Far infrared constraints on the contamination by dust obscured galaxies of high-z dropout searches

F. Boone, D. Schaerer, R. Pello, D. Lutz, A. Weiss, E. Egami, I. Smail, M. Rex, T. Rawle, R. Ivison, N. Laporte, A. Beelen, F. Combes, A. W. Blain, J. Richard, J.-P. Kneib, M. Zamojski, M. Dessauges-Zavadsky, B. Altieri, P. van der Werf, M. Swinbank, P. G. Pérez-González, B. Clement, R. Nordon, B. Magnelli, and K. M. Menten

1. Introduction

Observing galaxies up to very high redshifts allows us to study directly the formation and evolution of structures in the expanding Universe. Finding galaxies at ever higher redshifts has therefore become one of the main areas of extragalactic astronomy. The most common technique is to use broad features in the spectral energy distributions (SEDs) of galaxies to identify high redshift sources in deep optical and near infrared (NIR) multi-band observations. In particular the Lyman break is widely used to select sources by redshift noting their disappearance in bands below a given wavelength, the so-called drop-out technique (Steidel et al. 1996).

With this technique and state of the art telescopes and instruments it is now possible to select sources that are good candidates for being at the end or within the epoch of reionization (Richard et al. 2006; Zheng et al. 2009; McLure et al. 2010; Bouwens et al. 2010a, b; Wilkins et al. 2010; Oesch et al. 2010; Bouwens et al. 2010b).

Low redshift galaxies, however, can have very steep SEDs resembling a break in the UV/optical/NIR. This can lead to contamination of the dropout selection of very high-z galaxies, and hence to erroneous estimates of the star formation rate density, stellar masses, and others, although these effects are cur-
currently difficult to quantify. Such objects have been found and discussed by several authors (see e.g. Dickinson et al. 2000 Mobasher et al. 2005, Schaerer et al. 2007; Dunlop et al. 2007 Chary et al. 2007; Capak et al. 2011). Confirming the photometric redshifts of high-z galaxies by identifying spectral lines is challenging because the sources are generally too faint for spectroscopic follow up observations or because they may intrinsically lack Lyα emission (but see Vanzella et al. 2010).

The recent developments of space far infrared instrumentation offer new perspectives in this domain. In particular, with the advent of the Herschel Space Observatory it is now possible to sample the Far Infrared (FIR) SEDs of the galaxies, where the thermal dust emission dominates. The shape of the FIR SED universally looks like a broad bump which can be used to further constrain the optical/NIR photometric redshifts. Although the wavelength of the FIR SED peak also depends on the dust temperature, the limited range of average temperatures observed so far in galaxies (between 20 and 60 K averaged over the entire galaxies, see, e.g., Kovács et al. 2006; Magnelli et al. 2014; Magdis et al. 2014; Wardlow et al. 2011) can be used as a prior and makes it possible to discriminate between intermediate (z < 3) and very high redshifts (z > 6).

FIR observations of high-z candidates are also essential to characterize their star forming and dust properties and thus interpret correctly their contribution to the cosmic history of star formation and reionization.

Recently Laporte et al. (2011) identified ten z > 7 candidates in the field of the cluster Abell 2667 using photometric dropout criteria based on deep observations with HAWK-I on the ESO Very Large Telescope (VLT). Comparing to other studies and in particular to the WIRCAM Ultra Deep Field Survey (WUDS; Pello et al. in prep), which is based on deeper optical observations bluewards to the I-band, they estimated that 50-75% of these candidates could in fact be lower redshift interlopers. Here, we study two galaxies of this sample that are clearly detected by Herschel, namely the sources named ’z1’ and ’Y5’. Our goal is to determine whether they could be interlopers and to understand their nature. The redshift probability distributions of these two sources derived by Laporte et al. (2011) from SEY fitting to deep Optical/NIR photometry show a prominent peak at z ≈ 7.6 and 8.6 respectively. However, a secondary peak at lower redshift around z ≈ 2, indicates that they also could be interlopers. Laporte et al. (2011) also noted that the 24 μm detection of z1 with MIPS/Spitzer (Y5 is out of the Spitzer map) seems difficult to reconcile with the high-z solution. We use new Herschel and LABOCA observations of Abell 2667, to reconstruct the FIR part of their SEDs. We can thus further constrain their redshifts and study their physical properties.

