The primordial environment of supermassive black holes (II): deep Y and J band images around the z~ 6.3 quasar SDSS J1030+0524

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ABSTRACT

Many cosmological studies predict that early supermassive black holes (SMBHs) can only form in the most massive dark matter halos embedded within large scale structures marked by galaxy over-densities that may extend up to ~10 physical Mpc. This scenario, however, has not been confirmed observationally, as the search for galaxy over-densities around high-z quasars has returned conflicting results. The field around the z=6.28 quasar SDSSJ1030+0524 (J1030) is unique for multi-band coverage and represents an excellent data legacy for studying the environment around a primordial SMBH. In this paper we present wide-area (~25×25'), Y- and J-band imaging of the J1030 field obtained with the near infrared camera WIRCam at the Canada-France-Hawaii Telescope (CFHT). We built source catalogues in the Y- and J-band, and matched those with our photometric catalogue in the r, i bands presented in Morselli et al. (2014) and based on sources with z\_sp<25.2 detected in the LBT/LBC z-band images over the same field of view. We used these new infrared data together with H and K photometric measurements from the MUSYC survey and Spitzer/IRAC data to refine our selection of Lyman Break Galaxies (LBGs), extending our selection criteria to galaxies in the range 25.2 < z\_sp<25.7. We selected 21 robust high-z candidates in the J1030 field with photometric redshift z\_sp<6 and colors i-z\_sp≥1.3. We found a significant asymmetry in the distribution of the high-z galaxies in J1030, supporting the existence of a coherent large-scale structure around the quasar. We compared our results with those of Bowler et al. (2015), who adopted similar LBGs selection criteria, and estimated an over-density value and its significance are higher than those found in Morselli et al. (2014), and we interpret this as evidence of an improved LBG selection.

Key words. Galaxies: high-redshift, Galaxies: photometry

1. Introduction

Super-Massive Black Holes (SMBHs), found at the center of distant (z>6) and very luminous (>10^{47} erg s^{-1}) quasars (QSOs), are among the most challenging astronomical objects ever observed (Mortlock 2015; Wu et al. 2015). The mechanism by which these SMBHs of 10^{7}-10^{9} M_\odot formed and grew when the universe was only 1 Gyr old is the subject of many theoretical speculations. Recent simulations show that early SMBHs can only form in the most massive dark matter halos, that could eventually evolve into the present-day clusters of galaxies with M\_p>10^{14}-15 M_\odot (Costa et al. 2014). As such, high-z QSOs should be part of early large-scale structures marked by large galaxy over-densities that may extend up to radii of ~10 physical Mpc (pMpc), (e.g. Overzier et al. 2009; Di Matteo et al. 2012; Angela et al. 2013), corresponding to Δz ± 0.15 in redshift space at z = 6. Furthermore, these regions are expected to evolve at a substantially accelerated pace and should be populated by galaxies that are more massive, dusty, and star-forming than those in average-density fields, reaching star formation rates as high as ≥700 M_\odot yr^{-1} (Yajima et al. 2015).

Understanding how the largest observed structures have formed has fundamental implications on the standard formation model of the Universe. The suggested theoretical scenario is not confirmed, since currently we lack clear observations of the environment in which high-redshift QSOs reside. This research line has produced discrepant results: different authors found number densities of Lyman Break Galaxies (LBGs) around high-z QSOs that are higher (e.g. Garcia-Vergara et al. 2017 at z~4), lower or consistent with what is expected in blank fields (Kim et al. 2009). One possible reason for these inconsistent results is that most attempts used small-FoV instruments, like the 3′×3′ HST/ACS, or 6′×6′ imagers at best (e.g. Stiavelli et al. 2005; Husband et al. 2013; Simpson et al. 2014; Mazzucchelli et al. 2016), equivalent to distances of ~ 0.5-1 pMpc from the QSO, whereas these structures may extend well beyond. Furthermore, the intense UV radiation and gas outflows released by the quasar (feedback effects) might affect its environment ionizing and heating the intergalactic medium up to several Mpc away (e.g. Rees 1988; Babul...
The star formation could be prevented especially in less massive galaxies and this could cause the observed deficiency of Ly\textalpha emitters (LAEs) around QSOs (Kashikawa et al. 2007; Overzier 2016; Mazzucchelli et al. 2017). Therefore, the presence of an over-density of galaxies might then be best explored at larger scales. Indeed, measurement performed with the wide-field 33′×27′ Suprime-Cam at the Subaru Telescope revealed tentative evidence of an overdensity around two z∼6 QSO (Utsumi et al. 2010; Díaz et al. 2014), one of them being in fact SDSS J1030+0524 (Díaz et al. 2014).

With the goal of understanding the environmental properties of distant quasars on wide scales, we started a multi wavelength campaign in the fields around high redshift QSOs. In 2012 we obtained deep r, i, z imaging with the Large Binocular Camera (LBC) at the Large Binocular Telescope (LBT) of the fields around four SDSS QSOs in the redshift range z = 5.95 − 6.41, selected to have $M_{\text{BH}} > 10^9 M_\odot$. We produced photometric catalogues of all the sources detected in z-band. To identify candidates galaxies around the redshift of the quasars, we applied the drop-out technique (e.g. Steidel et al. 1996; Dickinson et al. 2004; Bouwens et al. 2015; Vanzella et al. 2009), looking for the Lyman-\alpha break feature that at z∼6 is redshifted between the i- and z-band. The LBC data depth combined with the large FoV (∼ 25′×25′), allowed the selection of i-band dropout galaxies down to z_{AB}=25.2 (5σ) in a sky area corresponding to ∼8×8 Mpc^2 at z ∼ 6.

After accounting for cosmic variance and photometric errors, we measured an i-band dropout overdensity in all fields, with significance ranging from 1.7 to 3.3σ (3.7σ when combining the four fields, Morselli et al. 2014, in the following M14). This suggests that the dense environment around early QSOs are best traced on large scales.

In this paper we focus on the most over-dense of our fields, i.e. the one around the z = 6.28 QSO SDSS J1030+0524 (hereafter the J1030 field). We present deep Y-band and J-band imaging with WIRCam at CFHT to integrate our photometric source catalogue with these two bands. These data are essential to discriminate between high redshift galaxies and stellar contaminants, by building diagnostic color-color diagrams or computing robust photometric redshift estimation. Deep Spitzer/IRAC imaging at 3.6 and 4.5 µm is available for most objects and some targets have also been detected in the MUlti-wavelength Survey by Yale-Chile (MUSYC, Quadri et al. 2007; Blanc et al. 2008). Our team was also granted 500ks with Chandra in 2015 (the observations are ongoing) with the main aim to search for the first detection of “satellite” AGN in this high density environment. All the data we are collecting make this field an excellent legacy site.

