

## THE CLOSE ENVIRONMENT OF 24 $\mu\text{m}$ GALAXIES AT $0.6 < z < 1.0$ IN THE COSMOS FIELD

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### ABSTRACT

We investigate the close environment of 203 *Spitzer* 24  $\mu\text{m}$ -selected sources at  $0.6 < z < 1.0$  using zCOSMOS-bright redshifts and spectra of  $I < 22.5$  AB mag galaxies, over 1.5 deg<sup>2</sup> of the COSMOS field. We quantify the degree of passivity of the luminous and ultra-luminous IR galaxy (LIRG and ULIRG, respectively) environments by analyzing the fraction of close neighbors with  $D_n(4000) > 1.4$ . We find that LIRGs at  $0.6 < z < 0.8$  live in more passive environments than those of other optical galaxies that have the same stellar mass distribution. Instead, ULIRGs inhabit more active regions (e.g., LIRGs and ULIRGs at  $0.6 < z < 0.8$  have, respectively,  $(42.0 \pm 4.9)\%$  and  $(24.5 \pm 5.9)\%$  of neighbors with  $D_n(4000) > 1.4$  within 1 Mpc and  $\pm 500 \text{ km s}^{-1}$ ). The contrast between the activities of the close environments of LIRGs and ULIRGs appears especially enhanced in the COSMOS field density peak at  $z \sim 0.67$ , because LIRGs on this peak have a larger fraction of passive neighbors, while ULIRGs have as active close environments as those outside the large-scale structure. The differential environmental activity is related to the differences in the distributions of stellar mass ratios between LIRGs/ULIRGs and their close neighbors, as well as in the general local density fields. At  $0.8 < z < 1.0$ , instead, we find no differences in the environment densities of ULIRGs and other similarly massive galaxies, in spite of the differential activities. We discuss a possible scenario to explain these findings.

*Key words:* galaxies: evolution – infrared: galaxies

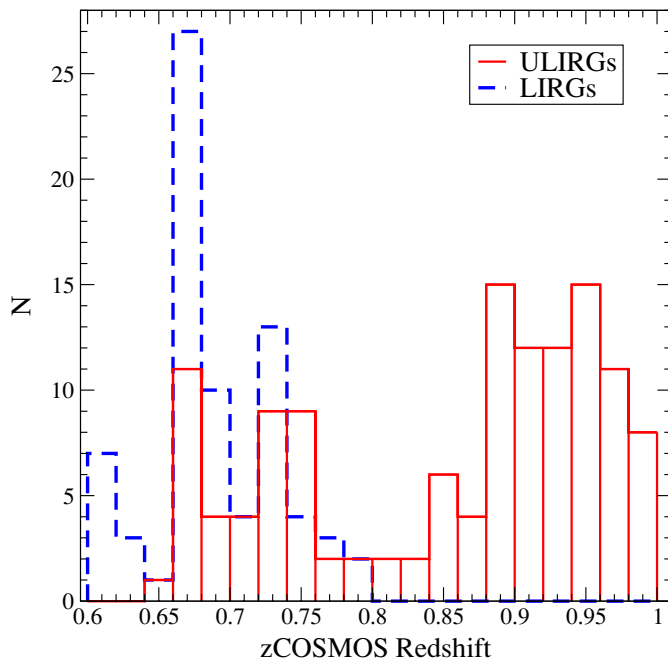
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### 1. INTRODUCTION

Our knowledge of the nature of the sources composing the extragalactic IR background (Puget et al. 1996; Dole et al. 2006) has been much clarified over the last years thanks to studies conducted with the *Spitzer Space Telescope* (Werner et al. 2004) and now also the *Akari Telescope* (Matsuhara et al. 2006). Many properties of these galaxies are now quite well known, including their redshift distribution (e.g., Rowan-Robinson et al. 2005; Caputi et al. 2006a; Desai et al. 2008); luminosity evolution (e.g., Le Floc'h et al. 2005; Pérez-González et al. 2005; Babbedge et al. 2006; Caputi et al. 2007); assembled stellar masses (Daddi et al. 2005; Caputi et al. 2006a, 2006b; Papovich et al. 2006; Noeske et al. 2007); and multiwavelength

spectral characteristics (e.g., Houck et al. 2005; Yan et al. 2005; Choi et al. 2006; Weedman et al. 2006; Berta et al. 2007; Lacy et al. 2007; Sajina et al. 2007; Caputi et al. 2008; Rigby et al. 2008).

The properties of the environment in which IR-selected galaxies reside are less well determined. This is mainly because environmental studies require the combination of wide area surveys with accurate redshift determinations that, in general, are only provided by large spectroscopic samples. Recent works have explored the link between environment and star formation activity in IR-selected galaxies. Elbaz et al. (2007) determined that the star formation rate (SFR)–density relation observed locally was reversed at  $z \sim 1$ . Serjeant et al. (2008) suggested that this reversed relation could also hold for submillimeter



**Figure 1.** Redshift distribution of the 203  $24\ \mu\text{m}$ -selected galaxies considered in this work. The terms LIRGs and ULIRGs refer to galaxies with rest-frame  $24\ \mu\text{m}$  luminosities below and above  $\nu L_{\nu}^{24\ \mu\text{m}} = 1.5 \times 10^{11}\ L_{\odot}$ , respectively. This cut has been chosen for being the luminosity completeness limit in the  $0.8 < z < 1.0$  redshift bin. Note that the flux limit  $S_{24\ \mu\text{m}} > 0.30\ \text{mJy}$  of the S-COSMOS shallow survey also imposes a completeness limit for the LIRG population observed at  $0.6 < z < 0.8$ , which is  $\nu L_{\nu}^{24\ \mu\text{m}} = 7 \times 10^{10}\ L_{\odot}$  (equivalent to a bolometric IR luminosity  $L_{\text{bol.}} \approx 3.4 \times 10^{11}\ L_{\odot}$ , using the Bavouzet et al. 2008 calibration).

