsim 1.8$) can be obtained by calibrating photo-$z$s on this sample with the more recent photometry from the Muzzin et al. (2013) UltraVISTA catalog, in agreement with – and only marginally better than – photo-$z$s obtained by Muzzin et al. (2013b), as will be discussed in a forthcoming paper (Strazzullo et al., in prep.). Here we use the M10 catalog, which includes the southern part of the 2 sq. deg COSMOS field where one of our overdensities (Sect. 3.1) is found, which is not covered by the UltraVISTA survey (McCracken et al. 2012).
by EAzY on the simulated SEDs would be 40–50% larger on average (reaching ~8% at \( K_{\text{AB}} \sim 23 \)). For this reason, we built our density maps in redshift slices of \( \Delta z = \pm 0.2 \) (corresponding to a \( \pm 1\sigma \) relative accuracy of \( 6–8\% \) at \( 1.5 < z < 2.5 \)) with a step of 0.05 in central redshift.

We used the \( \Sigma_5 \) (5th nearest neighbor) density estimator, probing for our sample a median (over the full map) distance of \( \sim 1.4 \) Mpc in the \( z \sim 2 \) slice, with minimum and maximum distances of \( 100–200 \) kpc and \( 4–5 \) Mpc in all redshift slices, thus properly probing the typical scales we are investigating. For comparison, a \( \Sigma_7 \) estimator would also probe such scales (median distance \( \sim 1.1 \) Mpc at \( z \sim 2 \), minimum and maximum distances \( \sim 50 \) kpc and \( 3–4 \) Mpc), while \( \Sigma_7 \) would probe median distances closer to \( 2 \) Mpc with minimum/maximum of \( 0.5/4.5 \) Mpc at \( z \sim 2 \), thus becoming less sensitive to the scales we need to probe. Figure 3 shows three examples of \( \Sigma_5 \) maps. For each map, we estimated the significance of overdensities by fitting the distribution of \( \log(\Sigma_5) \) in the whole map with a Gaussian (Fig. 3).

At the same time, we also used an independent approach to search for concentrations of massive passive galaxies with consistent photo-zs in a very small cluster-core sized area. In particular, based on observations of the \( z = 2 \) cluster CI J1449+0857 (Gobat et al. 2011, 2013; Strazzullo et al. 2013, other examples in Sect. 1), we searched our \( \log(M/M_\odot) > 10.9 \) passive sample for sources with at least three other passive galaxies within \( |\Delta z|(1+z) < 7.5\% \) (accounting for photo-z uncertainties described above) and a physical distance \( \leq 150 \) kpc\(^2\). This

2 Based on our sample of \( \log(M/M_\odot) > 10.9 \) passive galaxies, the Poissonian probability of finding \( \geq 3 \) neighbors at \( \leq 150 \) kpc (or

\[ \geq 4 \] sources within a radius of \( \leq 150 \) kpc) with a \( |\Delta z|(1+z) < 7.5\% \) is \( < 5 \times 10^{-4} \) (\( < 2 \times 10^{-2} \), respectively) at all redshifts probed.

\[ \geq 4 \] sources within a radius of \( \leq 150 \) kpc) with a \( |\Delta z|(1+z) < 7.5\% \) is

\[ < 5 \times 10^{-4} \] (\( < 2 \times 10^{-2} \), respectively) at all redshifts probed.

by EAzY on the simulated SEDs would be 40–50% larger on average (reaching ~8% at \( K_{\text{AB}} \sim 23 \)). For this reason, we built our density maps in redshift slices of \( \Delta z = \pm 0.2 \) (corresponding to a \( \pm 1\sigma \) relative accuracy of \( 6–8\% \) at \( 1.5 < z < 2.5 \)) with a step of 0.05 in central redshift.

We used the \( \Sigma_5 \) (5th nearest neighbor) density estimator, probing for our sample a median (over the full map) distance of \( \sim 1.4 \) Mpc in the \( z \sim 2 \) slice, with minimum and maximum distances of \( 100–200 \) kpc and \( 4–5 \) Mpc in all redshift slices, thus properly probing the typical scales we are investigating. For comparison, a \( \Sigma_7 \) estimator would also probe such scales (median distance \( \sim 1.1 \) Mpc at \( z \sim 2 \), minimum and maximum distances \( \sim 50 \) kpc and \( 3–4 \) Mpc), while \( \Sigma_7 \) would probe median distances closer to \( 2 \) Mpc with minimum/maximum of \( 0.5/4.5 \) Mpc at \( z \sim 2 \), thus becoming less sensitive to the scales we need to probe. Figure 3 shows three examples of \( \Sigma_5 \) maps. For each map, we estimated the significance of overdensities by fitting the distribution of \( \log(\Sigma_5) \) in the whole map with a Gaussian (Fig. 3).