The purpose of this paper is two-fold. First we present the new Y-band and J-band photometric catalogue in the J1030 field. We describe the observations (Sect. 2) and how we combine the Y, J photometry with the optical r, i, z multicolor catalogue (Sect. 3). Second, we use these data to improve the reliability of our LBG candidates with color plots and building the SEDs to derive photometric redshifts (Sect. 4). We discuss our results in Sect. 5 and we present our summary and conclusions in Sect. 6. Unless otherwise indicated, magnitudes are given on the AB system, for which, by definition, a constant flux of 3720 Jy represents mag=0. Throughout the paper we use $H_0=70$ km s⁻¹ Mpc⁻¹, $\Omega_m=0.3$, and $\Omega_L=0.7$.


1 http://www.oabo.inaf.it/-LBT/z6/.

2 Terapix is an astronomical data reduction centre dedicated to the processing of data from various telescopes and optical or near infrared cameras, such as WIRCam.
### Table 2. Multi-band photometry for the sample LBG primary, secondary and faint candidates.

| Id  | RA             | DEC             | r     | i     | z     | Y     | J     | ch1 | ch2 |
|-----|----------------|-----------------|-------|-------|-------|-------|-------|-----|-----|
| 2140| 10:30:00.4      | +05:16:02.4     | >27.60| 26.61±0.28 | 24.99±0.11 | >24.72 | 23.26±0.10 | 21.41±0.20 | –   |
| 3200| 10:31:05.2      | +05:16:52.7     | >27.61| 24.70±0.05 | 23.24±0.02 | 23.94±0.12 | 23.06±0.06 | –   |
| 6024| 10:30:07.9      | +05:18:58.6     | >27.82| 25.62±0.13 | 23.43±0.09 | 23.15±0.09 | >22.92 | –   |
| 11963| 10:31:57.1     | +05:23:22.7     | >27.90| 25.09±0.13 | >24.88 | >24.82 | >22.65 | >24.44 |
| 12265| 10:30:11.8     | +05:23:35.6     | >27.74| 25.64±0.16 | 24.07±0.08 | 23.38±0.10 | 23.40±0.10 | >23.22 |
| 18619| 10:30:19.6     | +05:28:00.7     | >27.76| 24.77±0.05 | 23.41±0.03 | 22.97±0.06 | 22.41±0.05 | 23.36±0.20 | >23.07 |
| 21438| 10:31:08.8     | +05:30:07.9     | >27.99| >26.93 | 24.99±0.12 | >24.78 | >24.60 | –   | >22.50 |
| 21596| 10:30:04.6     | +05:30:15.6     | >27.79| >27.02 | 24.66±0.08 | 23.82±0.15 | 22.98±0.07 | >22.65 | >24.27 |
| 23354| 10:30:08.3     | +05:31:33.4     | >27.43| >26.57 | 25.08±0.18 | >24.76 | >24.85 | >22.54 | >22.18 |
| 24071| 10:30:21.3     | +05:32:17.0     | >27.85| 26.47±0.27 | >24.81±0.11 | 24.38±0.19 | >24.11±0.17 | 23.12±0.50 | >20.81±0.25 |
| 25831| 10:30:54.8     | +05:33:59.9     | >27.78| 26.46±0.24 | 24.61±0.08 | 24.26±0.24 | 23.32±0.11 | –   | >23.23±0.30 |
| 25971| 10:30:58.9     | +05:34:07.8     | >27.62| >26.80 | 25.03±0.12 | >24.87 | >24.70 | >22.41 | >22.41 |
| 26728| 10:30:21.5     | +05:34:49.6     | >28.10| 24.81±0.05 | 23.44±0.03 | 22.80±0.06 | 22.45±0.05 | >22.54 | >22.41 |
| 28941| 10:30:05.2     | +05:36:57.1     | >27.94| >26.98 | 25.18±0.14 | >24.80 | >24.85 | >22.62 | >22.70 |

#### Column description:
- AB aperture corrected magnitudes in the r, i, z, Y, J band and IRAC/Spitzer Channel one and two for the primary, secondary and faint candidates. Upper limits are at 2σ.

- Seeing in the final mosaic, computed measuring the FWHM of morphological and color selected star candidates, and the Galactic dust absorption correction factor.

#### 2.2. Photometric catalogue in the Y and J band

We used the software SExtractor version 2.19.5 (Bertin & Arnouts 1996) to detect objects in the Y and J-band images. All the input parameters are fixed to the default values except the photometric zero points, adopting the values reported in Table 1 and corrected for Galactic dust extinction and the aperture correction, and the seeing FWHM. On the clean regions of the WIRCam images (after masking the noisy edges, a product of the dithering), we detect 13540 (14770) objects down to Y_{AB} ≈ 25.0 and the similar number of detected sources in the J-band with J_{AB} ≈ 24.5.

Our optical photometric catalogue, based on source detection in the z-band image, contains ~ 2.7 × 10^4 objects above the 50%
completeness limit\(^3\) of \(z_{AB}=25.2\) magnitude at 5\(\sigma\) (M14). We cross correlated the LBC photometric catalogue with the new Y and J catalogues, finding that about 49\% (46\%) of the objects detected in the \(z\) band are detected in the Y (J) band. Conversely, 94\% (91\%) of the source detected in the Y (J) catalogue are detected in the LBC \(z\) optical bands.

2.3. Multi band photometric measurements

We use the IDL routine aper (adapted from the IRAF/DAOPHOT package) to measure the brightness of LBGs candidates in the Y and J band, assuming a circular aperture of radius 0.8′′ (in M14 we choose this aperture size to collect a large fraction of the flux from the object while minimizing the contamination from neighboring sources). Comparing the magnitude measured in the adopted aperture with the total magnitude measured for a sample of stars, we derived the correction factor for the aperture, that takes into account the flux lost outside the aperture in unresolved sources due to seeing conditions (see Table 1). In the following we will use the aperture corrected magnitude for the photometric color measurements, a good proxy for the total magnitude for our faint, unresolved targets. We estimate the background in a circular region (with the same radius of the extraction region) randomly selected within 50′′ from the source. Therefore, to provide a robust estimate of the noise level, we evaluate the rms of the flux distribution by mirroring its negative part. We convert this value into a magnitude taking into account the aperture correction and finally we estimate the 2\(\sigma\) upper limits adopted throughout the paper.

3. Selection of LBGs around high-z QSO

Here we enlarge the number and improve the robustness of possible \(z=6\) galaxy candidates in the J1030 field with respect to M14.