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galaxies at  $1.0 < z < 1.5$ . Marcillac et al. (2008) found that luminous and ultra-luminous IR galaxies (LIRGs and ULIRGs, respectively) at  $0.7 < z < 1.0$  are present, on average, in denser environments than those of other optical galaxies, but they argued that this difference is mainly driven by stellar mass.

The Cosmic Evolution Survey (COSMOS; Scoville et al. 2007) has been designed to probe galaxy evolution and the effects of environment up to high redshifts over  $2\ \text{deg}^2$  of the sky. COSMOS observations include the coverage of the field with the Multiband Imaging Photometer for *Spitzer* (MIPS; Rieke et al. 2004) as part of two *Spitzer* Legacy Programs (S-COSMOS; Sanders et al. 2007). COSMOS also comprises a large spectroscopic follow-up (zCOSMOS; Lilly et al. 2007) with the Visible Multiobject Spectrograph (VIMOS; Le Fèvre et al. 2003) on the Very Large Telescope (VLT). The combination of the S-COSMOS and zCOSMOS datasets are ideal to characterize the environment of IR-selected galaxies and investigate the properties of their close neighbors.

In this paper, we make use of zCOSMOS-bright spectra to investigate the characteristics of the environment of the most luminous  $24\ \mu\text{m}$ -selected galaxies with  $I < 22.5$  AB mag at redshifts  $0.6 < z < 1.0$ . First, in Section 3, we analyze the activity and stellar masses of galaxies which are close to  $24\ \mu\text{m}$  galaxies of different IR luminosities. Second, in Section 4, we particularly study the activity of close neighbors of IR galaxies lying on the COSMOS field density peak at  $z \sim 0.67$ . Finally, in Section 5, we characterize the environment of  $24\ \mu\text{m}$  sources using the general density fields produced with zCOSMOS (Kovač et al. 2009). We adopt throughout a cosmology with  $H_0 = 70\ \text{km s}^{-1}\text{Mpc}^{-1}$ ,  $\Omega_{\text{M}} = 0.3$ , and  $\Omega_{\text{A}} = 0.7$ .

## 2. SAMPLE SELECTION AND CLOSE-ENVIRONMENT DEFINITION

The zCOSMOS-bright survey is now half-way complete and has already produced reduced spectra and redshifts for 10,644 sources over  $1.5\ \text{deg}^2$  of the COSMOS field (“the 10 k sample” hereafter). Most of the targets for zCOSMOS-bright are selected randomly from a complete  $I < 22.5$  AB mag catalog (the “parent catalog”). The sampling rate of the parent catalog achieved with the 10 k sample is  $\sim 1/3$ . All zCOSMOS-bright observations are performed with the  $R \sim 600$  VIMOS MR grism, with a spectral coverage of (5500–9500) Å and a dispersion of  $2.55\ \text{Å}$  (Lilly et al. 2007).

Using the zCOSMOS-bright 10 k sample, Caputi et al. (2008) identified 609 *Spitzer*/MIPS  $24\ \mu\text{m}$ -selected galaxies with  $S_{24\ \mu\text{m}} > 0.30\ \text{mJy}$  and  $I < 22.5$  AB mag, over  $1.5\ \text{deg}^2$  of the COSMOS field. The number of identified galaxies is the result of the optical  $I < 22.5$  AB mag selection and the zCOSMOS-bright 10 k sampling rate. As it was explained by Caputi et al. (2008), 66% of the  $S_{24\ \mu\text{m}} > 0.30\ \text{mJy}$  sources have an association in the zCOSMOS-bright parent catalog and  $\gtrsim 80\%$  of the missing sources are at  $z > 1$  (as determined from photometric redshifts; Ilbert et al. 2009; P. Oesch et al. 2009, in preparation). Thus, the  $I < 22.5$  AB mag cut is sufficient for the identification of the vast majority of the IR-bright galaxy population at  $z < 1.0$ .

Caputi et al. (2008) analyzed different optical spectral properties for their IR galaxies, depending on redshift. In particular, 217 out of the 609  $24\ \mu\text{m}$  galaxies have been identified to be at redshifts  $0.6 < z < 1.0$ . In this redshift range, the  $4000\ \text{Å}$  break is included among the features observed in the most secure part of the zCOSMOS spectra (i.e., far from the borders of the spectral coverage and, particularly, outside the region affected by fringing  $\lambda \gtrsim 8500\ \text{Å}$ ). The strength of the  $4000\ \text{Å}$  break  $D_{\text{n}}(4000)$  is directly related to the time since the last episode of star formation, so this parameter is very useful to quantify galaxy activity.

We use the zCOSMOS-bright 10 k sample to identify and characterize the  $I < 22.5$  AB mag galaxies that live in the close environment of IR galaxies at  $0.6 < z < 1.0$ . As in Caputi et al. (2008), we only consider sources with reliable spectroscopic redshifts, as defined by their zCOSMOS flags (see Lilly et al. 2007).

