Counterparts of Candidate Dusty Starbursts at $z > 6$

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ABSTRACT

We present an analysis of the optical-to-near-IR counterparts of a sample of candidate dusty starbursts at $z > 6$. These objects were pre-selected based on the rising trend of their far-infrared-to-sub-millimeter spectral energy distributions and the fact that they are radio-weak. Their precise positions are available through millimeter and/or radio interferometry, which enable us to search for their counterparts in the deep optical-to-near-IR images. The sample include five $z > 6$ candidates. Three of them have their counterparts identified, one is still invisible in the deepest images, and one is a known galaxy at $z = 5.667$ that is completely blocked by a foreground galaxy. The three with counterparts identified are analyzed using population synthesis model, and they have photometric redshift solutions ranging from 7.5 to 9.0. Assuming that they are indeed at these redshifts and that they are not gravitationally lensed, their total IR luminosities are $10^{13.8–14.1}L_{\odot}$ and the inferred star formation rates are $6.3–13 \times 10^3 M_{\odot} \text{yr}^{-1}$. The existence of dusty starbursts at such redshifts would imply that the universe must be forming stars intensely very early in time in at least some galaxies, otherwise there would not be enough dust to produce the descendants observed at these redshifts. The inferred host galaxy stellar masses of these three objects, which are at $\gtrsim 10^{11} M_{\odot}$ (if not affected by gravitational lensing), present a difficulty in explanation unless we are willing to accept that their progenitors either kept forming stars at a rate of $\gtrsim 10^3 M_{\odot} \text{yr}^{-1}$ or were formed through intense instantaneous bursts. Spectroscopic confirmation of such objects will be imperative.

Key words: infrared: galaxies; galaxies: starburst; galaxies: high-redshift; galaxies: evolution

1 INTRODUCTION

Ultra-luminous Infrared Galaxies (ULIRGs) have extremely high infrared luminosity of $L_{\text{IR}} \gtrsim 10^{12}L_{\odot}$ (integrated over the rest-frame 8 to 1000 $\mu$m). It is widely believed that they are starbursts enshrouded by dust, with star formation rates (SFRs) of $\gtrsim 100 M_{\odot} \text{yr}^{-1}$. The intense UV radiation from young stars in the starburst region is absorbed by dust, which is re-radiated in infrared (IR) and gives rise to the enormous IR luminosity.

ULIRGs must be heavily metal-enriched because metal is needed to form dust. It is therefore somewhat surprising that ULIRGs are seen at $z > 6$ (e.g., Riechers et al. 2013; Strandet et al. 2017), as there is only $\lesssim 1$ Gyr for the host galaxies to form sufficient stars and to pollute the ISM with metals. By the same token, ULIRGs at very high redshifts provide a new venue to probe the star formation processes in the early universe, and therefore it is important to assemble a large sample of such objects and to study them systematically.

As young stars nominally can only heat dust to a few tens of kelvin, the far-IR (FIR) to sub-millimeter (sub-mm) spectral energy distributions (SEDs) of ULIRGs can be approximated well by a modified blackbody emission that has a broad peak at roughly 80–100 $\mu$m. This offers a method to search for ULIRGs at high redshifts, which identifies the rising trend of the SED with wavelength. Tailored for the Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) on board the Herschel Space Observatory (Pilbratt et al. 2010), the so-called “500 $\mu$m peaker” or “500 $\mu$m riser” technique selects candidates of high-redshift (hereafter “high-$z$”) ULIRGs by searching for sources that are progressively brighter from 250 to 500 $\mu$m (Pope & Chary 2010; Roseboom et al. 2012). Presumably, this method can select ULIRGs at $z > 6$ (Riechers et al. 2013). Applying it to the wide-field Herschel SPIRE survey data, a number of 500 $\mu$m riser samples have been constructed (Dowell et al. 2014; Asboth et al. 2016; Ivison et al. 2016; Donevski et al. 2018; Yan et al. 2020). The method can be extended to longer wavelengths by adding sub-mm data to the SPIRE FIR data, which could potentially select ULIRGs at even higher redshifts. Depending on the exact location of the redder sub-mm band in use, it is referred to as the technique of “850 $\mu$m” or “870 $\mu$m” riser (Riechers et al. 2017). However, the existing sub-mm surveys cover too small areas as compared to the SPIRE surveys, and 850 $\mu$m or 870 $\mu$m risers cannot be directly selected in a significant number. A typical sub-mm source in the existing surveys has flux density...
of a few mJy, while a typical SPIRE source has flux density of \( \gtrsim 20 \) mJy. A systematic search for 850 \( \mu \)m risers and the like would have to wait for future sub-mm surveys over at least several tens of deg\(^2\) in the existing SPIRE survey fields so that a significant number of rare, bright (several tens of mJy) sub-mm sources would have a chance to be found in the first place. Nevertheless, Yan et al. (2020) have attempted an alternative within the limit of the current 850 \( \mu \)m surveys done by the Submillimetre Common-User Bolometer Array 2 (SCUBA2). This is to search for “SPIRE dropouts”, which are objects prominent in 850 \( \mu \)m but very weak or invisible in SPIRE and therefore could be potential 850 \( \mu \)m risers.

These 500 \( \mu \)m risers and SPIRE dropouts are only high-\( z \) candidates and could suffer from severe contaminations by interlopers at low redshifts. Even for the 500 \( \mu \)m risers, which have well-defined colour criteria, one would still expect a high contamination rate if the goal is to search for objects at \( z > 6 \). Due to the degeneracy between dust temperature and redshift, 500 \( \mu \)m risers actually can only select sources at \( z \gtrsim 4 \) in general (e.g., Pope & Chary 2010; Yan et al. 2020). To target the highest redshift range of \( z > 6 \), Yan et al. (2020, hereafter ‘YMHF20’) took an innovative approach. Using the fact that high-\( z \) ULIRGs should be radio weak, YMHF20 devised a “high-\( z \) index” (HiIdx) to further select \( z > 6 \) candidates among their “Tier 1” 500 \( \mu \)m risers and SPIRE dropouts. While only a small fraction of these objects (72 out of 629 500 \( \mu \)m risers and 29 out of 95 SPIRE dropouts) have sufficiently deep radio data to allow for a meaningful assessment of HiIdx, the total number of \( z > 6 \) candidates still amount to 20 objects (19 500 \( \mu \)m risers and 1 SPIRE dropout) and constitute the largest sample of \( z > 6 \) ULIRG candidates.

The true nature of such objects of course is still awaiting spectroscopic confirmation, which can be done in the millimeter regime with current technology (e.g., by identifying CO lines). On the other hand, a lot can be learned if we can identify their counterparts in optical to near-IR (NIR). In this regime, one would not be probing the dusty starburst site but would be detecting the associated host population. If the counterparts are bright enough, one could also pursue optical-to-NIR spectroscopy to confirm their high-\( z \) nature. Moreover, one could analyze their SEDs in this regime to gain knowledge about the host populations, including deriving their photometric redshifts (\( z_{\text{phot}} \)) to facilitate the interpretation of their nature.

In this work, we study the optical-to-NIR counterparts of the \( z > 6 \) ULIRG candidates YMHF20 in the COSMOS field that are culled by the HiIdx criteria. This work is enabled by the high-resolution interferometry data from the Atacama Large Millimeter/submillimeter Array (ALMA), which allow us to locate the accurate positions of our sources for follow-up studies. We made use of the data from the Automated Mining of the ALMA Archive in the COSMOS Field (\( \Lambda^3\)COSMOS Liu et al. 2019, v20200310). This ongoing ALMA data mining project processes all the non-proprietary continuum imaging data in the COSMOS field and releases the processed images as well as the source catalogs using a number of different extraction methods. The rich multi-wavelength data in the COSMOS field further enable us to study the identified sources in detail.