The redshift window sampled by the i-band dropout technique is broad (\(z \sim 5.6-7\), adopting a color threshold of \(i-z>1.3\) e.g. Beckwith et al. 2006), but we note that even objects at redshifts significantly different from that of the central QSO can still be part of its large structure (e.g. \(\Delta z = 0.15\) at \(z = 6\) is \(\sim 10\) physical Mpc, consistent with the large scale structure size in the Overzier et al. 2009 simulations).

Several contaminants at lower redshift can survive the \(i-z\) color selection. The most numerous ones are expected to be dwarf stars of M, L, T types in our Galaxy, whose colors can match those of candidate high-z galaxies. Additionally, dusty star forming galaxies and obscured AGN at lower redshift can mimic the Lyman break of true high redshift galaxy. Finally, the Balmer break at 4000Å (D4000) of a passively evolving galaxy at \(z \sim 1.1\) can be mistaken for the Lyman break (Dunlop 2013; Finkelstein 2015).

Full details on the adopted optical color selection criteria can be found in M14. Briefly, since most of the spectroscopically confirmed galaxies at redshift \(-6\) show \(i-z\) colors greater than 1.3 (e.g. Vanzella et al. 2009), we adopted this threshold value. In M14 we then created a catalogue of LBC primary dropouts adopting a stringent criterion \((i-z) - \sigma_{i-z} > 1.3\) and requiring that these objects are undetected in the \(r\)-band at 3\(\sigma\) (\(r_{AB} > 27.2\)) and are detected at 5\(\sigma\) in the \(z\)-band with \(z_{AB} < 25.2\), our completeness limit. In addition, in order to investigate the presence of interesting high-z outliers to be followed-up spectroscopically among bluer objects (e.g. the few galaxies at \(z \sim 5.7\) with strong Ly\(\alpha\) emission among the vast majority of stars and low-z galaxies), we created a catalogue of secondary drop-out candidates by relaxing our color criteria \([1.1 < (i-z) - \sigma_{i-z} < 1.3]\). In fact, these objects were excluded from the estimation of the over-density levels in M14.

Here we extended our analysis to \(z \sim 6\) LBG candidates at fainter magnitudes. In particular we selected objects undetected in the \(r\) band, with \(25.2 < z_{AB} < 25.7\) (5\(\sigma\)), and color \(i-z\geq1.3\). At \(z_{AB} > 25.2\) the predicted number density of \(z \sim 6\) LBGs is higher than that of dwarf stars, since the predicted number of dwarf stars, since the predicted number of dwarf

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\(^3\) The completeness limit was defined as the magnitude at which the number of detected objects fall at 50\% of the expected value.

\(^4\) see pag. 64 of the IRAC Instrument Handbook.
stars declines at brighter magnitudes, while the expected count of high redshift LBGs increases at fainter magnitudes. The selection of high-z LBGs should therefore be less susceptible to star contamination below this magnitude threshold (see Fig. 2 in Bowler et al. 2015). We visually inspected the images of all the candidates and rejected obvious image artifacts or problematic objects close to luminous stars or on the image edges. At the end we select 18 new LBG candidates to which we refer as faint candidates. In Fig. 2 we present the J1030 field in the J and Y band, with overlaid in different colors the primary and secondary candidates of M14 and the new faint candidates. In Table 2 we report the full photometric information for all these samples.

### 3.1. Color-color Diagram

A widely used technique to separate contaminants from genuine LBGs at $z \sim 6$ is to use color-color diagrams that involve near-IR colors, morphology and photometric redshift. In particular, color-color diagrams involving the i-, z- and Y-bands are effective in isolating candidate LBGs at $z > 6$ (Bowler et al. 2015; Matsuoka et al. 2016).

In Fig. 3 we show the position of our candidates in the z-Y vs i-z color-color diagram. The small grey dots represent the color of point like sources, likely stars in the J1030 field, selected to have the Sextractor morphological parameter CLASS_STAR$>0.95$ and stellar optical colors. The red, green, and cyan points represents the primary, secondary and faint candidates. Using the Hyperz code (Bolzonella et al. 2000), we derived the expected colors of a typical starburst galaxy and of a quasar at redshifts greater than 5.5, taking into account the IGM absorption and the convolution with the transmission function of the adopted filter. We assumed a template from Bruzual&Charlot (2003) with age 0.5 Gyr and metallicity $Z = 0.02 Z_\odot$ for the star forming galaxy, and a type 1 QSO template from the SWIRE library for the quasar (Polletta et al. 2007). All the 42 candidates are detected in the z band by selection, and show upper limits to the i-z color if undetected in the Y band and lower limits to the i-z color if undetected in the i band. Nineteen objects, mostly from the faint sample, have limits in both colors.

### 3.2. Morphological classification of LBGs

To perform a morphological classification, we use the classical mag(aperture) vs. mag(total) diagnostic plot, since the ratio between these two quantities represents a robust index of source concentration. By applying this diagnostic to the band with the highest S/N candidate detection, we classify all the primary and secondary targets as extended or point like (flag ‘e’ or ‘p’).

We do not attempt to assign a morphological description to the fainter candidates, since the technique is not reliable at the very faint flux level. We use the morphological classification as an exclusion criteria, taking out the stellar templates in the photometric redshift estimate in case of extended source. In fact, while the brown dwarf stars are always unresolved, the Lyman break galaxies could appear as spatially extended in ground based images. For example Willott et al. (2013) found that about 50% of their sample of galaxies at $z\sim 6$ are spatially resolved in 0.7 arcsec seeing images.