We analyze separately the neighbors of sources with rest-frame IR luminosities  $\nu L_{\nu}^{24\ \mu\text{m}} < 1.5 \times 10^{11}\ L_{\odot}$  and  $\nu L_{\nu}^{24\ \mu\text{m}} > 1.5 \times 10^{11}\ L_{\odot}$ , as only the latter IR luminosities are above the completeness limits of the  $S_{24\ \mu\text{m}} > 0.30\ \text{mJy}$  survey at  $0.8 < z < 1.0$ . The redshift distribution of the 203 considered  $24\ \mu\text{m}$ -selected galaxies is shown in Figure 1. There are 14 additional IR sources in the Caputi et al. (2008) sample at  $0.8 < z < 1.0$ , but their IR luminosities are below the completeness limit for this redshift bin. These 14 sources are statistically insufficient to reach any significant conclusion on the  $\nu L_{\nu}^{24\ \mu\text{m}} < 1.5 \times 10^{11}\ L_{\odot}$  population at  $0.8 < z < 1.0$ , so we do not consider them in our analysis.

Following the most recent calibration for the conversion between monochromatic ( $\nu L_{\nu}^{24\ \mu\text{m}}$ ) and bolometric ( $L_{\text{bol.}}$ ) IR luminosities made by Bavouzet et al. (2008), we obtain that  $\nu L_{\nu}^{24\ \mu\text{m}} = 1.5 \times 10^{11}\ L_{\odot}$  corresponds to  $L_{\text{bol.}} \approx 6 \times 10^{11}\ L_{\odot}$ . For the same rest-frame  $24\ \mu\text{m}$  luminosity, other previous calibrations would yield:  $L_{\text{bol.}} \approx 7 \times 10^{11}\ L_{\odot}$  (using the  $\nu L_{\nu}^{25\ \mu\text{m}}-L_{\text{bol.}}$  relation by Takeuchi et al. 2005) and  $L_{\text{bol.}} \approx 1.3 \times 10^{12}\ L_{\odot}$  (Sajina et al. 2006). Thus, our IR luminosity cut

$\nu L_{\nu}^{24\mu\text{m}} = 1.5 \times 10^{11} L_{\odot}$  very roughly separates LIRGs and ULIRGs (whose nominal separation is  $L_{\text{bol.}} = 10^{12} L_{\odot}$ ). In the following, we use the names LIRGs and ULIRGs to refer to the IR sources below and above our luminosity completeness limit in the highest redshift bin, which is  $\nu L_{\nu}^{24\mu\text{m}} = 1.5 \times 10^{11} L_{\odot}$ .

The flux cut of the S-COSMOS  $S_{24\mu\text{m}} > 0.30$  mJy survey also imposes a lower limit on the IR luminosities of the LIRGs we detect at  $0.6 < z < 0.8$ . We estimate that our completeness limit in this redshift bin is  $\nu L_{\nu}^{24\mu\text{m}} \approx 7 \times 10^{10} L_{\odot}$ , which corresponds to  $L_{\text{bol.}} \approx 3.4 \times 10^{11} L_{\odot}$  (Bavouzet et al. 2008).

To select the neighbors in the close environment of the zCOSMOS-identified 24  $\mu\text{m}$  galaxies at  $0.6 < z < 1.0$ , we look for the sources in the zCOSMOS-bright 10 k catalog that lie within cylinders centered at the zCOSMOS position and redshift (R.A., decl.,  $z$ ) of each 24  $\mu\text{m}$  source. We consider cylinders with a projected physical radius<sup>17</sup> of up to 2 Mpc and a velocity dispersion of  $\pm 500 \text{ km s}^{-1}$ . This velocity dispersion—which is  $\sim 5$  times the typical uncertainty of the zCOSMOS-bright redshifts—is small enough to expect the physical association of the neighbors with the central 24  $\mu\text{m}$  source. Also, such small dispersions ensure that the neighbors are observed while witnessing the IR phase of the central galaxy, which typically lasts  $10^7$ – $10^8$  years (Caputi et al. 2008).

The total numbers of nonrepeated neighbors within 2 Mpc are 220 and 131, for 74 LIRGs and 42 ULIRGs at  $0.6 < z < 0.8$ , respectively, and 154 for 87 ULIRGs at  $0.8 < z < 1.0$ . We note that only  $\sim 6\%$  of these neighbors are also 24  $\mu\text{m}$  galaxies with fluxes  $S_{24\mu\text{m}} > 0.30$  mJy.

We define three control samples, containing optical galaxies selected to mimic the stellar mass distributions of LIRGs and ULIRGs at  $0.6 < z < 0.8$ , and ULIRGs at  $0.8 < z < 1.0$ , respectively. By using this set of mass-selected control samples for each specific population, we can probe whether the differences in the environmental properties of IR and other optical galaxies are driven or not by differences in stellar mass.

To construct control samples that mimic the stellar mass distributions of each IR galaxy population, we select those (non-IR) zCOSMOS-bright galaxies whose stellar masses are within  $\pm 0.2$  dex of the stellar mass of each IR source. To guarantee that the resulting stellar mass distributions are the same as for IR galaxies, we weigh each galaxy in the control sample by a factor of  $f = (n_{\text{IR}}^i N_c) / (n_c^i N_{\text{IR}})$ , where  $N_{\text{IR}}$  and  $N_c$  are the total numbers of galaxies in the IR and control samples, respectively, and  $n_{\text{IR}}^i$  and  $n_c^i$  are the respective numbers of galaxies in each stellar mass bin.