The layout of the article is as follows: Section 2 gives a presentation of the observations and data analysis. In Section 3 the FIR part of the SEDs is analyzed. In Section 4 the complete SEDs are used to estimate the redshifts and discuss the physical properties of the two galaxies. In Section 5 we compare the two galaxies to other similar galaxies found in the literature. Section 6 gives the conclusions. We assume a Λ-cosmology with H₀ = 70 km s⁻¹ Mpc⁻¹, Ω₀ = 0.3 and Ωₐ = 0.7.

2. Observations and Data Analysis

2.1. Observations and reduction

Herschel observations were obtained in the framework of the Herschel Lensing Survey (HLS) described by Egami et al. (2010). They include PACS data at 100 and 160 μm, and SPIRE observations at 250, 350 and 500 μm. The data reduction was done with the HIPE software as described by Rex et al. (2010) and Rawle et al. (2011).

The large APEX Bolometer Camera (LABOCA Siringo et al. 2009) is a bolometer array operating at 870 μm and mounted on the APEX telescope in the desert of Atacama, Chile (Güsten et al. 2006). The LABOCA observations were conducted during the summer 2010. The cluster was mapped in spiral mode during 30 hours covering a circular field of ~6’ in radius. The data were reduced with the BoA software. The noise is not uniform over the map and the RMS is in the range 1.1–3.0 mJy, the highest values being reached at the edges of the map.

We also obtained a VLA 1.4 GHz continuum map of Abell 2667 (PI: R. Ivison) with an RMS of 46 μJy.

2.2. Analysis

The astrometry of all the maps was corrected to align them with the VLT Ks image. All the optical drop-out sources of Laporte et al. (2011) were inspected in the LABOCA and LABOCA A images. Two of them, z1 and Y5, are detected in several FIR bands. As IRAC/Spitzer and MIPS/Spitzer data are available for z1, the source can be followed from one band to the next one by increasing wavelength despite the decreasing resolution. Its identification is therefore robust.

For Y5 there is a larger gap in the SED due to the lack of data between 8 μm and 100 μm, and due to the fact that it lies at the noisy edges of the 100 and 160 μm maps, where it is not detected. However, Y5 is the only source detected at 4.5 μm within a radius of 3’’ (i.e., ~ 1/3rd of the 250 μm beam radius) around the 250 μm peak, its identification with the SPIRE detection is therefore very likely.

The fluxes are measured at the positions of the two galaxies by PSF fitting in apertures with a radius equal to FWHM/3, where FWHM is the PSF full width at half maximum, i.e., 5.6”, 11.3”, 18.1”, 24.9”, 36.6” and 22.5” from 100 to 870 μm. The last (LABOCA) FWHM corresponds to the APEX beam convolved by a gaussian of 12”. The sources were deblended from the neighbouring sources by subtracting PSFs at the positions of the neighbours derived from the 250 μm map. Observations at these wavelengths with these resolutions are affected by source confusion. As a consequence a measured flux cannot be directly interpreted as the true flux of a single underlying source. A correct treatment of the effect of source confusion on flux measurements (a.k.a. flux ‘deboosting’) requires a prior knowledge of the source counts towards low fluxes at the given wavelength. We followed the method presented by Crawford et al. (2010) based on a Bayesian analysis. For the prior source counts we extrapolated toward low fluxes the results of Berta et al. (2010) for PACS bands, Oliver et al. (2010) for SPIRE bands and Coppin et al. (2006) for the LABOCA band.

Blending affects z1 photometry at λ ≥ 250 μm and Y5 photometry at λ ≥ 500 μm. And the effect of deboosting is small (< 20%), except for the 870 μm measurement of Y5 that corresponds to a 2.6σ signal and that we chose to consider as a tentative detection. The deboosted flux of Y5 at 870 μm is 1.8±1 mJy for a measured flux of 2.5±0.95 mJy.

None of the two sources are detected in the VLA map. The measured FIR fluxes of the sources as well as their optical to near-IR photometry from Laporte et al. (2011) are listed in Table 1.