### Table 3. Colors, morphology, photometric redshift and final classification for our candidates.

| Id  | i-z  | z-Y  | z$_{phot}$ | $\chi^2_{red}$ | class     |
|-----|------|------|------------|----------------|-----------|
| 2140| 1.62 | <0.27| 0.6$^{+0.1}_{-0.2}$ | 1.5           | g e gal   |
| 3200| 1.46 | -0.70| 5.5$^{+0.1}_{-0.1}$ | 12.6          | g p gal   |
| 6024| 1.69 | 1.13 | 0.0         | 1.5           | s p star  |
| 11963|>1.65|<0.21|>5.7         | -             | g p highz |
| 12265|1.58 | 0.68 | 0.0         | 0.2           | s p star  |
| 18619|1.36 | 0.44 | 0.0         | 0.6           | s p star  |
| 21438|>1.94|<0.42|>5.7         | -             | g p highz |
| 21596|>2.35|0.84 | 0.0         | 0.6           | s? p star |
| 23354|>1.49|<0.32|>5.7         | -             | g ? highz |
| 24071|1.66 | 0.44 | 5.7$^{+0.1}_{-0.1}$ | 0.1          | g e highz |
| 25831|1.85 | 0.35 | 0.0         | 0.9           | g e gal   |
| 25971|>1.77|<0.16|>5.7         | -             | g p highz |
| 26728|1.37 | 0.64 | 0.0         | 0.4           | s p star  |
| 28941|>1.80|<0.37|>5.7         | -             | g ? highz |
| 1851|1.19 | 1.02 | 0.0         | 2.0           | s p star  |
| 4941|1.24 | 0.62 | 0.0         | 0.2           | s p star  |
| 10226|1.20 | 0.55 | 0.0         | 0.2           | s p star  |
| 14587|1.44 | 0.69 | 0.0         | 0.1           | s p star  |
| 18004|1.22 | 0.45 | 0.0         | 4.2           | s p star  |
| 19010|1.28 | 0.46 | 0.0         | 3.1           | s p star  |
| 20308|1.38 | 0.66 | 0.0         | 0.2           | s p star  |
| 28412|1.44 | 0.11 | 0.0         | 0.5           | g p star/gal |
| 30816|1.48 | 1.30 | 0.0         | 1.6           | s p star  |
| 31199|1.50 | 0.99 | 0.0         | 0.2           | s p star  |
| 2335|>1.71|<1.08|>5.7         | -             | s? highz  |
| 3909|>1.74|<0.84|>5.7         | -             | s? highz  |
| 5674|1.34 | <0.68| 0.8$^{+0.4}_{-0.4}$ | 0.3          | g gal     |
| 6250|>1.70|<0.48|>5.7         | -             | g highz   |
| 11792|>1.61|<0.97|>5.7         | -             | s? highz  |
| 12143|1.58 | 1.17 | 0.0         | 0.1           | s star    |
| 15042|1.64 | <0.44|>5.7         | -             | g highz   |
| 15901|1.80 | <0.36|>5.7         | -             | g highz   |
| 17435|1.58 | <0.62|>5.7         | -             | g highz   |
| 17470|1.63 | <0.49|>5.7         | -             | g highz   |
| 17612|1.52 | <0.77|>5.7         | -             | g? highz  |
| 18262|1.66 | <0.88|>5.7         | -             | s? highz  |
| 19668|1.49 | <0.66|>5.7         | -             | s? highz  |
| 20654|1.52 | <0.41| 5.7$^{+0.2}_{-0.3}$ | 0.2          | g highz   |
| 21945|>1.73|<0.27|>5.7         | -             | g highz   |
| 23132|>1.65|<0.54|>5.7         | -             | g highz   |
| 26972|1.80 | <0.31| 5.8$^{+0.3}_{-0.1}$ | 0.1          | g highz   |
| 30511|>1.30|<1.14|0.0         | 0.3           | s? star   |

Column description, Col. 1: Id from M14; Col. 2-3: i-z and z-Y colors; Col. 4: photometric redshift from Hyperz SED fitting with errors at 1$\sigma$; Col.5: reduced $\chi^2$ of the fit to the photometric sed; Col. 6: ‘s’ if the color of the target is more similar to stars or ‘g’ if it is more similar to galaxies in the i-z vs z-Y diagnostic plane; Col. 7: morphology of the targets in the z band, ‘e’ extended or ‘p’ point-like; Col. 8: our final classification in contaminant objects (star ‘star’ or low redshift galaxies ‘gal’) or genuine high redshift galaxies ‘highz’ candidates based on colors, morphology and photometric redshift.

### 3.3. Photo-z estimation of LBGs

In order to obtain photometric redshift measurements, we built the spectral energy distribution (SED) of the LBGs candidates, with aperture matched, multi-band photometry extending as much as possible the wavelength range considered. So, along...
Fig. 3. Diagnostic (z-Y) vs (i-z) color-color diagram. Small grey dots are point-like sources in the J1030 field (star locus). Red, green and cyan are the primary and secondary candidates of M14 and the new faint candidates, respectively. For those objects that are not detected at the 2σ level in i or in Y we used the 2σ local limiting magnitudes. The limits on their colors are marked with arrows. The black curve shows the expected color track (in steps of Δz = 0.1, starting from 5.5) of a high-z star forming galaxy with age 0.5 Gyr and Z = 0.02 Z⊙ (from Bruzual&Charlot 2003). The grey curve has been calculated with the same template but with an intrinsic absorption A_v equal to 1 and the green curve adding to the template a Lyα emission line with EW = 100 Å rest frame. The blue curve shows the expected color track of a Type 1 QSO (template from the SWIRE library). Objects that have now been classified as reliable z ~ 6 LBGs (see Table 3 and Section 4) are marked with large black open circles. The bigger magenta circle and the diamond symbol represent the colors of the stack of the LBGs candidates and stellar contaminants, respectively. The blue point marks the position of the central QSO SDSS J1030+0524 at z=6.28.

with the new Y and J WIRCam observations, we use the optical r, i, z photometric measurements (in blue-ward optical bands) we do not have images deep enough to detect sources with expected AB magnitudes fainter than 28, the median global upper limit in the r band in M14). We searched for H and K photometric measurements in the MUSYC survey, which includes a wide part covering our entire field down to a typical 5σ limit of K_{AB} = 21.7 (Blanc et al. 2008) and a of 10′ × 10′ central and deeper region down to H_{AB} and K_{AB} of 22.9 in both bands (5σ). We found that 2 primary candidates are detected in the H band (4 in the K band) and 3 secondary candidates are detected both in the H and K bands. Finally we searched the Spitzer Heritage Archive (SHA) for IRAC images in the 3.6 and 4.5 μm bandpasses (ch1 and ch2, respectively) to extend the photometric SED at longer wavelengths. Two Program IDs (namely 30873 and 10084) cover more than half of the field once combined. Only three primary and one secondary candidates have not Spitzer photometric coverage in the IRAC 3.6 band (three and one in the IRAC 4.5 band). We downloaded the Level 2 images of these two datasets, and we perform photometry of the targets as described in Sect.2.3.

We used Hyperz to refine our redshift estimates and pinpoint low-z interlopers. The photometric redshifts are based on a χ^2 fitting procedure to the observed fluxes (or magnitudes), and photometric errors. The SED is matched to the galaxy templates, convolved with the filter response in each of the input bands, and corrected for the absorption by intervening HI clouds following the Madau (1995) prescription. In literature updated versions of the so-called Madau model for the IGM attenuation have been proposed (e.g. Meiksin 2006; Inoue et al. 2014). However, the differences in the predicted colors and in the photometric redshift estimates should be small (about 0.05, see Inoue et al. 2014). We also accounted for possible internal reddening assuming the Calzetti extinction law (Calzetti et al. 2000). If an object is not detected in one band we set its flux to F_{lim} and its 1σ error to F_{lim}/2, where F_{lim} is the flux corresponding to the 2σ limiting magnitude in that band.