At the same time, we also used an independent approach to search for concentrations of massive passive galaxies with consistent photo-zs in a very small cluster-core sized area. In particular, based on observations of the \( z = 2 \) cluster CI J1449+0857 (Gobat et al. 2011, 2013; Strazzullo et al. 2013, other examples in Sect. 1), we searched our \( \log(M/M_\odot) > 10.9 \) passive sample for sources with at least three other passive galaxies within \( |\Delta z|(1+z) < 7.5\% \) (accounting for photo-z uncertainties described above) and a physical distance \( \leq 150 \) kpc\(^2\). This

2 Based on our sample of \( \log(M/M_\odot) > 10.9 \) passive galaxies, the Poissonian probability of finding \( \geq 3 \) neighbors at \( \leq 150 \) kpc (or

\[ \geq 4 \] sources within a radius of \( \leq 150 \) kpc) with a \( |\Delta z|(1+z) < 7.5\% \) is \( < 5 \times 10^{-4} \) (\( < 2 \times 10^{-2} \), respectively) at all redshifts probed.
Muzzin et al. (2013b) catalog, three out of four with a photo-
consistent with the mean $z_{\text{phot}}$ estimated here. The redshift distribution of the central sources is consistent with
the presence of a single structure. Another overdensity of
similar significance at a consistent photo-z is visible in the
$\Sigma_3$ map at $<4 \text{ Mpc}$ West (Fig. 3).

- CC0958+0158 at $z_{\text{phot}} \sim 2.35$ – A concentration of four passive
galaxies at RA, Dec $\sim 0^h58^m53^s, +0^\circ158^01^\prime$ within
$r < 130 \text{ kpc}$ and a $z_{\text{phot}}$ within $<0.8$ from the mean $z_{\text{phot}}$
(one further, lower mass galaxy at the same $z_{\text{phot}}$ is found at
$r < 290 \text{ kpc}$). Given their redshift (thus, faintness), all
of these sources were selected as UVJ-passive sBzKs (see
Sec. 3). One might be associated with a $24 \mu$m detection. All
are consistent with also being UVJ-passive in the Muzzin
et al. (2013b) catalog, with photo-z consistent within $1\sigma$
with the mean $z_{\text{phot}}$ estimated here. The photo-z distribution
is very compact, consistent with a single structure. An overdensity
at a consistent position and redshift is also visible in
Scoville et al. (2013) density maps. We also note the proxim-
ity (a few to $<14 \text{ Mpc}$) of confirmed/candidate structures at
similar redshift (Diener et al. 2014; Castignani et al. 2014;
Chiang et al. 2014; Yuan et al. 2014).

In Fig. 4 we show for comparison the photo-z distribution of
a mass-limited sample of the whole (passive and star-forming) galaxy population in the surroundings ($r < 600 \text{ kpc}$) of each
passive overdensity, with respect to the distribution in same-size
apertures at 100 random positions in the COSMOS field. These
distributions are based on public galaxy catalogs and photo-z
determinations, totally independent of those we use in this work.
For CC1003+0223 and CC0958+0158, we use the Muzzin
et al. (2013b) UltraVISTA catalog, while for CC1002+0134
– not covered by the UltraVISTA survey – we use the Ilbert
et al. (2009) catalog. (This is an i-selected catalog, thus not
optimal in this redshift range, as shown by the gray region in
Fig. 4, left.) We also show in Fig. 4 our photo-zs for our passive
galaxy sample around the overdensities in the same aperture
and mass range. Although clearly affected by limited statistics,
Fig. 4 shows the correspondence between our photo-zs of pas-
sive sources identifying the overdensities, and the excess in the
redshift distribution from completely independent photo-z deter-
minations of the whole galaxy population in their surroundings.