Postage stamps of the Herschel and LABOCA bands can be found at http://www.apex-telescope.org/bolometer/laboca/boa/
Table 1. Multi-wavelength SED of z1 (col 3) and Y5 (col 4). Optical and IR photometry (rows 1-10) is taken from Laporte et al. (2011). Upper limits are 3σ. Rows 12-17 give the Herschel and LABOCA source flux. When the measured flux (not the estimated flux) is < 2.5σ the 3σ value is given as an upper limit. No entry indicates the lack of data. All fluxes are given in milli-Janskys.

| Band/instrument | \( \lambda_{\text{eff}} \) [\( \text{\mu m} \)] | z1  | Y5  |
|-----------------|------------------|-----|-----|
| I               | 0.79             | <3.6e-5 | <3.6e-5 |
| z               | 0.92             | <1.4e-4 | <1.4e-4 |
| Y               | 1.02             | (2.0±0.3)e-4 | <6.3e-5 |
| J               | 1.26             | (1.75±0.05)e-3 | (6.9±0.5)e-4 |
| H               | 1.63             | (1.33±0.07)e-3 | (9.3±0.03)e-4 |
| Ks              | 2.15             | (2.29±0.06)e-3 | (1.77±0.07)e-3 |
| IRAC            | 3.6              | (6.98±0.06)e-3 | (2.91±0.11)e-3 |
|               | 4.5              | (10.20±0.09)e-3 | (3.73±0.10)e-3 |
|                | 8.0              | (9.91±0.96)e-3 | (3.03±0.24)e-3 |
| MIPS            | 24               | 0.340±0.040 | <20 |
| PACS            | 100              | <3.3   | <18 |
| 160             | 6.3±2.0          | <30   |
| SPIRE           | 250              | 19.4±1.6 | 45.5±1.6 |
| 350             | 15.7±1.4         | 30.3±1.2 |
| 500             | 7.5±1.7          | 19.2±2.1 |
| LABOCA          | 870              | <2.5   | 1.8±1.0 |
| VLA             | 2.1×10^3        | <0.14  | <0.14 |

centered at the source positions as well as FIR SED fits are shown in the Fig. [I] Y5 is close to the border of the PACS maps where the noise is higher, hence the high upper limits.

3. Analysis of the FIR SEDs

The following models or templates have been fitted to the FIR measurements (cf. Fig. [I]):

- A modified black body SED parameterized as described by Blain et al. (2003), with emissivity fixed to \( \beta = 1.5 \) and the Wien correction parameter \( \alpha = 2.9 \). These values are adapted to submillimeter galaxies (SMGs; Chapman et al. 2005) and local ultraluminous infrared galaxies (ULIRGs; Dunne et al. 2004, Blain et al. 2003). The free parameters are the total FIR luminosity, \( L_{\text{FIR}} \), defined as the luminosity emitted in the range 8–1000\( \mu \text{m} \), and the dust temperature, \( T_d \).

- The 105 galaxy templates built by Chary & Elbaz (2001). The templates are fitted without rescaling 3.

- ULIRG templates built by Vega et al. (2008), with a scaling parameter, \( L_{\text{FIR}} \).

- The starburst, Seyfert, and active galactic nuclei (AGN) templates of Polletta et al. (2007), with a scaling parameter, \( L_{\text{FIR}} \).

- Templates built by Michałowski et al. (2010a) to fit high redshift galaxies with detected but poorly sampled submm emission, with a scaling parameter, \( L_{\text{FIR}} \).

- The SED fit to the observations of SMM J2135-0102 Swinbank et al. (2010), with a scaling parameter, \( L_{\text{FIR}} \).

The fit is performed by finding the maximum likelihood assuming gaussian probability distributions for the measurements. When there is no detection the 3-σ value is used as a hard upper limit, i.e., the probability is assumed to be uniform in the [0, 3σ] interval and zero outside. The redshifts are fixed to the solutions derived by Laporte et al. (2011) from the optical/NIR photometry, i.e., \( z = 1.8 \) and 7.6 for z1 and \( z = 1.7 \) and 8.6 for Y5. The corresponding magnification factors are \( \mu = 1.12 \) and 1.71 for z1 and \( \mu = 1.04 \) and 1.15 for Y5. The MIPS/Spitzer 24\( \mu \text{m} \) flux of z1 (Y5 has no 24\( \mu \text{m} \) data available) was taken into account to fit various galaxy templates, but ignored to fit the modified black body since it is most likely dominated by polycyclic aromatic hydrocarbons (PAHs).