Our paper is organized as follows. The sample construction is described in §2. The optical-to-NIR counterpart identification is detailed in §3. The SED analysis is given in §4. The implication of our results is discussed in §5. We conclude with a summary in §6. All magnitudes quoted are in the AB system. All coordinates are of J2000.0 Equinox. We adopt the following cosmological parameters: \( \Omega_M = 0.27, \Omega_{\Lambda} = 0.73 \) and \( H_0 = 71 \) km s\(^{-1}\) Mpc\(^{-1}\).

## 2 SAMPLE DESCRIPTION

Our sample is made of the objects from YMHF20 that satisfy the HiIdx criteria for \( z > 6 \) and are identified in the \( \Lambda^3\)COSMOS data. While they are only a very small fraction of the 500 \( \mu \)m risers and SPIRE dropouts in YMHF20, these objects offer the best chance to date to study the most extreme star formation processes in the early universe.

### 2.1 ALMA identifications

In the COSMOS field, there are 11 500 \( \mu \)m risers and one SPIRE dropout satisfying the HiIdx criteria for \( z > 6 \) (see the bold-faced HiIdx entries of Table 7, 8 and 11 in YMHF20 in this field), which constitute the parent sample of this current work. To recapitulate YMHF20, HiIdx is the flux density ratio between FIR/submm and radio:

\[
\text{HiIdx} = \begin{cases} 
\frac{f_{500}}{S_{3.4}} & \text{(500} \mu \text{m risers)} \\
\frac{S_{850}}{S_{3.4}} & \text{(SPIRE dropouts)},
\end{cases}
\]

where \( f_{500} \), \( S_{850} \) and \( S_{3.4} \) are the flux densities at 500 \( \mu \)m, 850 \( \mu \)m and 1.4 GHz, respectively. Based on two known objects with spectroscopic redshifts below and above \( z = 6 \), respectively, YMHF20 selected \( z > 6 \) objects using an ad hoc criterion of HiIdx(500) \( \geq 0.7 \) for the 500 \( \mu \)m risers and HiIdx(850) \( \geq 0.5 \) for the SPIRE dropouts, respectively. The validity of these selections will be tested in this work.

Our current study is based on the latest source catalogs of \( \Lambda^3\)COSMOS (v20200310). We used the “blind” catalog, which contains the sources extracted without using any prior information. However, the publicly available images are still of the previous release (v20180801). As we will show later, one of our identified sources does not yet have publicly available ALMA image because of this reason.

While the SPIRE and the SCUBA2 data have coarse spatial resolutions (with the beam sizes of 18\(''\).1 and 14\(''\).9 in SPIRE 250 \( \mu \)m and SCUBA2 850 \( \mu \)m, respectively), their centroid positions should still have 1 \( \sigma \) accuracy of 3\(''\).1 and 2\(''\).5, respectively (see YMHF20). Here we adopted the matching radius of 9\(''\) when matching them to the ALMA positions. Among the 11 high-\( z \) 500 \( \mu \)m risers satisfying HiIdx(500) \( \geq 0.7 \), seven are in the current \( \Lambda^3\)COSMOS coverage and all were matched. The only SPIRE dropout satisfying HiIdx(850) \( \geq 0.5 \) was also matched. Table 1 shows the details of these matches. As it turns out, the ALMA positions and the SPIRE/SCUBA2 centroid positions are all within \( r < 6.5\)\(''\). The ALMA detections almost all have \( S/N \geq 3 \); the only exception is the one for 500R_COSMOS_T1_x08.

\(^1\) To convert from the flux density at an arbitrary frequency to that at 1.4 GHz, YMHF20 adopted a power-law spectrum of \( S_{\nu} \propto \nu^{-0.8} \). For what is relevant in this study, \( S_{1.4} = 1.84 \times S_{3.0} \), where \( S_{3.0} \) is the flux density at 3.0 GHz.
which has $S/N = 2.8$. We accepted this case because the ALMA source position coincides with that of the VLA detection (as presented in YMHF20) almost exactly, which gives credibility to the identification.

The VLA image has the synthesized beam size of $0''.75$, which is better than most of the ALMA observations listed in Table 1. Therefore, under the assumption that the radio and the FIR-to-mm emissions are originated from the same region in the host, the VLA data should provide better localizations for most of the sources. However, ALMA identifications are the least ambiguous in our context, and we adopt the ALMA positions except in the special case of $500R_{\text{COSMOS-T1}}x08$.

Figure 1 shows the SPIRE and the SCUBA2 images for all these eight objects as well as their ALMA identification images and their images in the VLA 3 GHz. In particular, $500R_{\text{COSMOS-T1}}x34$ is identified with two ALMA sources, which we call the “a” and “b” components, respectively.

2.2 Detections and non-detections in the VLA Image

We first revisit the HiIdx assessment of these objects based on the new identifications, because the calculations of HiIdx in YMHF20 used the $S/N = 5$ upper limit of the VLA 3 GHz map for the non-detections in this map. YMHF20 matched the 500 $\mu$m risers and the SPIRE dropouts with the VLA sources using the criterion of $\Delta/\sigma \leq 1.5$, where $\Delta$ is the positional offset to the nearest 3 GHz source and $\sigma$ is the overall positional uncertainty by adding in quadrature the errors of the reported SPIRE (or SCUBA2) and VLA positions. $\sigma$ is dominated by the SPIRE (or SCUBA2) positional error, which depends on the source $S/N$ in the SPIRE/SCUBA2 data, and the error term from the VLA positions is minimal (set to 0''.13 at the fixed $S/N = 5$). For the 500 $\mu$m risers and the SPIRE dropouts, $\sigma \leq 3''.1$ and 2''.2, respectively.

Following this matching criterion, four of the 11 aforementioned 500 $\mu$m risers were labeled as detected in radio by YMHF20. These are $500R_{\text{COSMOS-T1}}x08$, x24, x26, and x31, all among the seven that have ALMA coverage. The ALMA counterparts very well coincide with the VLA counterparts, and the slight differences in the positions are all consistent with the respective positional errors. Their HiIdx values remain the same as reported in YMHF20. Seven of the 11 sources were labeled by YMHF20 as undetected in radio, and their reported HiIdx values were above the threshold because of the use of the $S/N = 5$ upper limit for S3.0. On the other hand, YMHF20 did carry out a more generous match using a searching radius of 10'', and found that three of these seven had corresponding 3 GHz matches; they were still labeled as radio non-detections in YMHF20 only because these matches have $\Delta/\sigma > 1.5$ (see the bottom part of Table 7 in YMHF20). These three are $500R_{\text{COSMOS-T1}}x02$, x04 and x10, which are also within the ALMA coverage. The ALMA identifications now show that these 3 GHz matches are in fact the right counterparts (i.e., the no-match criterion in YMHF20 should be relaxed to $\Delta/\sigma > 3$). Therefore, their HiIdx must be revised. Similarly, the only previous $z > 6$ candidate among the SPIRE dropouts, SD850_COSMOS-T1_A03, is of the same situation (see the bottom part of Table 10 in YMHF20)\(^2\) and its HiIdx must also be revised.

The updated HiIdx(500|850) values are included in Table 1. To summarize, five of the seven 500 $\mu$m risers satisfy $\text{HiIdx}(500) \geq 0.7$ and are candidates at $z \geq 6$ (including $500R_{\text{COSMOS-T1}}x10$ whose HiIdx(500) has been revised), which we will refer to as the “high-$z$ candidates” in the rest of this paper. The other two 500 $\mu$m risers (including $500R_{\text{COSMOS-T1}}x34$, which is still considered as a single source in this context) no longer satisfy this criterion, which we will refer to as the “contaminators” hereafter. The SPIRE dropout, SD850_COSMOS-T1_A03, is also a contaminator. These eight sources constitute the sample of this study.