### 3. THE CLOSE ENVIRONMENT OF 24 $\mu\text{m}$ GALAXIES AT $0.6 < z < 1.0$

#### 3.1. The Activity of Close 24 $\mu\text{m}$ Galaxy Neighbors

We study the fraction of active galaxies around LIRGs and ULIRGs at  $0.6 < z < 0.8$ , and ULIRGs at  $0.8 < z < 1.0$ , as a function of their projected physical distance. We quantify the galaxy activity through the strength of the 4000  $\text{\AA}$  break  $D_n(4000)$ , defined as the ratio of the average flux density between the (4000–4100)  $\text{\AA}$  and (3850–3950)  $\text{\AA}$  bands (Balogh et al. 1999). The parameter  $D_n(4000)$  has the advantage of being quite independent of reddening (e.g., a typical extinction value  $A_V \approx 1$  only produces a correction of  $\sim 4\%$ ), so we do not apply any extinction correction to our measured  $D_n(4000)$  values.

Caputi et al. (2008) showed that all bright 24  $\mu\text{m}$ -selected galaxies at redshifts  $0.6 < z < 1.0$  are characterized by small values of the  $D_n(4000)$  parameter, typically  $D_n(4000) \lesssim 1.2$ . They interpreted these small values as the consequence of rejuvenating bursts of star formation, which are also responsible for the IR activity of these galaxies. On the other hand, large values of the  $D_n(4000)$  parameter such as  $D_n(4000) \gtrsim 1.4$  correspond to galaxies that have not suffered any new burst of star formation for at least  $\sim 0.5$  Gyr (see Caputi et al. 2008). Thus, by measuring the fraction of galaxies with large  $D_n(4000)$  values, one can quantify the degree of “passivity” (or inactivity) of a given galaxy population.

We note that a large  $D_n(4000)$  parameter value does not exclude the possibility of minor star formation activity, but indicates that the level of ongoing star formation is insignificant with respect to the galaxy’s already-assembled stellar mass. Also, in principle, very obscured ( $A_V > 4$ – $5$ ) bursts of star formation can as well produce large  $D_n(4000)$  values, due to differential extinction. However, such obscured bursts are very rare among optically bright galaxies. In particular, none of our galaxy neighbors in the zCOSMOS-bright 10 k sample at  $0.6 < z < 1.0$  has a best-fit UV through near-IR spectral energy distribution (SED) with  $A_V > 4$  (Bolzonella et al. 2009).

The  $D_n(4000)$  parameter value has a nonnegligible dependence on galaxy metallicity for ages  $\gtrsim 1$  Gyr (Kauffmann et al. 2003). However, we note that by imposing a cut  $D_n(4000) \gtrsim 1.4$ , we only select galaxies whose last burst of star formation happened at least  $\sim 0.5$  Gyr before, independently of their metallicity.

Figure 2 shows the percentages of (cumulative) close neighbors of 24  $\mu\text{m}$  galaxies that  $D_n(4000) > 1.4$ , versus the maximum projected physical distance, at  $0.6 < z < 0.8$  (left-hand panel) and  $0.8 < z < 1.0$  (right-hand panel). As a reference, we also show the fraction of close neighbors with  $D_n(4000) > 1.4$  for galaxies in the control samples (small black symbols) and for galaxies in a generic control sample that includes all non-IR optical galaxies with no mass selection (dashed lines). For the mass-selected control samples, each neighbor has been assigned the weight factor of its central galaxy, or the average of weight factors when it is associated with more than one galaxy.

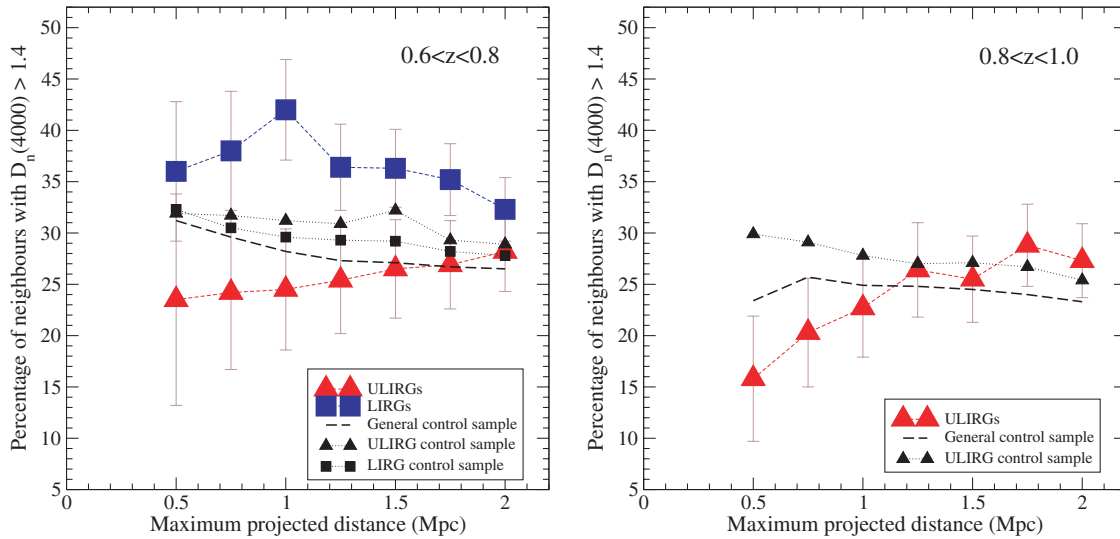
We compute the error bars on each percentage by assuming a binomial distribution, where each neighbor galaxy has two possibilities, either having  $D_n(4000) > 1.4$  or  $< 1.4$ . The error bars for the control samples are negligible in comparison to those for IR galaxies. The errors on the individual  $D_n(4000)$  measurements are only random and  $< 8\%$  in all cases.