Our primary templates are the four templates of Coleman et al. (1980) observed spectra (Ell, Sbc, Scd, Irr) extended into the UV and NIR using the spectral synthesis models of the Galaxy Isochrone Synthesis Spectral Evolution Library (GISSEL98; Bruzual A. & Charlot 1993). These five templates are
linearly interpolated to produce a total of 62 templates as described in Ilbert et al. (2006). We add an observed starburst SED from Kinney et al. (1996) and 6 additional templates generated using Bruzual & Charlot (2003, hereafter BC03) models with starburst (SB) ages of 0.05, 0.15, 0.50 Gyr and metallicity 0.02 and 0.2 solar. These templates are commonly used to estimate photometric redshifts (Brodwin et al. 2006; Ilbert et al. 2006). Finally, to account for stellar contamination, we add the 21 models of dwarf stars of ML and T type from the SpeX Prism Spectral Libraries\(^5\), whose colors can match those of our candidate galaxies. We extend the stellar templates from 2.5 to 4.5 \( \mu m \) assuming a simple power-law \( F_{\nu} \sim \nu^{\beta} \) with \( \beta = -4.0 \). We fit each photometric SED using the two sets of templates separately, considering a redshift range between 0 and 0.01 and between 0 and 7 for the stellar and galaxy solution, respectively, and we discriminate between the two solutions according to the \( \chi^2 \) value. We note that in many cases we obtained very low values for the reduced \( \chi^2 \) because of the many upper limits in the SEDs.

For each source, we derived photometric redshifts using the complete seven-band observed photometry when available. For those objects that are just detected in the \( z \)-band we just use photometric redshift measurement as a cross check of the information obtained through the \( z \)-\( Y \) vs \( i-z \) color-color diagram, and we report in Table 3 a lower limit of \( z > 5 \) to the redshift estimate that matches the adopted color cuts. In Fig. 4 we present postage stamps in the \( rizYJ \) filters, best fit photo-z solution and corresponding probability distribution function (PDF) as calculated by Hyperz for two objects, a likely star and a reliable high-z candidate. We provide images, photo-z solutions and PDFs for all our LBG candidates at the project webpage.

4. Results and discussion

We collect all the information available for each LBGs candidate, i.e. the position in the diagnostic color plane, a robust morphological classification, and the photometric redshifts, to produce a list of robust LBG candidates (see for example Fig. 4). In Table 3 we report the \( i-z \) and \( z-Y \) colors with a flag \( 's' \) to identify objects with colors similar to stars and a flag \( 'g' \) to identify candidates with colors similar to galaxies (located in the lower-right portion of the color plane in Fig. 4).

We select as reliable LBGs candidates (\( highz \) in Table 3) the 21 objects with photometric redshift higher than 5.7. For many targets the morphology is coherent with being an extended object at high redshift. In other cases the classification is more uncertain, because their colors are consistent with stellar objects (this is the case for 5 candidates). These sources are flagged with a question mark and classified as ("\( highz? \)"). Other 16 have a photometric redshift of zero (their SEDs are best fitted with a stellar template and we classify as \( stars \)), 4 are low redshift galaxy \( gal \) and 1 is best fitted with a stellar template but it has a typical galaxy color \( star/gal \). We conclude that \( \sim 40\% \) of the \( primary \) sample is made by robust \( z \sim 6 \) LBG candidates. The entire \( secondary \) sample, instead, appears to be made of contaminants. This is somewhat expected due to the fact that the \( secondary \) sample was composed, by construction, of bluer dropouts and of brighter objects, on average half magnitude brighter than the primary sample. Following this trend the percentage of contaminants in the \( faint \) sample is the lowest (\( \sim 20\% \)). We point out that in our previous paper (M14) we found an over-density of LBGs associated with the large scale structure of the quasar considering only the primary candidates with colors (\( i-z \)) < 1.8 (corresponding to \( z \geq 5.9 \)), that we reconfirm here to be mostly trustworthy LBG candidates.

To double check the reliability of our classification for targets with only a photometric detection in the \( z \)-band, as is the case for many of our faint candidates, for each filter we stacked the images of all objects classified as high-z galaxies and those of all objects classified as stars according to Tab. 3 and derived the photometry in the \( rizYJ \) bands for each of the two stacks. The colors of the stack of stellar candidates are \( (i-z)_{\text{star}} = 1.4 \) and \( (z-Y)_{\text{star}} = 0.6 \) and the stack of stellar candidates fall indeed well within the stellar locus (magenta diamond in Fig. 3). In the \( r \) band the stacked stars are marginally detected, providing a further confirmation that they can not be at high redshift, since we expect that at \( z \geq 5 \) all the emission in this band would be absorbed by the IGM. For the stack of \( highz \) candidates we derived \( (i-z)_{\text{highz}} > 2.7 \) and \( (z-y)_{\text{highz}} < 0.4 \). The colors of the high-z stack are instead closer to the tracks of high-z galaxies and AGN, well below the stellar locus, and hence reinforce our classification scheme. We note that the particularly blue \( z-Y \) color obtained for the stack of high redshift candidates could be due to the presence of strong Ly\( \alpha \) emission (e.g. Vanzella et al. 2009). At \( z > 5.9 \) the line indeed falls in the \( z \)-band, and its presence is taken into account only in our QSO template but not in the galaxy template. Based on these stacks, we found that the stack of stellar candidates is in fact best fit by a star template (at \( z=0 \)), whereas the stack of the 21 \( z < 6 \) LBG candidates is best fit by a galaxy template at \( z_{\text{phot}} = 5.95 \pm 0.06 \) (Fig. 5).

4.1. The spatial distribution of LBGs candidates

Another indication that our selected final LBGs candidates are probably not dominated by contaminants is that they are not randomly distributed, but they appear to be concentrated in a specific sky area (Fig. 6). In fact, the distribution of stars is expected to be random, whereas significant asymmetries may be found in the distribution of the high-z galaxies belonging to the quasar structure (e.g Overzier et al. 2009). We estimated the binomial probability to have 17 or more candidates out of the 21 candidates with RA values smaller than the central QSO, assuming the null hypothesis that they are randomly distributed. We repeat the same calculation for 12 or more out of 21 high-z candidates that populate the northern-western(NW) quarter of the field. We obtain a probability of obtaining these asymmetric spatial distributions as low as 0.3% and 0.2%, respectively. If we consider only the candidates robustly classified as ‘\( highz \)’ (i.e. excluding the ‘\( highz? \)’ candidates, in this case the probability are 1% (13 out of 16 candidates in the western half region) and 0.02% (11 out of 16 in the NW quarter of the field). If we do the same exercise considering only the \( primary \) sample, the probability is 4% (4 out of 6 of the high-z candidates in the primary sample are in the NW region). In order to test if the asymmetric distribution of the high-z candidates was not related to a global variation of objects detected in the field, we divided the parent photometric catalog in four quadrants with the quasar SDSS 1030+0524 as the central point. The density of detected objects in the whole field is remarkably constant, with a relative variation less than 3% of the number of galaxies included in each of the four quadrants. If we restrict such analysis to the reddest objects (with 0.8<(\( i-z \))<1.1), the uniformity holds, albeit with larger variation due to the reduced statistics.