3 MULTI-WAVELENGTH PROPERTIES OF THE COUNTERPARTS

3.1 Data Description

The COSMOS field has accumulated a wealth of multi-wavelength data, which make it possible to further study the properties of our sources. These include the HST Wide Field Camera 3 (WFC3) F160W (hereafter $H_{160}$) images from the COSMOS-Drift And SHift program (COSMOSDASH; Mowla et al. 2019) and Advanced Camera for Surveys (ACS) F814W (hereafter $I_{814}$) image that defines the original COSMOS field (Koekemoer et al. 2007), the VISTA VIRCAM $Y$, $J$, $H$, and $K_s$ images from the UltraVISTA program (McCracken et al. 2012), the Subaru Hyper Suprime-Cam $g$, $r$, $i$, $z$, and $y$ images from the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP; Aihara et al. 2018a,b), and the Spitzer Infrared Array Camera (IRAC) and Multi-Band Imaging Photometer for Spitzer (MIPS) images from the Spitzer COSMOS program (S-COSMOS; Sanders et al. 2007). These datasets are briefly described below. In most cases, we had to carry out our own photometry using SExtractor (Bertin & Arnouts 1996), for which we adopted its MAG_AUTO. In some cases we adopted the photometry from the relevant data releases, and these cases will be explicitly noted in the rest of the paper.

HST WFC3 $H_{160}$. We used the v1.2.10 data released by the COSMOS-DASH program, which incorporate its own observations as well as those from other programs in this field. The image mosaic effectively covers 0''.3 in diameter, but in some regions it is significantly deeper.

HST ACS $I_{814}$. We used the image mosaic with the scale of 0''.03 pix$^{-1}$ included in the v2.0 data release of the COSMOS program. The image covers ~1.7 deg$^2$ and reaches the 5 $\sigma$ sensitivity of $AB = 25.1$ mag for point sources (using an aperture of 0''.3 in diameter) in general, but in some regions it is significantly deeper.

VISTA near-IR. We used the v4.0 $YJHK_s$ image stacks of the UltraVISTA program, which cover 1.5 $\times$ 1.2 deg$^2$ in four “Ultra-deep” and four “Deep” stripes. The PSFs in all

\(^2\) We note that Table 10 in YMHF20 (for the radio matching of the SPIRE dropouts) has an error in reporting the $\Delta_{\text{pos}}$ and $\sigma_{\text{pos}}$ values for the bottom six objects; the values in these two columns should be swapped.
Figure 1. Image stamps of the eight sources in our sample, with the source “Short ID” (see Table 1) labeled in different background colours indicating those in the high-$z$ candidate subsample (cyan or green) and those in the contaminator subsample (grey). The SPIRE $250, 350, 500$ µm and the SCUBA2 $850$ µm images are $3' \times 3'$ in size, and the dashed green circles ($25''$ in radius) are centred on the SPIRE (for $500$ µm risers) or the SCUBA2 (for SPIRE dropout) positions. The ALMA identification images (with the central wavelengths of the identifications labeled) and the VLA images are $20'' \times 20''$ in size; the red circles ($1''$ in radius) are centred on the ALMA positions, while the green crosses mark the SPIRE/SCUBA2 positions. $500R\_COSMOS\_T1\_x24$ does not yet have the ALMA images publicly available. $500R\_COSMOS\_T1\_x34$ has two ALMA counterparts (“a” and “b”), which are labeled as “34a” and “34b” in yellow background colour.
Table 1. ALMA identifications of Tier-1 500 μm risers and SPIRE dropout in COSMOS field

| Short ID | R.A. & Decl. (HMS/°/″) | f(500 μm) (mJy) | R.A. & Decl. (VLA) | θ_{maj} (″) | θ_{maj} (ALMA) | φ (°) | θ_{maj} (mJy) |
|----------|-------------------------|----------------|-------------------|--------------|----------------|-------|---------------|
| 500R_x08 | 10:01:42.2 2:37:26.9     | 28 ± 5.0       | 10:01:42.20 2:37:27.10 | 18.7 ± 2.4   | 0.80           | 1.27  | 0.90 ± 0.32   |
| 500R_x24 | 10:02:40.4 1:45:40.2     | 31.4 ± 5.2     | 10:02:40.43 1:45:44.11 | 12.7 ± 2.4   | 0.72           | 0.83  | 1.00 ± 0.37   |
| 500R_x26 | 10:00:59.0 1:33:08.8     | 32.2 ± 5.1     | 10:00:59.18 1:33:06.73 | 24.3 ± 3.8   | 1.03           | 1.29  | 0.95 ± 0.25   |
| 500R_x31 | 10:01:26.1 1:57:50.4     | 36.0 ± 5.2     | 10:01:26.02 1:57:51.32 | 24.1 ± 2.6   | 0.81           | 1.25  | 0.84 ± 0.24   |
| 500R_x20 | 10:01:42.3 2:00:19.3     | 26.4 ± 5.0     | 10:01:42.55 2:00:14.69 | 109.0 ± 6.3  | 1.25           | 0.83  | 1.25 ± 0.30   |
| 500R_x18 | 10:01:40.5 2:30:14.7     | 28.3 ± 5.2     | 10:01:40.44 2:30:10.44 | 11.6 ± 2.3   | 1.34           | 1.25  | 1.24 ± 0.24   |
| 500R_x34a| 10:00:09.9 2:22:22.0     | 39.8 ± 5.1     | 10:00:09.49 2:22:19.48 | 142.0 ± 7.5  | 1.87           | 1.25  | 1.25 ± 0.24   |
| 500R_x34b| 10:00:59.0 1:33:08.8     | 32.2 ± 5.1     | 10:00:59.18 1:33:06.73 | 24.3 ± 3.8   | 1.03           | 1.29  | 0.95 ± 0.25   |
| SDSS_A01 | 9:59:57.4 2:27:28.6      | 11.8 ± 1.9     | 9:59:57.29 2:27:30.74 | 28.8 ± 2.7   | >0.56          | 0.22  | 13.87 ± 0.53  |
| SDSS_A02 | 9:59:57.4 2:27:28.6      | 11.8 ± 1.9     | 9:59:57.29 2:27:30.74 | 28.8 ± 2.7   | >0.56          | 0.22  | 13.87 ± 0.53  |
| SDSS_A03 | 9:59:57.4 2:27:28.6      | 11.8 ± 1.9     | 9:59:57.29 2:27:30.74 | 28.8 ± 2.7   | >0.56          | 0.22  | 13.87 ± 0.53  |
| SDSS_A04 | 9:59:57.4 2:27:28.6      | 11.8 ± 1.9     | 9:59:57.29 2:27:30.74 | 28.8 ± 2.7   | >0.56          | 0.22  | 13.87 ± 0.53  |

Note. — The “Short ID” column omits the string “COSMOS_T1_x” in the formal object names. The object marked with “†” turns out to be the z = 5.667 galaxy (nickname “CRL6”) reported in Pavesi et al. (2018). The HiZidx values are HiZidx(500) and HiZidx(850) for the 500 μm risers and the SPIRE dropout, respectively; the values marked with “∗” are the revised values based on the new identifications of the 3 GHz counterparts, while the corresponding values to the left side of the arrow are the original values from Y20. The θ values represent the spatial resolutions of the corresponding ALMA observations, which are calculated by adding the beam sizes along the major and the minor axis in quadrature. The adopted positions are all the ALMA positions excepted for 500R_x08, whose position is based on the VLA measurement (highlighted in bold-face font) because its uncertainty is 10× better than the ALMA one.

these four bands have FWHM of 0′.76–0′.78. The 5 σ limiting magnitudes (2′ diameter aperture) in Y, J, H, and Ks are 25.8, 25.6, 25.2, and 24.9 mag in the Ultra-deep stripes, respectively, and 24.7, 24.5, 24.1, and 24.5 mag in the Deep stripes, respectively.