The plot in the left-hand panel of Figure 2 shows that, at  $0.6 < z < 0.8$ , the fraction of close passive ( $D_n(4000) > 1.4$ ) neighbors is significantly different for LIRGs and ULIRGs. The maximum difference is observed within a projected physical distance of 1 Mpc, where the percentage of passive neighbors of ULIRGs is only  $(24.5 \pm 5.9)\%$ , while the percentage for LIRGs is  $(42.0 \pm 4.9)\%$ .

This difference is not an effect of stellar mass. When we compare the fractions of passive neighbors of LIRGs and ULIRGs with those of other similarly massive galaxies, we still see that LIRGs prefer more passive environments, while ULIRGs prefer more active ones. At  $0.8 < z < 1.0$ , ULIRGs also live in more active environments than those of other similarly massive galaxies, but this effect is only seen within less than 1 Mpc.

When considering up to larger scales, the differences in the fractions of passive neighbors are smaller. Within  $\sim 2$  Mpc of

<sup>17</sup>  $r = D_A \Delta\theta$ , where  $D_A$  is the angular diameter distance in Mpc and  $\Delta\theta$  is the angular separation in radians.



**Figure 2.** Percentages of (cumulative) neighbors with  $D_n(4000) > 1.4$  for LIRGs (large blue squares), ULIRGs (large red triangles), and for galaxies in their respective control samples (small black squares and triangles), vs. the maximum projected physical distance. All neighbors are selected within  $\pm 500 \text{ km s}^{-1}$  of the central source. The dashed lines indicate the fraction of neighbors with  $D_n(4000) > 1.4$  for generic control samples that include all non-IR zCOSMOS galaxies, independent of their stellar mass.

(A color version of this figure is available in the online journal.)

projected physical distance, the fractions of passive sources around LIRGs, ULIRGs, and other optical galaxies are all very similar. Besides, our results show that these fractions within 2 Mpc evolve very little from  $0.8 < z < 1.0$  to  $0.6 < z < 0.8$ .

If we adopted a more strict cut for the  $D_n(4000)$  parameter value, we would also observe a differential activity for the LIRG and ULIRG neighbors at  $0.6 < z < 0.8$ . At a maximum projected physical distance of 1 Mpc, where the differences are the largest, ULIRGs have  $(18.9 \pm 5.3)\%$  of neighbors with  $D_n(4000) > 1.5$ , while LIRGs have  $(33.0 \pm 4.7)\%$ . When considering a  $D_n(4000) > 1.6$  cut, the percentages of passive neighbors are  $(13.2 \pm 4.7)\%$  and  $(25.0 \pm 4.3)\%$ , for ULIRGs and LIRGs, respectively. At  $0.8 < z < 1.0$ , ULIRGs have similar fractions of  $D_n(4000) > 1.5$  or  $1.6$  neighbors as ULIRGs at  $0.6 < z < 0.8$ .

Of course, our selection of close neighbors within a velocity dispersion of  $\pm 500 \text{ km s}^{-1}$  from the central source, and the measurement of the  $D_n(4000)$  parameter, require the availability of spectra. Thus, it is not possible for us to conclude on the presence and activity of other possible close neighbors rather than those sampled by the zCOSMOS-bright 10 k sample. However, it is worth noting that most of the results presented in this work correspond to fractions rather than absolute numbers, so the effects of incompleteness in the sampling of  $I < 22.5$  AB mag galaxies should have very little impact (if any) on the quoted values.

In any case, to show that there is no statistical bias in the sampling of neighbors of LIRGs and ULIRGs, we perform the following test. We use the very good quality photometric redshifts ( $z_{\text{phot}}$ ) obtained in the COSMOS field (Ilbert et al. 2009), to select all those  $I < 22.5$  AB mag sources that lie within a projected physical distance of 2 Mpc and  $\Delta z = \pm 1\sigma$  of each IR source, where  $\sigma$  is the typical dispersion of the COSMOS photometric redshifts. For  $I < 22.5$  AB mag sources at  $z < 1$ , Ilbert et al. obtain  $\sigma = 0.007 \times (1 + z)$  (note that this corresponds to a velocity dispersion more than four times larger than the one we use to define the close environment in this work). Out of these  $I < 22.5$  AB mag  $z_{\text{phot}}$ -defined neighbors, we check the fractions of those included in the