For both sources we find reasonable fits at low redshift for the modified black body and the various galaxy templates. A ULIRG template from the Vega et al. (2008) library, a submillimeter detected galaxy template from the Michałowski et al. (2010a) library and a Seyfert template from the Polletta et al. (2007) library are able to reproduce the 24\( \mu \text{m} \) emission of z1. The modified black body model gives dust temperatures of 34 and 40 K, for z1 and Y5 respectively, which are typical values for integrated dust temperatures in LIRGs. The infrared luminosities, \( L_{\text{FIR}} \), are in the range (1.2 – 1.7) \( \times 10^{10} \text{L}_\odot \) and (3.1 – 4.7) \( \times 10^{12} \text{L}_\odot \) for z1 and Y5 respectively. There is a noticeable agreement in \( L_{\text{FIR}} \) between the modified black body model and the various templates. These galaxies would therefore be typical ULIRGs/SMGs at \( z = 2 \). This is consistent with the general picture of galaxy evolution now widely observed, i.e., that the contribution of ULIRGs to the cosmic SFR is expected to peak at \( z = 2 \) where it should be comparable to that of the more ‘normal’ galaxies (see e.g. Murphy et al. 2011).

For the high redshift solutions (\( z > 7.5 \)), instead, the modified black body requires for both sources very high dust temperatures, i.e., 105 and 129 K for z1 and Y5, respectively. Such high temperatures averaged over an entire galaxy are extreme. This can be seen from the impossibility to find any good fit in the different template libraries, which were built from observed galaxies. However, the dust properties of galaxies at such high redshifts are unknown and dust temperatures above 100 K cannot be ruled out. This would imply that the FIR luminosities are of the order 0.5 and 1.5 \( \times 10^{14} \text{L}_\odot \) for z1 and Y5, respectively, i.e. both sources would be classified as Hyper Luminous Infrared Galaxies (HyLIRG). While the nature of HyLIRGs is still a matter of debate (e.g. Ruiz et al. 2010) and their density at very high redshift is not well known, they are extreme sources with a lower number density than ULIRGs.

The radio continuum upper limits are too high to constrain the SED fitting. We find that for Y5 only at the low redshift solution (\( z = 2 \)) the Chary & Elbaz template is close to the 3σ upper limit. Thus, in summary, by comparing the FIR photometry to known galaxy SEDs and by taking into account the expected temperature and luminosity range of high redshift galaxies, the very high redshift solutions derived from the optical/NIR photometry seem to be less likely than the low redshift solutions. The two sources are most likely typical ULIRGs at \( z = 2 \). This result puts strong constraints on the optical/NIR analysis which gave a much higher probability to the very high redshift solution when no prior luminosity function was taken into account. The FIR data alone, however, cannot be used to derive any acc...
Fig. 1. The top figures show the postage stamps in the five Herschel bands (100, 160, 250, 350, 500 $\mu$m from left to right) and the LABOCA band (870 $\mu$m, the right-most stamp) centered on z1 and the best fit SEDs for the low redshift (left) and high redshift (right) solutions. The bottom figures show the same for the source Y5. The red circle in the postage stamps is meant to guide the eye, it has a radius of 27\arcmin and it is centered on the source position. The blue curves correspond to the best fit modified black body SEDs with the parameters written in blue, the magenta curves correspond to the SMM J2135-0102 model (Swinbank et al. 2010; Ivison et al. 2010), the other curves correspond to the best fit templates of the Chary & Elbaz (2001) library (red), the Vega et al. (2008) library (green), the Michałowski et al. (2010a,b) library (cyan) and the Polletta et al. (2007) library (orange). The names of the best fit templates as well as $L_{\text{FIR}}$ are written on the figure with the same color codes.

4. Analysis of the complete SED from visible to FIR

We will now examine all the data from the visible to the FIR ranges to improve the redshift estimate of our galaxies and to examine the nature and physical properties of these sources.
4.1. Method

To model the SED of the two sources we use a modified version of the Hyperz photometric redshift code of Bolzonella et al. (2000) described in Schaerer & de Barros (2009). Non-detections are treated as the usual case of Hyperz, i.e., the flux in these filters is set to zero, with an error bar corresponding to the flux at 1σ level. The basic spectral templates are taken from the Bruzual & Charlot models (Bruzual & Charlot 2003), computed for a variety of star-formation histories and metallicities. Although applicable only to a limited part of the spectrum, we use these templates here to constrain redshift, extinction, and stellar mass in particular. For the Bruzual & Charlot templates we consider variable extinction with $A_V$ up to 8 magnitudes for the Calzetti et al. (2000) attenuation law. We have also explored other extinction laws.