**Subaru optical.** We used the five broad-band image stacks from the third public data release (PDR3) of the HSC-SSP program, which has observed the COSMOS field as one of the survey’s UltraDeep fields. These data have reached the 5 σ limits (within aperture of 2′ diameter) of 28.2, 27.9, 27.7, 27.1, and 26.1 mag in g, r, i, z, and y, respectively, with the PSF sizes varying from 0′.7 to 0′.8.

**Spitzer IR.** We used the data from the S-COSMOS program, which include the IRAC data in Ch1 through Ch4 (3.6 to 8.0 μm) and the MIPS data in 24 μm. For the IRAC photometry, we adopted the GO2 catalog. Specifically, we used the fluxes extracted through a 2′.9 aperture. These fluxes were corrected to the total fluxes by dividing the correction factors of 0.90, 0.90, 0.84, and 0.73 in Ch1, Ch2, Ch3, and Ch4, respectively, as per the instruction of the data release. The MIPS data were only used to aid the visual inspection of the sources; for the sake of completeness, the 24 μm photometry, which was taken from the GO3 catalog, will be listed when appropriate.

### 3.2 counterparts of the high-z candidates

We start from identifying the optical-to-NIR counterparts of the five high-z candidates using the positions verified by the ALMA data.

#### 3.2.1 500R_COSMOS_T1_x08

As mentioned earlier, its ALMA detection has only S/N = 2.8. This is largely because the source is at the very edge of the field. However, the separation of ALMA and radio position is only 0′.58, and this lends strong support to the identification and the localization of the source. We adopt the VLA position as its final position, as the ALMA position has much larger uncertainty of 0′.85 (as compared to the uncertainty of 0′.08 of the VLA position). The optical-to-NIR images of this source and its vicinity are shown in Figure 2. At this position, there is no visible source in J1814, and only a diffuse source in H160 of 22.15 ± 0.11 mag by our photometry. This source has two very close companions at ~1″, both of which could confuse the identification and contaminate its photometry. We designate the one to its north-west as “C-NW” and the one to its east as “C-E”, respectively.

In J1814, C-NW is clearly an edge-on disk galaxy (J1814 = 25.12 ± 0.13 mag), while C-E is very diffuse and is extracted as three components (I1814 = 25.67 ± 0.18 mag after combing the three). In H160, C-E is not visible and C-NW is barely detected (H160 = 22.87 ± 0.22 mag).

This source is visible in the HSC griz images. There is a hint that it is detected in y, however, it is severely blended with the companion C-E, which becomes fainter in the redder bands but is still visible in y. This is evident from our own extraction of C-E in y, whose centroid has an offset of 0′.3 with respect to that extracted in g band. The offset is towards the position of 500R_x08, which suggests that it is caused by the blending of the weak detection of this 500 μm riser in y. The photometry in y is further complicated by the contamination from the edge of the bright halo of the saturated star. The blending with C-E is more simply seen in the UltraVISTA Y-band. The 500 μm riser becomes distinctly visible in the UltraVISTA J-band, and is brighter in H and Ks. C-E seems to disappear in JHKs. C-NW on the other hand, persists from g through Ks. Nevertheless, our
The counterpart is not visible in the “detection” could be a false positive. Sources are too severely blended to extract fluxes in these bands. The in AB magnitudes except for MIPS 24 μm. While those without are contaminators. Object 500R_x26 is not included for the reason explained in the text. From top to bottom, the photometry is quoted in AB magnitudes except for MIPS 24 μm, where the values are in μJy. The limits are 5σ limits, while no values (“...”) indicate that the sources are too severely blended to extract fluxes in these bands. The g-band magnitude for 500R_x24 is marked with “??”, indicating that the “detection” could be a false positive.

Figure 2. Image stamps showing the optical-to-NIR counterpart of 500R_COSMOS_T1_x08 and its vicinity. The red circles are 1″ in radius, and are centred on the VLA position as reported in Table 1. Passbands are labeled. The left panel shows the high-resolution HST images in ACS I814 (top) and WFC3 H160 (bottom), which are 3″.9×3″.9 in size. The counterpart is clearly detected in H160 but is invisible in I814. Two companion objects by projection, “C-NW” and “C-E”, are visible in I814. The right panel shows the images in the HSC g, r, i, z, and y (top), the VISTA Y, J, H, and KS (middle), and the IRAC Ch1, Ch2, Ch3, and Ch4 (bottom), all 8″×8″ in size. The counterpart is not visible in griz but is clearly detected in JHKs images. The companion C-E is visible in from g to Y, and C-NW persists through KS. C-NW is severely blended with the counterpart in the IRAC images.

Table 2. Photometric Information

| Short ID | 500R_x08* | 500R_x24* | 500R_x31* | 500R_x10* | 500R_x02 | 500R_x34a | 500R_x34b | SD850_A03 |
|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| g        | >28.2     | ?28.7±0.4 | >28.2     | >28.2     | 26.78±0.07 | 25.03±0.05 | 27.14±0.20 | 27.23±0.10 |
| r        | >27.9     | >27.9     | >27.9     | >27.9     | 25.82±0.05 | 24.13±0.03 | 26.64±0.19 | 26.78±0.10 |
| i        | >27.7     | >27.7     | >27.7     | >27.7     | 25.51±0.04 | 23.77±0.03 | 25.89±0.10 | 25.77±0.05 |
| z        | >27.1     | >27.1     | >27.1     | >27.1     | 25.02±0.05 | 23.23±0.03 | 25.33±0.11 | 25.27±0.05 |
| y        | >26.1     | >26.1     | >26.1     | >26.1     | 25.00±0.08 | 24.15±0.13 | 25.44±0.22 | 24.91±0.07 |
| Y        | >25.8     | >24.7     | >25.8     | >24.7     | 24.73±0.04 | 22.35±0.01 | 24.10±0.03 | >24.7     |
| J        | 22.47±0.04 | >24.5     | 24.91±0.31 | 26.52±0.81 | 24.31±0.03 | 21.57±0.01 | 23.97±0.03 | >24.5     |
| H        | 21.61±0.02 | >24.1     | 24.46±0.24 | 24.53±0.17 | 23.29±0.02 | 21.30±0.01 | 23.01±0.02 | >24.1     |
| Ks       | 21.03±0.02 | >24.5     | 24.19±0.14 | 23.55±0.09 | 22.93±0.02 | 20.89±0.01 | 22.24±0.01 | 23.77±0.16 |
| I814     | >27.2     | >27.2     | >27.2     | >27.2     | 26.67±0.22 | >27.2     | >27.2     | >27.2     |
| H160     | 22.15±0.11 | N/A       | 24.61±0.25 | 25.1     | 24.02±0.29 | 21.60±0.09 | 23.35±0.33 | N/A       |
| Ch1 (3.6 μm) | ... | >24.1     | 22.35±0.05 | ...     | 21.72±0.03 | 20.32±0.01 | 20.70±0.01 | 22.88±0.07 |
| Ch2 (4.5 μm) | ... | >23.3     | 21.75±0.04 | ...     | 21.32±0.03 | 20.02±0.01 | 20.31±0.01 | 22.69±0.10 |
| Ch3 (5.8 μm) | ... | >21.3     | 21.40±0.13 | ...     | 21.04±0.10 | 19.92±0.03 | 20.04±0.04 | >21.3     |
| Ch4 (8.0 μm) | ... | >21.0     | 21.52±0.33 | ...     | 20.55±0.13 | 20.36±0.11 | 20.49±0.13 | >21.0     |
| MIPS (24 μm) | ... | <71       | <71       | ...     | 167±16   | 381±14   | 414±15    | <71       |

Note. — The “Short ID” row is the same as in Table 1. The objects labeled with “*” are high-z candidates based on the revised HiIdx, while those without are contaminators. Object 500R_x26 is not included for the reason explained in the text.
This object in fact is the

3.2.3 500R_COSMOS_T1_x26

covered during ALMA observations of a normal galaxy in its vicinity, and its redshift was determined through the identification of atomic fine-structure lines ([C II] 158 µm and [N II] 205 µm) in the ALMA data as well as the CO(2-1) 1.301 mm transition line in the follow-up VLA observations. Had there not been such spectroscopic identifications, it would be impossible to reveal the nature of this source because it is completely blocked by a foreground, edge-on disk galaxy at $z_{\text{ph}} \sim 0.35$ from UV to mid-IR; its FIR-to-mm emissions, on the other hand, are transmissible through this foreground galaxy (Pavesi et al. 2018). Its redshift, however, is still below $z = 6$. We refer the reader to Pavesi et al. (2018) for the optical-to-NIR images around this position, and will not discuss this source further because the optical-to-NIR images would provide information only on the foreground object.