To better quantify whether the spatial distribution of the 21 high-z galaxy candidates differs from a random distribution, we compared their angular correlation function with that of objects classified as contaminants (either stars or low-z galaxies). The
two-point angular correlation function \( w(\theta) \) is defined as the excess probability over random of finding a pair of galaxies in the two small sky areas \( d\Omega_1 \) and \( d\Omega_2 \), separated by an angle \( \theta \) (Peebles 1980), that is: \( dP = n^2[1 + w(\theta)]d\Omega_1d\Omega_2 \), where \( n \) is the mean galaxy density.

To measure \( w(\theta) \), we used the minimum variance estimator proposed by Landy & Szalay (1993):

\[
w(\theta) = \frac{[DD] - 2[DR] + [RR]}{[RR]}, \tag{1}
\]

where [DD], [DR] and [RR] are the normalized data-data, data-random and random-random pairs, i.e.

\[
[DD] \equiv DD(\theta) \frac{n_r(n_r - 1)}{n_d(n_d - 1)}, \tag{2}
\]

\[
[DR] \equiv DR(\theta) \frac{(n_r - 1)}{2n_d}, \tag{3}
\]

\[
[RR] \equiv RR(\theta), \tag{4}
\]

where \( DD \), \( DR \), and \( RR \) are the number of data-data, data-random, and random-random pairs at separations \( \theta \pm \Delta \theta \) and \( n_d \)
and \( n_r \) are the total number of sources in the data and random sample, respectively. Random sources were distributed across the field according to a spatial mask that follows the geometry of the LBC field of view and removes the same regions excluded when selecting i-band dropouts (e.g. noisy regions around bright stars). Each random sample is built to contain more than 10000 objects. We considered a range of separations of \( \sim 1 - 30 \) arcmin and binned the source pairs in intervals of \( \Delta \log(\theta/\text{arcmin}) = 0.2 \).

As shown in Fig. 7, high-z galaxy candidates show a positive clustering signal (significant at the \( \sim 3\sigma \) level) on scales \( \lessapprox 10 \) arcmin, whereas the spatial distribution of the contaminants is fully consistent with random. These results do not change significantly if the most uncertain high-z candidates are removed (i.e. the 5 objects with a question mark in Table 3). This strongly supports the goodness of our color-morphology classification described in Section 4.1.

We also fitted to our data a functional form \( w(\theta) = A_w(\theta^\beta - C) \), where \( \theta \) is expressed in arcsec, and \( A_wC \) is the so-called integral constraint, that accounts for the underestimate of \( w(\theta) \) in finite-size fields. Following Roche & Eales (1999) we computed \( C \) using the number of random-random pairs in each angular bin as: \( C = \sum \frac{R R(\theta)}{\sum R R(\theta)} \). The best-fit parameters were determined via \( \chi^2 \) minimization. Given the small number of pairs that fall into some bins (especially on the smallest scales), we used the formulae of Gehrels (1986) to estimate the 68% confidence interval (i.e. 1\( \sigma \) errorbars in Gaussian statistics. We fixed \( \beta = 0.8 \), as commonly found in galaxy clustering stud-
A constraint. The best fit to the high-z galaxy correlation function including the integral correlation is observed for the contaminants. The red dashed line is for highz candidates at \( \delta = 2.4 \) and for the sample of 22 contaminants with \( \delta_{ap} < 25.6 \). Based on the histogram in Fig. 6 of Bowler et al. (2015), we counted 61 such objects in their surveyed area of 1.65 deg\(^2\). Rescaling for the different area of 0.144 deg\(^2\) of our field, we would expect a number of dropouts in our field area of 5.3, whereas we selected 18 candidates with \( \delta_{ap} < 25.6 \) (see Fig. 8). The Poisson probability of observing 18 or more objects when only 5.3 are expected is 1.2 \( \times 10^{-5} \), corresponding to a significance of \( > 4 \sigma \) assuming a normal distribution (considering our primary and faint LBG candidate samples separately, we obtained measured overdensity levels of 2 and 3.7\( \sigma \), respectively). Based on these numbers, we estimate that the J1030 field features an over-density of \( \Delta \rho \sim 6 \) LBGs equal to \( \Delta \delta = 2.4 \) (defined as \( \delta \geq 2 - 1 \), where \( \rho_0 \) is the expected number counts, see M14 for details). We then confirm and reinforce the over-density of LBGs found in the J1030 field in M14 (\( \delta = 2.0 \) at 3.3\( \sigma \)), where we compared the number of i-band dropouts in our field with that expected over a blank sky field when observing 18 or more objects at 3\( \sigma \). Even after accounting for the different image depths and photometric systems, this suggests that the new selection criteria based on optical/near-IR colors and photometric redshifts have in fact improved the selection of robust LBG candidates.

### 4.2. The overdensity of LBGs

We then compared the total number of i-band dropouts observed in the J1030 field with that expected over a blank sky field when using similar photometric bands and images depths, and adopting similar LBG selection criteria. A reference work that satisfies these requirements is that of Bowler et al. (2015). These authors perform a selection of LBGs in the redshift range between 5.5 and 6.5 within a 0.91 deg\(^2\) of imaging in the UltraVISTA/Cosmological Evolution Survey (COSMOS) fields and within a 0.74 deg\(^2\) imaging in the United Kingdom Infrared Telescope Deep Sky Survey (UKIDSS) Ultra Deep Survey (UDS) fields. They used multi-wavelength data in the optical (u, g, r, i) and near infrared bands (Y, J, H, K) and their selection is based on photometric redshifts. Their images reach a 5\( \sigma \) depth of \( m_{AB} = 26.7 \) in the z-band and a 5\( \sigma \) depth of \( m_{AB} = 25.3 \) in the Y-band.