The code, initially designed to fit rest frame UV to near-IR (stellar) emission, can also easily be used to include the thermal mid-IR and beyond. To cover the entire spectral range from the visible to the millimeter domain, and to compare our sources with SEDs of very different galaxy types, we have compiled a large variety of spectral templates from the GRASIL models of Silva et al. (1998), the library of Charly & Elbaz (2001), Rieke et al. (2009), the starburst, Seyfert, and AGN templates of Polletta et al. (2007), the ULIRG templates of Vega et al. (2008), the sub-mm galaxy templates of Michałowski et al. (2010a), and the model fit to SMM J2135-0102 (Swinbank et al. 2010; Ivison et al. 2010). Extinction can also be added to these spectral templates; SED fits with and without additional extinction will be discussed below.

We have carried out both fits of the entire SED (optical, near-IR, and IR) and fits up to 8 μm only (for the Bruzual & Charlot templates). For each template set the free parameters are redshift and (additional) $A_V$. Physical parameters such as the infrared luminosity, $L_{IR}$, defined as the luminosity emitted in the range 2-1000 μm; the IR star-formation rate, SFR; and the stellar mass, are subsequently derived from the best-fit templates. In contrast to the IR fits discussed in Sect. 4.1, we have no handle on the dust temperature, since this is not a parameter describing the SEDs used here. We have also checked that the two independent fitting methods used here and in Sect. 4.1 give consistent results.

4.2. Photometric redshifts

As discussed in depth by Laporte et al. (2011) the best-fit photometric redshifts of our sources derived from the optical to near-IR photometry (up to 8 μm) and using standard spectral templates is consistently found at $z > 7$ with a lower probability at low $z$. This result remains unchanged with the exploration of a wider range of extinction, different attenuation/extinction laws, and templates sets used here compared to Laporte et al. (2011). On the other hand, analysis of the IR SED and other arguments clearly favour low redshifts ($z \sim 1.5$–2.5) as discussed above. Subsequently we therefore limit ourselves to $z < 4$ and attempt to refine the photometric redshift of the two sources.

4.3. Results for $z_1$

Overall the global, multi-wavelength SED fits for this source are rather satisfactory, as shown in Fig. 4.1 albeit there are important discrepancies in the optical domain (cf. below). Several templates (i.e. Polletta’s, the ULIRGs of Vega et al. (2008), and the best-fit SMG template from Michałowski et al. (2010a)) also reproduce the 24 μm flux, and the observed 100 and 870 μm fluxes are within 2–3 σ of the model. Interestingly, the best fits for both sets of Polletta’s and Michałowski’s templates are found with templates for active galaxies.

The best-fit redshift found with these templates are between $z \approx 2.24$ and 2.57. The resulting IR luminosity is $L_{IR} \sim (2.6$–3.2)$ \times 10^{12} L_{⊙}$, the corresponding SFR $\approx 450$–550 $M_{⊙}$ yr$^{-1}$ using the standard Kennicutt (1998) calibration. Fits to the IR part with the SMM J2135-0102 template yield $z_{phot} \approx 2.0$. A somewhat lower redshift of $z \approx 1.7$ is found with Bruzual & Charlot (2003) templates using the SED up to the IRAC bands. The estimated extinction is $A_V \sim 2.6$, the stellar mass $M_⋆ \sim 6 \times 10^{10}$ $M_{⊙}$ for the same Salpeter IMF adopted by Kennicutt (1998). However, these values should be taken with caution as the fits are not of good quality. For comparison from the absolute H-band magnitude ($M_H \approx -23.0$) one obtains $M_⋆ \sim 3 \times 10^{10}$ $M_{⊙}$ using the mass-to-light ratio adopted by Wardlow et al. (2011) for SMGs.

At a more detailed level (see right panel), all spectral templates have some difficulty to reproduce the steep, observed SED between the visible (I, z bands) and the near-IR (Y and J here), and they predict a flux excess in the optical domain. Below we will show that this also holds when variable extinction is added to the empirical templates. The same is also true for all other templates we have examined, including the theoretical galaxy templates of Bruzual & Charlot (2003). This sharp drop is of course the reason why this source was selected as an optical dropout (Y-drop).