3.2.2 500R_COSMOS_T1_x24

While the A$^3$COSMOS image for this source is not yet available, the A$^3$COSMOS position coincides with that of the VLA position ($0''.16$ separation). Figure 4 shows the optical-to-NIR images around this location. There is no visible $I_{s14}$ source at the ALMA position. Unfortunately, it has no $H_{160}$ image because it is out of the COSMOS-DASH coverage.

This source is invisible in the HSC grizy images. On the other hand, there seems to be a weak detection in $g$. In our extraction, it has $28.7 \pm 0.4$ mag at the exact location. However, due to its low S/N, it is highly likely that this “detection” is a false positive. The source is also invisible in the UltraVISTA images and the S-COSMOS IRAC images. We cannot rule out the possibility that it is at high-$z$.

3.2.3 500R_COSMOS_T1_x26

This object in fact is the $z = 5.667$ galaxy reported by Pavesi et al. (2018). Nicknamed “CRLE”, it was serendipitously dis-
Figure 4. Optical-to-NIR images at the vicinity of 500R_COSMOS_T1_x24. The image arrangement is the same as in Figure 2, except that there is no H160 image available. The red circles (r = 1″) are centred on the ALMA position. The counterpart is invisible in I814. It is also invisible in all bands except in the HSC g band, where there is a very weak positive signal (S/N ≈ 2.5) at its location. However, this “signal” could also be a false positive. The seemingly positive “detection” in IRAC Ch4 is consistent with being a noise spike.

Figure 5. Image stamps showing the optical-to-NIR counterpart of 500R_COSMOS_T1_x31 and its vicinity. The image arrangement is the same as in Figure 2, and the red circles (r = 1″) are centred on the ALMA position. The counterpart is invisible in I814, but appears in H160 as a faint detection. A companion object by projection, labeled as “C-1” in I814, is visible in both I814 and H160. The counterpart is clearly detected in the VISTA Ks and barely visible in the VISTA H, but is not visible in any bluer bands. It has a second companion object by projection, “C-2”, which is the most obviously seen in the HSC i and the VISTA Ks. The counterpart is detected in IRAC Ch1 and Ch2, but it might be blended with the two companions if they persist in these two bands. Its IRAC Ch3 and Ch4 images are consistent with being noise.

part is revealed in the UltraVISTA images, especially in Ks. The UltraVISTA DR4 catalog, however, only extracts this counterpart together with C-1 and C-2 as a single, blended object. We were able to separate the three in Ks. Following the same procedure as in the case of 500R_COSMOS_T1_x08, we subtracted C-1 and C-2 from the UltraVISTA images for the photometry of the 500 μm riser counterpart. The comparison of the original and the neighbour-subtracted images is shown in Figure 6. The subtraction in YJH does not create any notable effect, as C-1 and C-2 are almost invisible in these bands. The YJHKs MAG_AUTO photometry, done using the neighbour-subtracted Ks image as the detection image to define the aperture, are listed in Table 2.

In the S-COSMOS catalog, there is an IRAC source at
Candidate Dusty Starbursts at $z > 6$

Figure 6. Same as Figure 3, but for 500R_COSMOS_T1_x31. The two close neighbours, C-1 and C-2 (see Figure 5), are almost invisible in the original $YJH$ images, and therefore their subtractions do not create any notable effect in these three bands.

3.2.5 500R_COSMOS_T1_x10

This is one of the sources whose $H_{\alpha}$ line flux has been revised because of the new ALMA identifications, and yet still survives the criterion of $H_{\alpha}$ line flux ($500 \mu m$ riser counterpart). However, this is admittedly uncertain, and we will consider two scenarios, with and without the IRAC photometry, respectively, in the follow-up SED analysis.

3.3 Counterparts of the contaminators

3.3.1 500R_COSMOS_T1_x02

The counterpart identified by the ALMA data corresponds to a bright VLA source at exactly the same location, which is 6".13 away from the HerMES centroid. The VLA source was noted in YMHF20, but it was not taken as the right counterpart due to the large positional separation. With the new identification, its $H_{\alpha}$ line flux ($500 \mu m$ riser counterpart) is revised to 0.13 and no longer satisfies $H_{\alpha}$ line flux ($500 \mu m$ riser counterpart) $> 0.7$. Its optical-to-NIR images are shown in Figure 7.

At the ALMA location, the source is invisible in $I_{814}$ and is very weak in $H_{160}$ ($24.02 \pm 0.29$ mag). However, it is clearly detected in the HSC $g$ and $r$ bands, which means that it must be at $z < 4$. It is prominent in the other HSC images as well as in the UltraVISTA images. Its photometry, which is from the team catalogs, is listed in Table 2. The $K_s$ image is significantly more extended than the PSF, and is elongated in the N-S direction. This suggests that it might have two components. Moreover, it is detected in IRAC. In MIPS, its has $S_{24\mu m} = 167 \pm 16$ µJy.

3.3.2 500R_COSMOS_T1_x34

As revealed by the ALMA data, this source has two counterparts that are separated by 14".0, both of which have VLA counterparts included in the 3 GHz catalog. We designate the one to the South-West as the “34a” component and the one to the North-East as the “34b” component, respectively. The HerMES centroid falls in between these two components, and the separation between this centroid to either is larger than the criterion adopted in YMHF20. As the result, YMHF20 treated it as with no counterpart in 3 GHz, although component 34a was noted in YMHF20 as being a close neighbour at 6".0 from the HerMES centroid. With the new identification, we combine the radio flux densities of both 34a and 34b and revise the $H_{\alpha}$ line flux value of this source to 0.12.

The optical-to-NIR images of this source is shown in Figure 8. Component 34a is visible in both $I_{814}$ and $H_{160}$ images, while component 34b is almost invisible in $I_{814}$ and $H_{160}$ images.
Figure 7. Image stamps showing the optical-to-NIR counterpart of 500R_COSMOS_T1_x10 and its vicinity. The image arrangement is the same as in Figure 2, and the red circles \( (r = 1\arcsec) \) are centred on the ALMA position. The counterpart is invisible in either \( I_{814} \) or \( H_{160} \). It is prominent in the VISTA \( K_s \) and \( H \) images and barely visible in \( J \), but is invisible in any bluer bands. Its \( K_s \) image appears bigger than in \( H \) and \( J \); in other words, it seems that only part of its \( K_s \) counterpart is visible in \( H \) and \( J \). There are two unrelated objects in the neighbourhood, which are more than 1\arcsec away and are not labeled. The counterpart is visible in all IRAC channels, however it is severely blended with at least one of the neighbours.

Figure 8. Similar to Figures 3 and 6, but for 500R_COSMOS_T1_x10. The two close neighbours are masked instead of subtracted (see text for details).

\( H_{160} \), and our photometry gives \( I_{814} = 26.67 \pm 0.22 \) and \( H_{160} = 21.60 \pm 0.09 \) mag, respectively. Component 34b is only visible in \( H_{160} \), which we obtained \( H_{160} = 23.35 \pm 0.33 \) mag. Both components are clearly detected in the HSC, the Ultra-VISTA and the S-COSMOS images. The quoted photometry in Table 2 are from the respective catalogs in the data releases.