4. Discussion and summary

This letter has investigated the identification of first cluster-like
environments by using evolved galaxy populations as tracers of
an early-quenched cluster core. We described the identification
of three candidate overdensities of passive galaxies, selected in
redshift-sliced density maps and with properties similar to passive
galaxy concentrations in $z \sim 2$ clusters. This study relies on
accurate photo-z determination for high-redshift passive sources
calibrated on one of the largest spectroscopic samples available
to date. We presented only first results for the strongest candi-
date overdensities. Further investigation focusing on alternative
sample selections and the identification of lower mass structures,
with improved photo-zs based on more recent, deeper photome-
try (Sect. 2), will be presented in a forthcoming paper.

We currently have no proof that the candidate overdensi-
ities we identified are real structures. Even if they were actually
clusters, their expected mass and redshift would put them be-
tween reach of the Chandra C-COSMOS (Elvis et al. 2009) and
XMM-Newton (Hasinger et al. 2007; Cappelluti et al. 2009) pro-
grams in COSMOS, which place 3$\sigma$ limits of $4 \times 10^{12} \text{ erg s}^{-1}$
on their X-ray luminosity, thus $5 \times 10^{13} \text{ M}_\odot$ on their mass
(Leauthaud et al. 2010; Finoguenov et al. 2015). This would be
consistent with their similarities with the passive concentration
in Cl J1449+0857 ($M \sim 5 \times 10^{13} \text{ M}_\odot$, Gobat et al. 2011, 2013;
Strazzullo et al. 2013). As a reference, in a WMAP7 (Komatsu
et al. 2011) cosmology, we expect to find about two to eight
structures that are more massive than $5 \times 10^{13} \text{ M}_\odot$ in the
$1.7 < z < 2.5$ range in a $2 \text{ sq. deg}$ field (or a factor $\sim 2$ higher
with a Planck cosmology, Planck Collaboration XVI 2014).

A final confirmation necessarily relies on spectroscopic follow-up,
which is not available yet. For the time being, only for CC0958+0158 we have been able to combine available spec-
troscopic redshifts – all of star-forming galaxies – from the
zCOSMOS-deep survey (Lilly et al. 2007, and in prep.) and
a Subaru/MOIRCS program (Valentino et al. 2014), to tenta-
ively probe the redshift distribution in its surroundings. This
small, a posteriori-assembled spectroscopic sample, is hampered
by poor sampling of the central, densest cluster-candidate re-
region and by suboptimal target selection. Nonetheless, a possible

\[ \text{CC1003+0225:} \text{Muzzin et al. (2013b) for CC1003+0223 and CC0958+0158, and from Ilbert et al. (2009) for CC1002+0134 (see text). In each panel, the blue line and dotted area show the median and 16th–84th percentiles of the photo-z distribution (from the same catalogs) in } r < 600 \text{ kpc apertures at 100 random positions in the COSMOS field, while the grayed-out region shows the redshift range where the sample is no longer mass-complete. Black filled (empty) circles scattered above the histograms (at random y-axis coordinates) show our photo-z determinations for the passive sample used in this work within 300 kpc (600 kpc) from the overdensity center (larger/smaller symbols show galaxies more/less massive than log(M/M_\odot) = 10.9).} \]
Fig. 5. Distribution of spectroscopic redshifts around the CC0958+0158 overdensity (see text). The gray and black histograms show the distribution within 600 and 2000 kpc, respectively. The inset shows the spatial distribution around the overdensity center of galaxies within Δz ~ 0.1 (or Δz ~ 0.2, smaller symbols) of the three spikes at z ~ 2.17, 2.19, 2.44, as indicated. The three gray circles have radii of 0.5, 1, 2 Mpc proper.

redshift appears at z ~ 2.19 with 5(3) galaxies at 2.18 ≤ zspec ≤ 2.2 within ~1600 (500) kpc of the overdensity center, plus two more spikes of galaxies within 2 Mpc of the center: at z ~ 2.17 and z ~ 2.44 (6 and 5 galaxies within Δz ~ ±0.01, respectively, Fig. 5). Although the spikes contain a similar number of galaxies, their spatial distribution (Fig. 5) might suggest that the passive overdensity is more likely at z ~ 2.2. Even if somewhat lower than the estimated photo-z of the passive galaxies, this would still be consistent within the uncertainties.