Based on the z-band magnitude distribution of our LBG candidates (see e.g. Fig. 8), we see that our sample is severely incomplete at aperture-corrected magnitudes of \( z_{AB} > 25.5 \). To allow a proper comparison with our sample, we therefore considered those LBG candidates of Bowler et al. (2015) at \( z > 5.7 \) and with aperture magnitudes of \( z_{ap} < 25.6 \). Based on the histogram in Fig. 6 of Bowler et al. (2015), we counted 61 such objects in their surveyed area of 1.65 deg\(^2\). Rescaling for the different area of 0.144 deg\(^2\) of our field, we would expect a number of dropouts in our field area of 5.3, whereas we selected 18 candidates with \( z_{ap} < 25.6 \) (see Fig. 8). The Poisson probability of observing 18 or more objects when only 5.3 are expected is 1.2 \( \times 10^{-5} \), corresponding to a significance of \( > 4 \sigma \) assuming a normal distribution (considering our primary and faint LBG candidate samples separately, we obtained measured overdensity levels of 2 and 3.7\( \sigma \), respectively). Based on these numbers, we estimate that the J1030 field features an over-density of \( \Delta \rho \sim 6 \) LBGs equal to \( \Delta \delta = 2.4 \) (defined as \( \delta \geq 2 - 1 \), where \( \rho_0 \) is the expected number counts, see M14 for details). We then confirm and reinforce the over-density of LBGs found in the J1030 field in M14 (\( \delta = 2.0 \) at 3.3\( \sigma \)), where we compared the number of i-band dropouts in our field with that expected over a blank sky field when observing 18 or more objects at 3\( \sigma \). Even after accounting for the different image depths and photometric systems, this suggests that the new selection criteria based on optical/near-IR colors and photometric redshifts have in fact improved the selection of robust LBG candidates.

### 4.3. Properties of LBGs candidates

We finally investigated the properties of the "highz" candidates. The rest-frame UV continuum luminosity results from the integrated light emitted by young stars (mainly O and B massive stars) and it is widely considered as a good proxy of the star formation rate (SFR) in the galaxy. At these redshifts, the z-band is very close to rest-frame 1350\( \AA \). We corrected the z-band magnitude for the IGM opacity assuming a UV slope \( \beta = -2 \) (with \( \beta > -2 \) for objects with \( z > 6 \) and \( z < 4 \)) and \( \beta = -1 \) (with \( \beta > -1 \) for objects with \( z > 6 \)).

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6 We assume gaussian error since in Gilli et al. (2005, 2009) we verified that bootstrap errors are on average a factor of 2 higher than the simple 1\( \sigma \) errors. If we would assume bootstrap errors, we will obtain a clustering signal still significant within \( \sim 2 \sigma \) level.

7 Bowler et al. use apertures similar to ours for the photometry (1.8 vs 1.6 arcsec diameter) and their data have been taken under similar seeing conditions, so we expect aperture corrections similar to those we found in M14, i.e. \( \Delta \text{mag} \sim 0.1 \).

8 Bowler et al. found a factor of 2 of difference between the counts in Ultravista/COSMOS and UDS/XDS. At the magnitude limits \( z > 25.6 \) this factor reduces to \( \sim 1.5 \), corresponding to a maximum of 7.6 objects expected in our 0.144 deg\(^2\) area vs the 18 observed at that limit. Even conservatively assuming this high "background" value, the overdensity in the J030 field would be significant at more than 3\( \sigma \).
The first indications about the existence of a galaxy overdensity environments as found in some simulations Yajima et al. (2015).

The radial separation between the \( z = 5.97 \) object of Stiavelli et al. (2005) and SDSS J1030+0524 is \( \Delta z = 0.34 \), corresponding to \( \sim 20 \) physical Mpc. This seems larger than the size of the largest galaxy overdensities expected at \( z \approx 6 \) (\( \approx 10 \) physical Mpc; Overzier et al. 2009). Interestingly, the redshift measured in our LBG candidate stack is \( z = 5.95 \pm 0.06 \). Should this average redshift be confirmed by the forthcoming spectroscopic observations of our targets, this would point towards a \( z = 5.95 - 5.97 \) LSS that is likely a foreground structure with respect to the QSO.

Further investigations of the environment around SDSS J1030+0524 were presented by D14, who used deep narrow-band (at 8162Å) and broad band \( riz \) imaging obtained with the 30 \( \times \) 27 arcmin\(^2\) Subaru Suprime-Cam to select samples of candidate LAEs and LBGs at \( z \approx 5.7 \) (to study the environment of high-z absorbers along the QSO line of sight; D’Odorico et al. 2013) and candidate LBGs at \( z \approx 6 \) (selected as i-band dropouts). Their observations cover a FoV that is comparable to (even larger than) our FoV at the same depth, and for their i-band dropout sample they used selection criteria very similar to what we used in M14. It is therefore interesting to compare our findings with that of D14. According to D14, the most significant excess of i-band dropouts is indeed in the NW direction as we found, but it is on scales smaller than 3 arcmin from the QSO, and is made by only three objects. As described in Section 6.4.2, and Table 3 of D14, the significance of that excess is \( \approx 1.5 \sigma \). We verified that 5 out of the 23 i-band dropouts in the D14 catalog fall in the NW quarter of the LBC field where we find the largest overdensity. The binomial probability of finding 5 out of 23 objects in that area is 0.3, to be compared with the value of 0.002 that we found in our data. Therefore, our LBC/WIRCAM measurements provide the most significant detection of an overdensity in the J1030 field to date.

To better understand the differences in the i-band dropout samples of D14 and our samples, we also cross matched the source lists. The 23 i-band dropouts of D14 (see their Table E3) are distributed over a wider field, and only 12 of them fall within our field. Five of them are below our \( z \)-band detection threshold and hence are not present in our LBC source catalog (M14; most of them appear as low S/N detections in the LBC \( z \)-band image though). Among the seven LBC-detected objects, two belong to our primary sample (IDs 11963 and 25831), one to our faint sample (ID 5674), whereas four do not satisfy our color selection criteria. On the one hand, this small overlap can be explained by the somewhat different S/N and colors that we measured in our LBC data. For instance, by slightly relaxing our requirements on the \( z \)-band detection significance and \( i-z \) color cuts, we would have found five more matches between the i-band dropout samples, bringing the overlap to 8/12. Instead, for the remaining 4 objects we measured significantly bluer \( i-z \) colors than in D14. In some cases the presence of a nearby bright star in LBT images may have affected the accuracy of the photometry and partly explain this color discrepancy. On the other hand, the addition of NIR imaging with WIRCAM (plus Spitzer and MUSYC), allows us to perform a more efficient rejection of contaminants. As a matter of fact, more than half of the “primary” objects in M14 were found to be contaminants, and their selection closely resembles that of i-band dropouts in D14. In the end, only one of the 12 i-band dropouts of D14 that are covered by our data, namely ID 11963 (see Table 3), was classified by us as “highz”.