4.4. Results for Y5

For this source the global fits are less good than for $z_1$. This is due to the fact that Y5 shows a higher flux ratio between the thermal-IR and the near-IR than $z_1$, whose SED already required templates with extreme IR/near-IR fluxes. For example, the Arp 220 template from Polletta et al. (2007), shown in red, underpredicts the IR flux by a factor $\approx 5$. The only template coming near the observed IR emission is from the SMG library of Michałowski et al. (2010a) (SMMJ221725.97+011238). With a best-fit redshift of $z_{phot} \approx 2.15$ this translates to $L_{IR} = 2.2 \times 10^{12}$ $L_{⊙}$ corresponding to SFR $\approx 380$ $M_{⊙}$ yr$^{-1}$. Fits to the IR part with the SMM J2135-0102 template yield $z_{phot} \approx 1.8$. A best-fit redshift of $z \approx 1.95$ is found with Bruzual & Charlot (2003) templates using the SED up to the IRAC bands. The estimated extinction is $A_V \sim 1.6$, the stellar mass $M_⋆ \sim 3 \times 10^{10}$ $M_{⊙}$. However, these values should be taken with caution as the fits in the domain close to the optical are not of good quality. Again, using the absolute H-band magnitude ($M_H \approx -22.3$) one obtains $M_⋆ \sim 2 \times 10^{10}$ $M_{⊙}$ with the assumptions already mentioned above.

As for $z_1$, the visible–near-IR drop of the SED (see right panel) is not well fit by the spectral templates, predicting that the source should be detectable in the visible (I, z, Y bands in particular), in contrast to our observations. The template fitting best this part of the spectrum is an S0 template from Polletta et al. (2007), shown in green. However, this template underpredicts the IR emission by several orders of magnitudes.

4.5. Possible explanations for the strong SED break/very red spectrum

As already seen, the common, observed spectral templates fail to reproduce the steep, observed SED between the visible (I, z bands) and the near-IR (Y and J here), and they predict a flux excess in the optical domain. What causes the sharp ob-
Fig. 2. Fits to the observed SED of source z1 (photometry shown by blue symbols, including 3σ upper limits) using different spectral templates: Chary & Elbaz (2001) (black = best-fit template, and magenta = template with maximum IR luminosity), Polletta et al. (2007) (red = global best-fit template, and green = best-fit to visible–near-IR SED excluding the thermal IR), and Michałowski et al. (2010a) (blue). The best-fit SED with the templates of Vega et al. (2008), very similar to the one using Polletta’s templates, is not shown here for simplicity. **Left:** Global visible to sub-mm SED. **Right:** Zoom on visible to near-IR part of the SED including for comparison also the best-fit SED at high redshift (z = 7.5) from Laporte et al. (2011, dashed line), which is most likely excluded due to our Herschel detections.

Fig. 3. Same as Fig. 2 for Y5. The best-fit SED at high redshift (black dashed line) is for z = 8.28.

served decrease of the flux between the near-IR and the optical for these sources? The main difficulty provides from the fact that the largest spectral break known in galaxy spectra is the Lyman break, whereas the typically observed Balmer (or “4000 Å”) break is smaller than that of our two galaxies. We have examined various possibilities, but with no convincing answer.

For example, as shown in Fig. 4 for z1, adding variable extinction to the empirical templates allows one to diminish somewhat their optical flux excess. For the Chary & Elbaz templates, the best-fit (to the domain shown here) is then with an additional extinction ΔAV = 1.4 for the Calzetti law. However, the templates are too smooth to reproduce the apparent break. The
Finally, could composite populations not taken into account by our models help to explain the observed SED? Certainly the theoretical SED models may suffer from this simplification. However, we do not see how this could help to resolve the problem with the large observed spectral break, since a superposition of individual simple stellar populations (not capable of reproducing this observation) can only average out spectral features. We conclude that we have no convincing explanation for the observed rapid drop of the observed SED of our two sources.

5. Discussion

5.1. Comparison with other objects in the literature

How do our sources compare with other known galaxies and what is their nature?