### 3.3.3 SD850_COSMOS_T1_A03

At \( \sim 20\arcsec \) away from this SCUBA2 source, there is a prominent HerMES source in all three SPIRE bands. This HerMES source is different from this SPIRE dropout, and in fact has a different 3 GHz counterpart. For this SPIRE dropout, the ALMA data has identified its counterpart at \( 3\arcsec.0 \) from the SCUBA2 centroid. There is a prominent 3 GHz source at this location, which was noted in YMHF20 but was discarded because the separation is larger than the adopted criterion. With the new identification, this 3 GHz source is in fact the
Figure 9. Image stamps showing the optical-to-NIR counterpart of 500R_COSMOS_T1_x02 and its vicinity. The image arrangement is the same as in Figure 2, and the red circles ($r = 1''$) are centred on the ALMA position. It is invisible in $I_{814}$ and is weakly detected in $H_{160}$. It is clearly detected in all the HSC, VISTA and IRAC images.

Figure 10. Image stamps showing the optical-to-NIR counterpart of 500R_COSMOS_T1_x02 and its vicinity. The image arrangement is the same as in Figure 2, but the image sizes are different. This source has two components as revealed by ALMA (labeled as “34a” and “34b”), and the red circles ($r = 1''$) are centred on the ALMA positions. Based on these images, neither component could be at high-$z$.

Its optical-to-NIR images are shown in Figure 11. The source is invisible in $I_{814}$. Unfortunately, it does not have $H_{160}$ coverage. In the HSC images, the source seems to have two very close components that cannot be separated for photometry. However, one can still tell that the ALMA position is closer to the northern component, which is also the fainter one among the two in the HSC images. Both components are visible in $r$, and this rules out the possibility that this SPIRE dropout could be at $z > 5$. In the UltraVISTA images, it is only visible in $K_s$, and one can also identify the two close components as suggested by the HSC images. It is impossible to separate these two objects for photometry in any of the current images, and we treat them as being physically associated. The quoted photometry in HSC images is taken from the HSC catalog, and include both components as a single clump. The UltraVISTA catalog does not include this source; by our photometry, the clump of two components has $K_s = 23.77 \pm 0.16$ mag. It is detected in the IRAC Ch1/2 but is invisible in Ch3/4, and is also invisible in MIPS 24 $\mu$m.
pletely blocked by the foreground galaxy (see §3.2.3), and except two of them: (1) 500R_COSMOS_T1_x26 to the others. The analysis included the objects in Table 1 causes of their very different spatial resolutions as compared introduce large systematic errors in the SED analysis be-

The photometry is listed in Table 2, but 500R_COSMOS_T1_x31 is not detected in any of these optical-to-NIR bands. For 500R_COSMOS_T1_x31, we considered two scenarios, one with the IRAC photometry and the other without. We took this approach because it is uncertain whether the IRAC detections are significantly contaminated by the two neighbours visible in the UltraVISTA images, a reason detailed in §3.2.4. We fit these SEDs to the population synthesis models of Bruzual & Charlot (2003, “BC03”). This resulted in their model that results in the lowest χ^2 and produces a probability distribution function over the allowed redshift range (PDF; ∝ e^{−0.5χ^2_{min}(z)}). The redshift at which the PDF has its peak (i.e., the lowest χ^2_{min}(z)) is deemed as the best-fit z_{ph}, and its errors are computed using the redshifts where χ^2_{min} are ±1 from the lowest value. The model that results in the lowest χ^2_{min} at this redshift is what Le Phare calls as the best-fit model, and its associated parameters (such as M_*, T, τ etc.) are the best-fit values of these parameters. The common practice, however, is to adopt the median values instead of the best-fit values for these other parameters, because Le Phare generates errors associated with the median but not the best-fit values. We also adopted this common practice. A slight complication would occur when the PDF has more than one peak. In this case, we ran the software for the second time, which was to fix the fitted redshift. The step-size in redshift was set to δz = 0.1. Le Phare also allows adjustments of photometric errors to account for the possible systematic errors across different instruments. For this purpose, we added in quadrature 0.1 mag to the photometric errors of the IRAC bands and 0.05 mag to the others. To guard against obviously inappropriate fits, we also applied a loose prior that the absolute magnitude in K_s must be within −10 and −26 mag.

Le Phare takes the minimum χ^2 approach in doing fitting, and produces a probability distribution function over the allowed redshift range (PDF; ∝ e^{−0.5χ^2_{min}(z)}). The redshift at which the PDF has its peak (i.e., the lowest χ^2_{min}(z)) is deemed as the best-fit z_{ph}, and its errors are computed using the redshifts where χ^2_{min} are ±1 from the lowest value. The model that results in the lowest χ^2_{min} at this redshift is what Le Phare calls as the best-fit model, and its associated parameters (such as M_*, T, τ etc.) are the best-fit values of these parameters. The common practice, however, is to adopt the median values instead of the best-fit values for these other parameters, because Le Phare generates errors associated with the median but not the best-fit values. We also adopted this common practice. A slight complication would occur when the PDF has more than one peak. In this case, we ran the software for the second time, which was to fix the fitted redshift. The step-size in redshift was set to δz = 0.1. Le Phare also allows adjustments of photometric errors to account for the possible systematic errors across different instruments. For this purpose, we added in quadrature 0.1 mag to the photometric errors of the IRAC bands and 0.05 mag to the others. To guard against obviously inappropriate fits, we also applied a loose prior that the absolute magnitude in K_s must be within −10 and −26 mag.
Candidate Dusty Starbursts at $z > 6$

Figure 12. Optical-to-NIR SED fitting results for three high-$z$ candidates. The short ID of each object is indicated in each panel. For 500R_COSMOS_T1_x31, two scenarios are shown (one with the IRAC photometry and the other without). The magnitudes are presented as red circles, while the limits are shown as black circles with downward arrows. The relevant passbands are labeled for ease of reading. The inset shows the PDF of $z_{ph}$, where the dotted blue line indicates the peak that corresponds to the best-fit $z_{ph}$. When multiple peaks exist, the second peak is indicated in dotted green line. The blue curve is the best-fit model spectrum. The best-fit model corresponds to the secondary $z_{ph}$, if exists, is shown in green. The fitted parameters are labeled in the boxes, where those associated with the first and the second $z_{ph}$ peaks are coded in blue and green, respectively. The age ($T$, in yr) and the stellar mass ($M_*$, in $M_\odot$) are in logarithmic scale.

Figure 13. Similar to Figure 12, but for the contaminators. The small open circles are the simulated magnitudes (based on the best-fit models) in the corresponding bands. Object 500R_COSMOS_T1_x34 has two components (“a” and “b”), and they are fitted separately. The large $\chi^2$ in both cases are driven by the discrepancy in the photometry of the HSC-SSP $y$-band and the UltraVISTA $Y$-band.
the redshift to the secondary peak to derive other parameters around this secondary solution.

The results are summarized in Figure 12 and 13 for the high-$z$ candidates (500R COSMOS T1 x08, x31 and x10) and the contaminators (500R COSMOS T1 x02, x34 and SD850 COSMOS T1 A03), respectively. Obviously, the analysis for the high-$z$ sample suffers from the limited number of passbands that have positive detections. However, the non-detection bands are deep enough that they play a critical role in narrowing down the possible solutions. While the $z_{ph}$ estimates cannot be taken as the confirmations, they do lend support that the HiIdx(500) criterion works: 500R COSMOS T1 x08 has $z_{ph} = 9.0$; x31 has $z_{ph} = 8.0$ and 7.5 in the scenarios with and without the IRAC photometry, respectively; x10 has a rather chaotic PDF whose first peak is at $z_{ph} = 2.5$, but it still has the second peak at $z_{ph} = 9.5$. In other words, the objects in the high-$z$ sample all have acceptable solutions at $z > 6$.