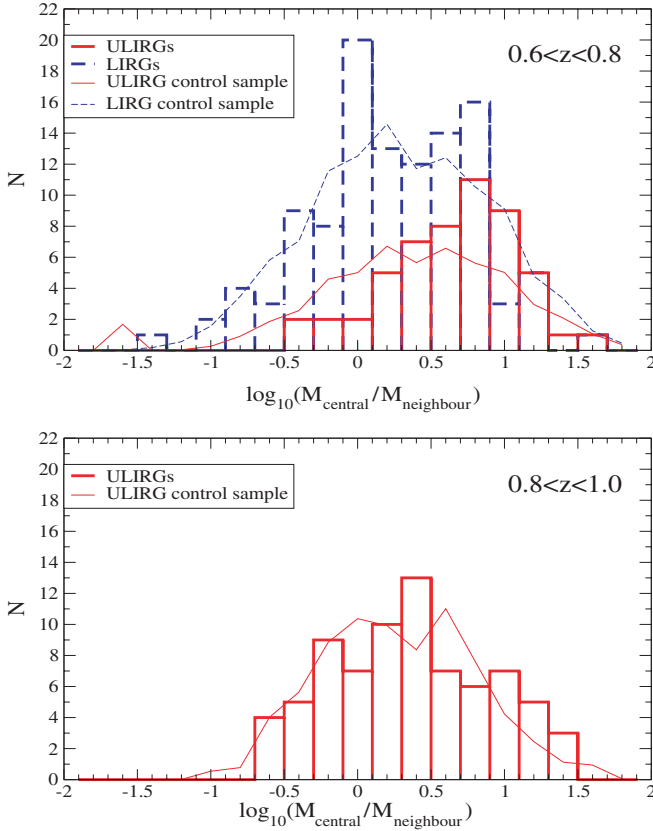
zCOSMOS-bright 10 k sample, for our different IR galaxy populations. We find that 28.0% and 29.0% of the  $z_{\text{phot}}$ -defined neighbors around our  $0.6 < z < 0.8$  LIRGs and ULIRGs, respectively, are included in the zCOSMOS-bright 10 k sample. For the respective control samples, the percentages are very similar (28.7% and 29.1%). At  $0.8 < z < 1.0$ , we find that 31.4% of the ULIRG  $z_{\text{phot}}$ -neighbors have a spectroscopic redshift, while the control sample neighbors are targeted at a rate of 29.1%. The similarity of these percentages shows that there is no statistical bias in the spectroscopic sampling of neighbors for LIRGs and ULIRGs, or their respective control samples. These percentages are consistent with the overall sampling rate of  $\sim 1/3$  estimated for  $I < 22.5$  AB mag galaxies in the zCOSMOS-bright 10 k sample.

### 3.2. The Stellar Masses of Close $24 \mu\text{m}$ Galaxy Neighbors

To investigate whether the differential activity of the close environments of LIRGs and ULIRGs is related to other environmental differences, we study the distribution of stellar mass ratios ( $M_{\text{central}}/M_{\text{neighbor}}$ ) between the central source and each of its neighbors within 1 Mpc of projected physical distance (Figure 3). The red solid and blue dashed histograms in Figure 3 correspond to ULIRG-neighbor and LIRG-neighbor pairs, respectively. The thin lines with the same style code show the renormalized numbers of central-neighbor pairs for galaxies in the corresponding control samples.

All stellar masses have been taken from Bolzonella et al. (2009), who obtained UV through  $4.5 \mu\text{m}$  best-fit SEDs and derived stellar masses for all galaxies in the zCOSMOS-bright 10 k sample. The  $\chi^2$  best-fit SEDs have been determined using HYPERZ (Bolzonella et al. 2000) and the Bruzual & Charlot (2003; also Bruzual 2007) template library with solar metallicity. For the fitting of each source SED, the redshift has been fixed to the known spectroscopic value, while the star formation history, age, and reddening have been taken as free parameters. All stellar masses considered here correspond to a Chabrier (2003) initial mass function (IMF).

The two histograms in the top panel of Figure 3 show that the stellar mass ratios ( $M_{\text{central}}/M_{\text{neighbor}}$ ) are substantially different



**Figure 3.** Histograms of stellar mass ratios between  $24\ \mu\text{m}$  galaxies and each of their close zCOSMOS neighbors within 1 Mpc of projected physical distance. The thin lines show the renormalized distributions for galaxies in the respective control samples.

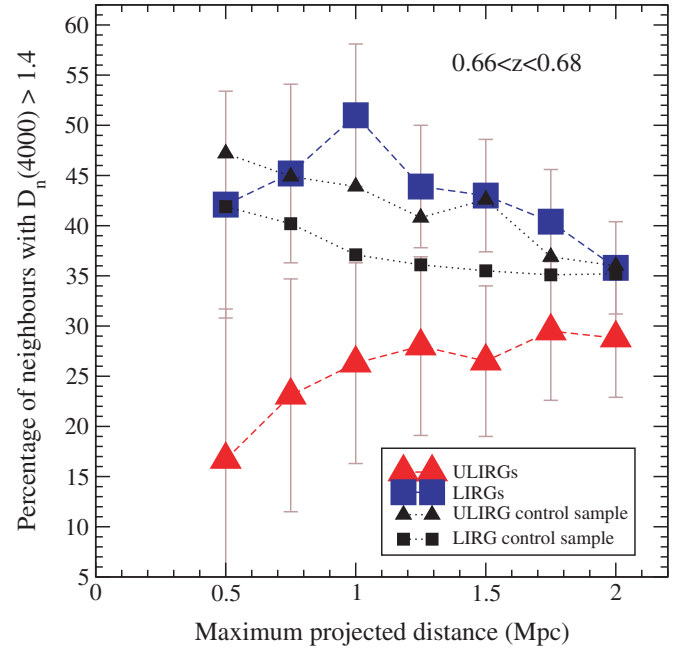
(A color version of this figure is available in the online journal.)

for LIRGs and ULIRGs. While  $\sim 30\%$  of LIRGs have smaller stellar masses than their close neighbors, ULIRGs are the most massive galaxy of their surroundings in more than 90% of the cases.