By design our sources are near-IR selected, optical dropout sources, i.e. sources with a very red color between the J and z band and/or between Y and J. Our sources can therefore be compared to those selected by Capak et al. (2011) from the COSMOS survey. From their Fig. 13 we note that with (J - z) > 5.4 and 4.4 and (z - J) > 3.9 and 3.1 for z1 and Y5 both sources show extreme (very red) optical to near-IR colors, when compared to other low redshift galaxies with red (J-z) colors. z1 and Y5 are also similar to the z-dropout galaxy HUDF-J2 identified by Mobasher et al. (2005) as a z \approx 6.5 post-starburst galaxy candidate, but later shown to be most likely at z = 1.8–2.5 interloper by Schreier et al. (2007); Dunlop et al. (2007); Chary et al. (2007). Although similar in several respects, HUDF-J2 shows a more monotonously rising SED between z, J, and H than our objects exhibiting a “sharper” break. The colors and fluxes of our sources are also very similar to those of the lensed optical drop-out galaxy #2 found behind the cluster Abell 1835, identified with the z = 2.93 sub-mm galaxy SMMJ14009+0252 (see Schreier et al. 2007; Weiβ et al. 2009 and references therein).

Our sources are obviously also characterised by a large IR to optical flux ratio, a criterium which has been used by various authors. For example, Rodighiero et al. (2007) have studied IRAC 3.6 \mu m selected sources undetected in deep optical RST images. The (K-3.6) and (z-3.6) colors of z1 and Y5 are comparable to those of our sources and our objects are bluer than those of Rodighiero et al. (2007). z1 and Y5 appear to be related to the very dusty z ~ 2–3 sources from this study. Fiore et al. (2008) and Dey et al. (2008) have examined 24 \mu m selected sources with very red colors between 24 \mu m and the R band (S(24)/S(R) \approx 1000). They concluded that the bulk of these sources are very luminous strongly dust-obsured galaxies referred to as DOGs at z \approx 2, powered by AGN and/or by starbursts. Using the I band as a proxy for R, we obtain a flux ratio S(24)/S(R) \approx 20000 for z1, an extremely high flux ratio compared to the other samples. From the SED of Y5 (cf. Fig. 3), we also expect this galaxy to show a high 24 \mu m to optical ratio. According to the source density from Dey et al. (2008) we would have expected \approx 4 strongly dust-obsured galaxies down to \approx 0.3 mJy at 24 \mu m in our 45 arcmin^2 field. The depth of our MIPS observations being similar, this value is comparable to our source density, although our selection is different. Pope et al. (2008) have also compared DOGs and sub-mm galaxies (SMGs) in the same R-K-24 \mu m colors, showing that ~ 30% of SMGs satisfy the DOG criteria, the remainder showing less extreme (i.e. bluer) colors. This confirms that the SEDs of our sources are comparable to a subset of SMGs with the most extreme optical to IR/sub-mm colors, as already confirmed by the large IR to optical flux ratio.

As already mentioned by Laporte et al. (2011) we have also attempted to fit the SEDs with our models including nebular lines (see Schaerer & de Barros 2009). Indeed, in this case the best-fit is found at z \approx 1.5 such that the [OIII] \lambda 4959,5007 lines, and Hβ boost somewhat the J-band flux, and Hα the H-band to a lesser extent, contributing thus to the flux decrement between J and Y. However, this solution requires also a very large attenuation (A_V \approx 4.0 for the SMC law) to reproduce the steeply rising SED towards longer wavelengths. Although to the best of our knowledge objects with such red SEDs and strong emission lines are not known, this extreme explanation should be easy to test with spectroscopic observations.
seen above (Sect.3). Our optical data is not deep enough to ascertain whether z1 and Y5 fulfill the usual criteria for extremely red objects (EROs), \((R - K) \gtrsim 5.6\) in Vega magnitudes, at least as estimated from (I-Ks).

Among known sub-mm galaxies, one source, GN10 or GOODS 850-5, stands out as having particularly extreme IR/sub-mm to visible/near-IR properties, similar to our two galaxies. Indeed, this source is undetected down to \(0.01\,\mu\)Jy (1\)\(\sigma\) in the visible, shows fluxes of \(\sim 1 - 5\,\mu\)Jy in the IRAC bands \((3.6-8\,\mu\)m\), and peaks at \(\sim 10 - 20\,\mu\)Jy around 1 mm \(\text{Wang et al.} 2004, 2008; \text{Daddi et al.} 2009\), quite comparable to z1 and Y5. However, GN10 remains undetected even at JHK \(\text{Wang et al.} 2009\), which can be explained by its higher redshift \((z \sim 4)\), recently confirmed from CO spectroscopy \(\text{Daddi et al.} 2009\). The observed spectral break of GN10 found between 3.6 and 2.2\(\mu\)m and other considerations \(\text{Wang et al.} 2009; \text{Daddi et al.} 2009\) suggest a very high attenuation of \(A_V \gtrsim 4.5 - 5\) for this source, or at least for the star-forming part of it, if hosting multiple components. If we assume constant star-formation as \(\text{Daddi et al.} 2009\) for their SED modeling, we would infer \(A_V \sim 3\) \((7.8)\) mag for z1 \((Y5)\). Comparing the infrared-derived SFR with the upper limits in the rest-frame UV domain, we can also estimate the attenuation of our sources. Adopting the I-band flux as a constraint for the UV flux at \(\sim 2300-2500\,\AA\) and using the \(\text{Kennicutt (1998)}\) calibration, we obtain \(A_V \gtrsim 4\) mag for both sources.