In contrast, the contaminators all have best-fit $z_{ph}$ at $z \approx 1–3$ where the bulk of FIR/sub-mm sources lie. For 500R COSMOS T1 x34, its two components (“a” and “b”) were fitted independently and the results are also shown as such; it is very likely that they are at the same redshift and therefore physically associated, however the conclusion is not yet definite.

4.2 Total IR luminosity and instantaneous SFR

Using the derived $z_{ph}$, we fit the FIR-to-mm SEDs of our objects to the starburst models of Siebenmorgen & Kriigel (2007) to obtain their total IR luminosity ($L_{IR}$; integrated over rest-frame 8–1000 μm), following Ma & Yan (2015). The SPIRE photometry is taken from YMHF20. The ALMA photometry (see Table 1) are incorporated. This analysis includes three objects in the high-$z$ sample: 500R COSMOS T1 x08, x31 (both of its $z_{ph}$ peak solutions are used) and x10 (its secondary $z_{ph}$ peak solution is used). It also include one object (500R COSMOS T1 x02) in the contaminator sample. We do not fit the other two contaminators: 500R COSMOS T1 x34 is made of two components and we cannot obtain their fluxes separately in their SPIRE bands, and SD850 COSMOS T1 A03 only has photometry at the Rayleigh-Jeans tail.

Figure 14 shows the fitting results. For 500R COSMOS T1 x31, its $z_{ph}$ peak solutions in both scenarios are used. For 500R COSMOS T1 x10, its secondary $z_{ph}$ peak solution is used. Without exception, all the three high-$z$ candidates have $L_{IR} > 10^{13} L_\odot$: 500R COSMOS T1 x08, x31 and x10 have $L_{IR} = 1.0 \times 10^{14}, 6.3 \times 10^{13}$ and $1.3 \times 10^{14} L_\odot$, respectively. Applying the standard conversion given by Kennicutt (1998), which is $SFR_{IR} = 1.0 \times 10^{-19} L_{IR}$ after adjusting for a Chabrier IMF, the inferred instantaneous SFRs are $10^{4}, 6.3 \times 10^{3}$ and $1.3 \times 10^{4} M_\odot$ yr$^{-1}$, respectively.

4.3 Stellar masses: potential problem or not

While the counterpart SED fitting gives $z_{ph} > 6$ for the high-$z$ candidates, there could be a potential problem with the inferred stellar populations. The high-$z$ solutions of 500R COSMOS T1 x08, x31 and x10 report stellar masses of $10^{11.5}$, $10^{12.1}$ ($10^{10.6}$) and $10^{11.1} M_\odot$ at $z_{ph} = 9.0, 8.0$ (7.5) and 9.5, respectively. These are extremely high values, previously unseen in such early epochs (and in fact very rare in any epochs). At these redshifts, the age of the universe was only $\sim 555, 651$ (709) and 516 Myr, respectively. If the epoch of first stars was at $z = 17.2$ (Bowman et al. 2018), i.e., $\sim 225$ Myr after the Big Bang, there would only be $\sim 330, 426$ (484) and 291 Myr at most, respectively, for them to assemble such huge stellar masses, and therefore their average SFRs over these periods would have to be $\sim 958, 2,955$ (82) and 1,722 $M_\odot$ yr$^{-1}$, respectively. To make the situation worse, the best-fit models all have very small $\tau$ values of 10–90 Myr, which means that almost all their stars are formed instantaneously at the observed redshifts, a scenario that is to the opposite of the hierarchical formation picture of high-mass objects.

However, we should point out that these inferred parameters need to be treated with caution. As explained in §4.1, the reported $log(M_*)$ (and other parameters such as $\tau$ as well) value is the median value of all the fits weighted by the relative likelihood ($\propto 1/\sqrt{\chi^2}$). This would work if the relative likelihood function behaves reasonably well. Unfortunately, it is not the case for these high-$z$ objects. Figure 15 shows the relative likelihood distributions of $M_*$ for both the high-$z$ objects and the contaminators. It is obvious that the distributions for the contaminators are approximately log-normal while those for the high-$z$ objects are completely chaotic. The major cause of the difference is that the contaminators all have at least eight bands of detections while the high-$z$ objects only have three to five bands. This has made the fits of the high-$z$ objects not well constrained. In these cases, the “median” values lose the physical meaning.

Nevertheless, it is also worth pointing out that the best-fit models still give rather high stellar masses for the high-$z$ objects. This is not unexpected from their optical-to-near-IR photometry, because the bright observed magnitudes in the near-IR indeed would imply such high stellar masses under any reasonable assumption of the mass-to-light ratio. In other words, if we accept the high $z_{ph}$ for these objects, we will have to accept that the aforementioned tension still exists (albeit to a lesser degree) between the huge stellar mass and the limited time to assemble stars.

One might argue that these sources could have significant AGN contribution and therefore fitting the SEDs to stellar population synthesis models is not appropriate. However, there is no indication that these host AGN. The COSMOS field has deep X-ray observations from the Chandra Cosmos Legacy Survey (Civano et al. 2016), and none of our sources are detected in these data.

There is an alternative that would make the situation less problematic. If these objects are gravitationally lensed by a large factor (e.g., $\mu \sim 10$), the intrinsic stellar masses would then be smaller by the same factor and therefore the tension will be reduced (although still not eliminated). All the three high-$z$ objects have very close foreground companions (see Figure 2, 5 and 7), making gravitational lensing an attractive explanation. However, we will not be able to have a definite answer until spectroscopic redshifts are obtained for the counterparts and the companions.

5 DISCUSSION

Despite the difficulty with $M_*$ as mentioned above, the derived $z_{ph}$ for the high-$z$ objects should have better reliability
Candidate Dusty Starbursts at \( z > 6 \)

**Figure 14.** FIR-to-mm SED fitting results for three high-\( z \) candidates (plots without shadow) and one contaminator (plot with shadow). The SPIRE and ALMA photometry are shown in orange and red symbols, respectively, which are fitted to the models of Siebenmorgen & Krügel (2007) at the fixed \( z_{\text{ph}} \) values as described in §4.1. The best-fit model spectra are superposed, and the derived \( L_{\text{IR}} \) values are labeled. For 500R_COSMOS_T1_x10, only the fit at \( z_{\text{ph}} = 9.5 \) is shown. For 500R_COSMOS_T1_x31, the fits correspond to the first \( z_{\text{ph}} \) peaks in both scenarios (with and without IRAC photometry when deriving \( z_{\text{ph}} \)).

**Figure 15.** Relative likelihood distributions of derived stellar masses. The top three panels are for the high-\( z \) candidates in Figure 12 and the bottom four panels are for the contaminators in Figure 13. The red dots are for the fitted templates at all redshifts, while the blue dots are for the fits at the labeled \( z_{\text{ph}} \). The large filled, green (yellow) circles represent the corresponding values of the first (second) \( z_{\text{ph}} \) peaks. The fits of the contaminators all have reasonably well defined, approximately log-normal distributions at the adopted \( z_{\text{ph}} \), thanks to the large number of passbands with positive detections. In contrast, the fits of the high-\( z \) objects have very chaotic distributions due to the limited passbands with positive detections, which makes their derived stellar masses less trustworthy.