Dedicated follow-up work is obviously still needed to verify whether these candidate overdensities are indeed signposts for early cluster environments. If successful, this approach would provide a further option for extending the investigation of distant cluster-like structures to the z ~ 2–2.5 range. In comparison with most other (proto-)cluster search techniques at these redshifts, e.g. the “IRAC selection” (e.g., Papovich et al. 2010; Stanford et al. 2012), targeted searches around radio galaxies (e.g., Venemans et al. 2007; Chibou谐te et al. 2010; Wylezalek et al. 2013), 3D mapping (with spectroscopic or photometric redshifts, e.g., Diener et al. 2013; Scoville et al. 2013; Chiang et al. 2014; Mei et al. 2014), or overdensities of optically red galaxies (e.g., Andreon et al. 2009; Spitler et al. 2012), the approach discussed in this work is likely, by definition, to favor the most evolved environments, thus allowing a better probe of the diversity of cluster progenitors at a crucial time for the formation of evolved environments, thus allowing a better probe of the diver-

References

Andreon, S., Maughan, B., Trinchieri, G., & Kurk, J. 2009, A&A, 507, 147
Andreon, S., Newman, A. B., Trinchieri, G., et al. 2014, A&A, 565, A120
Aravena, M., Carilli, C. L., Salvato, M., et al. 2012, MNRAS, 426, 258
Bell, E. F., van der Wel, A., Papovich, C., et al. 2012, ApJ, 753, 167
Bell, S., Newman, A. B., Ellis, R. S., & Konidaris, N. P. 2014, ApJ, 788, L29
Bernardi, M., Nichol, R. C., Sheth, R. K., et al. 2006, AJ, 131, 1288
Brammer, G. B., van Dokkum, P. G., & Coppi, P. 2008, ApJ, 686, 1503
Brammer, G. B., van Dokkum, P. G., Franx, M., et al. 2012, ApJS, 200, 13
Brodwin, M., Stanford, S. A., Gonzalez, A. H., et al. 2013, ApJ, 779, 138
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Cappelluti, N., Brusa, M., Hasinger, G., et al. 2009, A&A, 495, 635
Castignani, G., Chibou谐te, M., Celotti, & Whatever, X. 2014, ApJ, 792, 114
Chabrier, M., Capetti, A., Machetto, F. D., et al. 2010, ApJ, 710, L107
Chiang, Y.-K., Overzier, R., & Gehhardt, K. 2014, ApJ, 782, L3
Cimatti, A., Daddi, E., Renzini, A., et al. 2004, Nature, 430, 184
Cimatti, A., Cassata, P., Pozzetti, L., et al. 2008, A&A, 482, 21
Daddi, E., Cimatti, A., Renzini, A., et al. 2004, ApJ, 617, 746
Daddi, E., Renzini, A., Pirzkal, N., et al. 2005, ApJ, 626, 680
De Lucia, G., Springel, V., White, S. D. M., et al. 2006, MNRAS, 366, 499
Diener, C., Lilly, S. J., Knobel, C., et al. 2013, ApJ, 765, 109
Diener, C., Lilly, S., Ledoux, C., et al. 2014, ApJ, submitted

Acknowledgements. We thank M. Pannella and A. Saro for helpful input. V.S., E.D., R.G., and F.V. were supported by grants ERC-StG UPALG 24039 and ANR-08-JCJC-0008. A.C. and M.M. acknowledge grants ASI n.1023/12/0 and MIUR PRIN 2010-2011 “The dark Universe and the cosmic evolution of baryons; from current surveys to Euclid”. Based on observations from ESO Telescopes under program IDs 086.A-0681, 088.A-0671, LP175.A-0839, and 179.A-2005.

References

Andreon, S., Maughan, B., Trinchieri, G., & Kurk, J. 2009, A&A, 507, 147
Andreon, S., Newman, A. B., Trinchieri, G., et al. 2014, A&A, 565, A120
Aravena, M., Carilli, C. L., Salvato, M., et al. 2012, MNRAS, 426, 258
Bell, E. F., van der Wel, A., Papovich, C., et al. 2012, ApJ, 753, 167
Bell, S., Newman, A. B., Ellis, R. S., & Konidaris, N. P. 2014, ApJ, 788, L29
Bernardi, M., Nichol, R. C., Sheth, R. K., et al. 2006, AJ, 131, 1288
Brammer, G. B., van Dokkum, P. G., & Coppi, P. 2008, ApJ, 686, 1503

V. Strazzullo et al.: Passive overdensities at z ~ 2