Sub-mm galaxies are also known to exhibit very strong attenuation. For example, sources with Balmer decrement measurements indicate \(A_V \sim 1-3\) \(\text{Swinbank et al.} 2004; \text{Takata et al.} 2006\), and from SED fits \(\text{Swinbank et al.} 2004\) estimate \(A_V = 3.0 \pm 1.0\) for their sample. \(\text{Wardlow et al.} 2011\) find \(A_V = 2.6 \pm 0.2\) from the median SED of sub-mm galaxies, but more extreme attenuations are found within the sub-mm galaxy samples (see e.g. \(\text{Smail et al.} 2004\)). Also, the extremely red object, sub-mm detected galaxy HR10 studied by \(\text{Dey et al. (1999)}\) shows \(A_V \sim 4.5\), as inferred from comparison of the IR and H\alpha star-formation rate. In short, although higher than the typical/median value of sub-mm galaxies, the attenuation of the sources z1 and Y5 is similar to that of some sub-mm galaxies, such as GN10 at \(z = 4.04\) and others at lower \(z\). Our sources are also somewhat fainter, both in the rest frame near-IR and in the IR than the typical sub-mm galaxies (cf. \(\text{Wardlow et al.} 2011\)). Finally, our sources stand out by their large spectral break, which – to the best of our knowledge – is unusual among intermediate redshift sources.

### 5.2. The other high-z candidates of the survey

Based on our FIR detections we have identified two potential interlopers among the ten high-z candidates discovered by \(\text{Laporte et al. (2011)}\). Most of the other candidates are in crowded regions where several sources emit in the FIR and are blended with each other, making any FIR measurement impossible. Two other candidates only seem to be clean from any contamination in the MIPS, PACS and SPIRE maps, namely Y3 and Y4. They remain undetected in all the bands. However, the FIR upper limits obtained do not allow us to discriminate between low and high redshift. On the other hand we can rule out that these sources are as extreme as z1 and Y5 in their IR/sub-mm to near-IR flux ratio, since they should otherwise clearly be detected in our Herschel images.

### 6. Conclusions

Analyzing the FIR SED of two high redshift dropout candidates we find that both galaxies are likely at \(z \sim 2\) rather than \(z \sim 7\). From the FIR point of view alone, both galaxies could be similar to ULIRGs or SMGs which are common at \(z \sim 2\). At \(z > 7\) the SEDs would imply even higher temperatures and luminosities. Fitting the global SEDs considering all the data available from visible to submm we estimate \(z \sim 1.6-2.5\).

However, the optical/NIR part of both objects remains difficult to understand if at \(z > 2\). They show a very strong and well defined spectral break (presumably the Balmer break), unusual among intermediate redshift sources. The source z1 is extreme for both IR/visible and near-IR/optical colors. The source Y5 has a somewhat smaller drop between the near-IR/optical domain.

We have examined several possible explanations for the extreme colors of these galaxies but none of them is entirely satisfactory. More observations are required to understand their nature. Once a spectroscopic confirmation of their redshift is obtained we will be able to create new SED templates.

Other extreme sources \(\text{e.g.} \text{GN10} \text{Wang et al.} 2004; \text{Lutz et al.} 2005 \text{Wang et al.} 2009; \text{Daddi et al.} 2009\) were found from MIPS observations and submm searches. There could therefore be two complementary paths leading to similar, extreme sources.

Although spectroscopic confirmation is still required and all possible interlopers may not be detected in the FIR, this work shows that FIR observations can be very helpful to constrain the contamination of high-z dropout searches by lower redshift galaxies.

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