4.4. Comparison with previous results

The first indications about the existence of a galaxy overdensity around the QSO SDSS J1030+0524 (within 1.5 arcmin scales) were presented by Stiavelli et al. (2005) and Kim et al. (2009), who analyzed HST/ACS data at \( z_{\text{spec}} < 27 \) depth and found a \( \approx 2\sigma \) excess of objects with \( f_{775} - f_{850} > 1.3 \) with respect to what was expected based on the density of sources in the GOODS fields with the same colors and at the same depth. To date the only HST/ACS i-band dropout in the J1030 field with measured spectroscopic redshift is at \( z = 5.790 \) (Stiavelli et al. 2005, confirmed also by Díaz et al. 2011). The search for emission lines in the other ACS/HST dropouts proved inconclusive (Kim et al. 2009). The \( z = 5.97 \) object has \( z_{\text{spec}} = 25.74 \) and is visible in our LBC \( z \)-band image but falls below our catalog detection threshold. To date, this is the object with redshift closest to that of the QSO. Spectroscopy of a sample of \( z \approx 5.7 \) candidate LAEs was presented by Díaz et al. (2015), and the overall redshift range was found to be \( 5.66 < z_{\text{spec}} < 5.75 \). Only two of these LAEs appear in our LBC catalogs but with colors too blue (\( i-z = 0.72 - 0.95 \)) to be selected in any of our dropout samples. In any case, these objects are foreground to the QSO.
The large-scale overdensity measured around SDSS J1030+0524 is one of the few examples of \( z \approx 6 \) galaxy overdensities extending on scales larger than 1 physical Mpc. In most cases, these measurements were performed around \( z \approx 6 \) QSOs and based on imaging data only (e.g. Utsumi et al. 2010, M14), hence awaiting spectroscopic confirmation. A clear, spectroscopically confirmed overdensity at \( z = 6.01 \) has been instead reported by Toshikawa et al. (2012, 2014) in the Subaru Deep Field (Kashikawa et al. 2004), which does not contain any known luminous QSO at that redshift. By means of imaging data obtained with the wide-field Suprime-Cam at Subaru and subsequent optical spectroscopy at the Keck telescope, Toshikawa et al. (2014) measured an overdensity of i-band dropout targets that reaches a significance of 6\( \sigma \) at its peak and extends over \( 10 \times 8 \) arcmin\(^2\), i.e. \( 3 \times 2.2 \) physical Mpc\(^2\), down to the 2\( \sigma \) level. About 50 i-band dropouts have been selected by Toshikawa et al. (2014) within this area down to \( \text{AB} < 27 \), i.e. at limiting fluxes significantly deeper than our data, and for about half of them, they were able to measure the redshift through the detection of Ly\( \alpha \) emission. The redshifts of their spectroscopic sample cover the range \( 5.7-6.6 \). Ten objects with average redshift \( \langle z \rangle = 6.01 \) were found within a narrow redshift slice of \( \Delta z < 0.06 \) (i.e. within 3.7 physical Mpc radial), marking an early protocluster structure that is expected to grow into a massive cluster of \( 5 \times 10^{14} M_\odot \) by \( z = 0 \). Because of the brighter magnitude range covered by our observations (actually Toshikawa et al. excluded all the i-band dropout with \( z < 25 \) from their analysis), it is difficult to compare the candidate overdensity we measured in the J1030 field with that measured in the SDF. We note, however, that the angular scales over which we measure the highest density of dropouts, i.e. the NW quadrant, is \( \sim 12 \times 12 \) arcmin\(^2\), i.e. it has similar size to the structure measured in the SDF. A more detailed comparison will be possible after spectroscopic observations of our i-band dropout targets.

### 5. Summary and conclusions

The ultimate goal of this series of paper is to investigate the properties of the environment of high redshift SMBHs that, according to cosmological simulations, should be characterised by large over-densities of primordial galaxies. In M14 we selected a catalogue of i-dropout candidates around four high redshift quasars using wide-field LBT images in \( r, i \) and \( z \) band.

Here we present deep-and-wide (\( \sim 25' \times 25' \)) \( Y \)- and \( J \)-band images obtained with the near infrared camera WIRCam at CFHT around one of these quasars, SDSS J1030+0524 at \( z=6.28 \). The field of view, the resolution and the sensitivity match the LBT observations. We use these new data to improve the selection of LBG candidates rejecting potential contaminants (stars or galaxies at lower redshift). With respect to M14, we added 18 new faint candidates using a color criterion similar to the one adopted for primary candidates (\( i-z > 1.3 \)), but applied to fainter objects (\( 25.2 < \text{AB} < 25.7 \)).

We estimated the photometric redshifts of the objects in the primary, secondary and faint samples by fitting their SEDs from \( \sim 0.9 \) to 3.2 \( \mu \)m, using our own photometric data in the \( r, i, z, Y \) bands and, if available, also those in the \( H \) and \( K \) bands (from the MUSYC survey) and at 3.4 and 4.5 \( \mu \)m (from public Spitzer/IRAC data). We evaluated the position of each target in the \((r-z)\) vs \((z-Y)\) color-color diagnostic plot and made a robust morphology classification. We combined all these informations to divide the objects in our samples into reliable LBG candidates at \( z \approx 6 \) ("highz") or contaminants ("star" or "galaxy"), and we finally identify a sample of 21 trustable high-z objects.

To confirm the goodness of our selection method, we performed several tests: 1) we stacked the images of the 21 "highz" and of the 17 objects classified as stars and measured the \( \text{rizYJ} \) magnitudes in the stacks. The colors and the best fit SEDs of the two stacks are very different. The stack of star-like objects is indeed well fit by a stellar template at \( z = 0 \), whereas the stack of "highz" candidates is well fit by an LBG template at \( z_{\text{phot}} = 5.95 \pm 0.06 \); 2) we investigated the clustering properties of the two populations. We observed a clear asymmetric spatial distributions for the "highz" candidates in the field, which is significant at the > 3\( \sigma \) level. We also verified that the angular correlation function of "highz" shows a significant positive signal at scales < 10arcm, whereas the angular correlation function of "stars" is consistent with zero, suggesting that these objects are randomly distributed in the field, as indeed expected for galactic stars. The strong clustering signal measured for the 21 "highz" objects instead again suggests the presence of a coherent high-z large-scale structure in the field.

We finally compared the number of robust \( z \approx 6 \) LBG candidates with that observed by Bowler et al. (2015) in blank sky fields, which was obtained by applying similar selection methods. We measured an LBG over-density of \( \delta = 2.4 \) that is significant at the > 4\( \sigma \) level. We therefore confirm and reinforce the high-z galaxy over-density reported by M14. We are planning spectroscopic observations of these LBG candidates in the next months to confirm whether they are actually at the same redshift of the quasar.

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