Comparison with the respective control samples shows that there are also some differences in the  $(M_{\text{central}}/M_{\text{neighbor}})$  distributions for IR galaxies and other optical galaxies with equivalent stellar masses at  $0.6 < z < 0.8$ . We perform a Kolmogorov–Smirnov test for each IR galaxy population and its respective control sample, properly incorporating the weight factors for the latter. We find that the null hypothesis that the  $(M_{\text{central}}/M_{\text{neighbor}})$  distributions for ULIRGs and their control sample at  $0.6 < z < 0.8$  are drawn from the same parent sample can be rejected at a 99.9% level (i.e., within our sample, ULIRGs are surrounded by less massive neighbors than other galaxies with similar stellar masses). For LIRGs and their control sample at  $0.6 < z < 0.8$ , the rejection of the null hypothesis is weaker, but still can be done at a 76% level. For ULIRGs at  $0.8 < z < 1.0$ , the null hypothesis cannot be rejected (56% confidence for the rejection).

#### 4. THE CLOSE ENVIRONMENT OF $24\ \mu\text{m}$ GALAXIES IN THE DENSITY PEAK AT $z \sim 0.67$

Figure 1 shows that 36.5% of our LIRGs and 26.2% of our ULIRGs at  $0.6 < z < 0.8$  lie on a density peak at  $0.66 < z < 0.68$ . It is then interesting to compare the activity of the IR-galaxy close neighbors appearing in this narrow redshift range, with the global neighbor activity analyzed in Section 3.1.



**Figure 4.** Percentages of (cumulative) neighbors with  $D_n(4000) > 1.4$  for the LIRGs, ULIRGs, and their respective control samples, that lie on the density peak at  $0.66 < z < 0.68$ . All neighbors are selected within  $\pm 500\ \text{km s}^{-1}$  of the central source. The symbols are the same as in Figure 2.

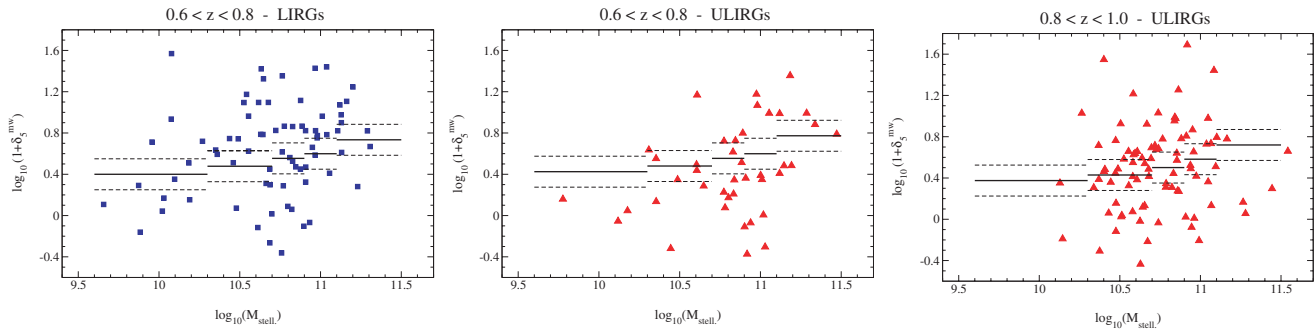
(A color version of this figure is available in the online journal.)

We recompute the percentages of (cumulative) close neighbors of  $24\ \mu\text{m}$  galaxies which have  $D_n(4000) > 1.4$ , versus the maximum projected physical distance, but this time considering only those IR galaxies at  $0.66 < z < 0.68$ . The results are shown in Figure 4. By comparing this figure with the left-hand panel of Figure 2 we clearly see that, within the density peak, the percentages of close passive neighbors for LIRGs and optical galaxies in the control samples are higher than the percentages obtained when considering the full redshift range  $0.6 < z < 0.8$ . This effect is consistent with the general fact that the fraction of red galaxies at  $z \lesssim 1$  is larger in higher density environments (e.g., Hogg et al. 2003; Balogh et al. 2004; Baldry et al. 2006; Cooper et al. 2006; Cucciati et al. 2006; Willmer et al. 2006).

Surprisingly, instead, ULIRGs on the density peak are characterized by very active close environments, presenting no differences with respect to the total ULIRG population at  $0.6 < z < 0.8$ . It is particularly noteworthy the difference in the environment activities for ULIRGs and other optical galaxies with similar stellar masses. The high degree of activity in the ULIRG close neighborhood suggests that this activity is directly linked to the ULIRG phase of the central galaxy, independently of the effects of structure at very large scale.

We note that the average number of close neighbors per ULIRG on the structure is higher than per LIRG ( $\sim 5.4$  against  $\sim 4$ , within 2 Mpc of physical distance). However, the stellar mass ratio  $(M_{\text{central}}/M_{\text{neighbor}})$  distributions follow the same trends as those shown in the upper panel of Figure 3, i.e., LIRGs have companions of different relative stellar masses, while ULIRGs are virtually always the most massive galaxy of their close neighborhood.

As a result, we find that the differential activities in the close environments of LIRGs and ULIRGs is especially enhanced in the density peak at  $z \sim 0.67$ . Within 1 Mpc of projected physical distance, the percentages of passive neighbors are  $\sim 51\%$  and  $\sim 26\%$ , for LIRGs and ULIRGs, respectively. Outside the



**Figure 5.** Mass-weighted overdensities for LIRGs and ULIRGs, vs. stellar masses (corresponding to a Chabrier IMF). The horizontal lines indicate the mean and typical errors on the mass-weighted overdensities for the galaxies in the respective control samples, in different stellar mass bins. (A color version of this figure is available in the online journal.)

density peak, we find that there are milder but still non-negligible differences in the degrees of activity of LIRG and ULIRG neighbors at  $0.6 < z < 0.8$  ( $\sim 33\%$  against  $\sim 23\%$  of passive neighbors within a distance of 1 Mpc, for LIRGs and ULIRGs, respectively).