because these largely depend on the locations of the Lyman-break signature, which is determined by the intervening H I absorption but not the intrinsic properties of the galaxies. Trusting their high-\( z \) solutions in §4.1, we can estimate the surface density of ULIRGs at \( z > 6 \). In YMHF20, there are a total of 17 Tier 1 500 \( \mu \)m risers in the COSMOS field that fall within the coverage (2 deg\(^2\)) of the VLA 3 GHz data. Based on the revised matching criterion as described in §3.1, nine of them have \( \text{HzIdx}(500) \geq 0.7 \). We are able to study five of these nine in this work, thanks to the A\(^3\)COSMOS positions.
Among these five, only one (500R_COSMOS_T1_x26; “CRLE” at \(z = 5.667\)) is definitely at \(z < 6\), three (500R_COSMOS_T1_x08, x10 and x31) have optical-to-NIR counterparts consistent with being at \(z > 6\), and one (500R_COSMOS_T1_x24) is inconclusive due to the lack of optical-to-NIR counterpart. Therefore, the success rate of Hi\(z\)Idx(500) \(\geq 0.7\) selection among 500 \(\mu\)m risers is 60–80\% (three or four out of five, depending on whether 500R_COSMOS_T1_x24 is counted as a legitimate high-z candidate). The overall success rate of YMHF20’s 500 \(\mu\)m risers in selecting \(z > 6\) objects is 32–42\% (nine out of seventeen and multiplied by 60\% or 80\%). The surface density of \(z > 6\) dusty starbursts selected as 500 \(\mu\)m risers is therefore 2.7–3.6 deg\(^{-2}\). On the other hand, the SPIRE dropouts so far do not seem to be able to select any objects at \(z > 6\), as no such object satisfies Hi\(z\)Idx(850) \(\geq 0.5\) (SD850_COSMOS_T1_A03 has the revised Hi\(z\)Idx(850) = 0.22).

As already discussed, accepting the three objects shown in Figure 12 being at \(z > 6\) also means that we probably need to accept the high stellar masses of their host galaxies, which are at \(\gtrsim 10^{11} M_\odot\) if they are not gravitationally lensed. The possible formation scenarios have two extremes: they kept forming stars at an average rate of hundreds or even a few thousand \(M_\odot\) yr\(^{-1}\), or they formed all their stars instantaneously through enormous bursts. While such very high-mass, high-SFR objects at high-redshifts are at odd with the currently accepted picture of the early star formation, there are now theoretical arguments that their existence is needed to explain the supermassive black holes in the early universe (Kroupa et al. 2020). Regardless of their detailed formation histories, the progenitors of such objects must once be very luminous in the rest-frame UV, i.e., before they were heavily enriched by metal and formed large amount of dust. For example, using the conversion between \(L_\text{UV}\) and SFR as formulated in Madau et al. (1998), SFR = 500 \(M_\odot\) yr\(^{-1}\) would translate to \(M_\text{UV} = -24.9\) mag. Such a progenitor, if observed at \(z = 12\), would show up as a bright H-band dropout with \(K \sim 22.9\) mag. \(^3\) If we accept the surface density derived above, we should expect a similar surface density of their progenitors that manifest themselves as bright K-band objects.

### 6 SUMMARY

In this work, we study a subsample of the high-z ULIRG candidates selected by YMHF20 as 500 \(\mu\)m risers and SPIRE dropouts. Our objects are in the COSMOS field, where the archival ALMA data from the A\(^3\)COSMOS program offer the opportunity to pinpoint their exact locations. We aim at the candidates at \(z > 6\), which are those so weak in radio that they meet the Hi\(z\)Idx criteria for \(z > 6\). In total, our sample includes seven 500 \(\mu\)m risers and one SPIRE dropout. Based on the ALMA positions, we have found that the matching criteria adopted by YMHF20 between the FIR/sub-mm and the radio positions are too stringent and need to be relaxed slightly. Based on the subsequent revision of their Hi\(z\)Idx values, the eight objects form the true high-z subsample at \(z > 6\) consisting of five objects and the contaminator subsample consisting of three objects (including the SPIRE dropout). We searched for their counterparts in the deep optical-to-NIR images available in the field, and carried out SED analysis of the host galaxies using population synthesis model. The objects in the contaminator sample all have optical-to-NIR SEDs consistent with being interlopers at \(z \sim 1–3\). In the high-z subsample, one object turns out to be a known galaxy at \(z = 5.667\), one has no visible counterpart in any of the optical-to-NIR images, and the other three have solutions with \(z_{\text{ph}} > 6\). If we trust this assessment, the overall success rate of YMHF20’s 500 \(\mu\)m riser in selecting dusty starbursts at \(z > 6\) is \(\sim 32–42\%\), and the success rate increases to \(\sim 60–80\%\) after the purification by applying the Hi\(z\)Idx criterion. The surface density of \(z > 6\) 500 \(\mu\)m risers is \(\sim 2.7–3.6\) deg\(^{-2}\). The very existence of dusty starburst at \(z > 6\) implies that the universe must have been actively forming stars very early in time so that dust could be present at the redshifts where these ULIRGs are observed. The inferred stellar masses of their host galaxies also suggest that their progenitors could have been in starburst state since formation. Spectroscopic confirmation of such objects, both in the millimeter regime and in the near-IR regime, will be critical in understanding the star formation processes in the very early universe.

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### DATA AVAILABILITY

The data underlying this article are available in the article.

### REFERENCES

Aihara H., et al., 2018a, PASJ, 70, S4
Aihara H., et al., 2018b, PASJ, 70, S8
Arnouts S., Cristiani S., Moscardini L., Matarrese S., Lucchin F., Fontana A., Giallongo E., 1999, MNRAS, 310, 540
Asboth V., et al., 2016, MNRAS, 462, 1989
Bertin E., Arnouts S., 1996, A&AS, 117, 393
Bowman J. D., Rogers A. E. E., Monsalve R. A., Mozdzen T. J., Mahesh N., 2018, Nature, 555, 67
Bruzual G., Charlot S., 2003, MNRAS, 344, 1000

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\(^3\) We note that the same argument was presented in Yan et al. (2006) for the progenitors of high stellar mass galaxies observed at \(z \approx 6\), although the implication there was less extreme because those \(z \approx 6\) galaxies have stellar masses on the order of several \(10^{10} M_\odot\).

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Calzetti D., Kinney A. L., Storchi-Bergmann T., 1994, ApJ, 429, 582
Chabrier G., 2003, PASP, 115, 763
Civano F., et al., 2016, ApJ, 819, 62
Donevski D., et al., 2018, A& A, 614, A33
Dowell C. D., et al., 2014, ApJ, 780, 75
Griffin M. J., et al., 2010, A&A, 518, L3
Ilbert O., et al., 2006, A&A, 457, 841
Ivison R. J., et al., 2016, ApJ, 832, 78
Kennicutt Jr. R. C., 1998, ARA&A, 36, 189
Koekemoer A. M., et al., 2007, ApJS, 172, 196
Kroupa P., Subr L., Jerabkova T., Wang L., 2020, MNRAS, 498, 5652
Liu D., et al., 2019, ApJS, 244, 40
Ma Z., Yan H., 2015, ApJ, 811, 58
Madau P., 1995, ApJ, 441, 18
Madau P., Pozzetti L., Dickinson M., 1998, ApJ, 498, 106
McCracken H. J., et al., 2012, A&A, 544, A156
Mowlia L. A., et al., 2019, ApJ, 880, 57
Pavesi R., et al., 2018, ApJ, 861, 43
Peng C. Y., Ho L. C., Impey C. D., Rix H.-W., 2002, AJ, 124, 266
Peng C. Y., Ho L. C., Impey C. D., Rix H.-W., 2010, AJ, 139, 2097
Pilbratt G. L., et al., 2010, A&A, 518, L1
Pope A., Chary R.-R., 2010, ApJ, 715, L171
Riechers D. A., et al., 2013, Nature, 496, 329
Riechers D. A., et al., 2017, ApJ, 850, 1
Roseboom I. G., et al., 2012, MNRAS, 419, 2758
Sanders D. B., et al., 2007, ApJS, 172, 86
Siebenmorgen R., Krügel E., 2007, A&A, 461, 445
Strandet M. L., et al., 2017, ApJ, 842, L15
Yan H., Dickinson M., Giavalisco M., Stern D., Eisenhardt P. R. M., Ferguson H. C., 2006, ApJ, 651, 24
Yan H., Ma Z., Huang J.-S., Fan L., 2020, ApJS, 249, 1

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