### 5. $24\ \mu\text{m}$ GALAXIES IN THE zCOSMOS-RECONSTRUCTED DENSITY FIELDS

The zCOSMOS-bright 10k catalog has been used to reconstruct density fields up to  $z = 1$  (Kovač et al. 2009). It is of our interest to analyze the overdensities at the positions of the  $24\ \mu\text{m}$ -selected sources in comparison to other optical galaxies with similar stellar masses. A detailed explanation of the computation of these density fields is presented by Kovač et al. (2009). Here, we consider only mass-weighted density fields computed using the 5th nearest neighbor method. These density fields are fully corrected for the sampling effects of the zCOSMOS-bright 10k sample.

The three panels of Figure 5 show the mass-weighted overdensities ( $1 + \delta_5^{mw}$ ) for galaxies in our three IR galaxy populations, versus their stellar mass. For reference, we also plot the mean values and typical errors of the overdensities for galaxies in the respective control samples, in different stellar mass bins. The typical errors on the mass-weighted overdensities are  $\Delta \log_{10}(1 + \delta_5^{mw}) \lesssim 0.15$ , as determined by tests made on mock catalogs (Kovač et al. 2009).

We see that the IR galaxy overdensities are distributed around the mean values of the galaxies in the respective control samples. Globally, these results agree with the conclusions of Marcillac et al. (2008), who found that the differences between the environment densities of IR galaxies (LIRGs and ULIRGs altogether) and other optical galaxies at  $0.7 < z < 1.0$  are not important, when both samples are restricted to have similar stellar masses.

However, within our sample at  $0.6 < z < 0.8$ , we find that there are twice as many ULIRGs in underdense regions as in overdense ones (i.e., beyond the error bars of the control sample means). Instead, there are  $\sim 70\%$  more LIRGs in overdense regions than in underdense ones. Finally, at  $0.8 < z < 1.0$ , the number of ULIRGs in our sample that are present in over and underdense regions are quite similar. The differences in the general overdensities we find for LIRGs and ULIRGs are totally consistent with our results at smaller scales for the stellar mass ratio ( $M_{\text{central}}/M_{\text{neighbor}}$ ) distributions (see Section 3.2).

Our findings are not in contradiction with Marcillac et al. (2008) conclusions. If we considered our LIRGs and ULIRGs altogether, we would recover the result that IR sources at

$0.6 < z < 1.0$  do not prefer either under or overdense environments with respect to other similarly massive galaxies.

## 6. DISCUSSION

We conclude that LIRGs and ULIRGs at  $0.6 < z < 0.8$  have close (within 2 Mpc and  $\pm 500\ \text{km s}^{-1}$ ) environments characterized by significantly different degrees of activity: the fraction of “passive” galaxies around LIRGs is substantially higher than the fraction around ULIRGs. Remarkably, the differential activity is especially enhanced in the COSMOS density field peak at  $z \sim 0.67$ . By analyzing control samples with the same stellar mass distributions as the two respective populations of IR galaxies, we show that the differences in environment activity are not an effect of the central-galaxy stellar mass.

Instead, this is probably a consequence of the IR galaxy density fields. LIRGs and ULIRGs at  $0.6 < z < 0.8$  are surrounded by close neighbors of different stellar masses, and their general local overdensities are also different. ULIRGs inhabit underdense environments, while LIRGs prefer overdense regions. Thus, the differential activities observed in the environments of the two populations are related to their density fields.

At  $0.8 < z < 1.0$ , we also find that ULIRGs reside in more active, close ( $< 1$  Mpc) environments than those of other optical galaxies with similar stellar masses. However, we do not find any difference between the stellar mass distributions of their close neighbors. This is in contrast with the environmental properties of ULIRGs at  $0.6 < z < 0.8$ .

At  $0.8 < z < 1.0$ , the similarities of the environments in which ULIRGs and other equally massive galaxies live suggest that these other galaxies might have also passed by a ULIRG phase at some moment in the past (consistently with the high incidence of ULIRGs among massive galaxies at  $z \gtrsim 1.5$  found by Daddi et al. 2005 and Caputi et al. 2006b). The quenching of the IR phase in these galaxies could have happened along with the cessation of star formation in some of their close neighbors, raising the fraction of inactive sources in the surroundings.

The number density of ULIRGs has a rapid decline at  $z < 1$  and, in particular, it reduces to around a half in the 1 Gyr of elapsed time between redshifts  $z \sim 0.9$  and  $z \sim 0.7$  (Le Floc’h et al. 2005; Caputi et al. 2007). This evolution occurs together with a change of environments, suggesting that the conditions under which ULIRGs occur are not the same at  $z \sim 0.9$  and  $z \sim 0.7$ . ULIRGs at  $z \sim 0.9$  are found in similar kinds of sites as other equally massive galaxies, while those at  $z \sim 0.7$  appear mostly restricted to regions where they are the dominant galaxy of their close neighborhood. It is plausible that the ULIRGs

we observe at  $z \sim 0.7$  have been produced after the merging of close galaxies, leaving the final ULIRG close neighborhood empty of massive neighbors. At  $z \sim 0.9$ , even when mergers could also have been a possible mechanism for triggering the ULIRG phase, it seems that there has been no need to consume most of the close environment for these ULIRGs to be produced.

This paper is based on observations made with the VIMOS spectrograph on the VLT telescope, undertaken at the European Southern Observatory (ESO) under Large Program 175.A-0839, and also based on observations made with the *Spitzer* Observatory, which is operated under NASA contract 1407.

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