| | |
|---|---|
| ***Publication Year*** | 2018 |
| ***Acceptance in OA@INAF*** | 2021-01-21T11:46:31Z |
| ***Title*** | Chasing passive galaxies in the early Universe: a critical analysis in CANDELS GOODS-South |
| ***Authors*** | MERLIN, Emiliano; FONTANA, Adriano; CASTELLANO, MARCO; SANTINI, Paola<br>Torelli, M.; et al. |
| ***DOI*** | 10.1093/mnras/stx2385 |
| ***Handle*** | http://hdl.handle.net/20.500.12386/29917 |
| ***Journal*** | MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY |
| ***Number*** | 473 |

### 4.1 The SED-fitting method

The SED-fitting has been performed on the 19 bands catalogue described in Section 2 using our code *zphot*, in which we have implemented the TH models in addition to standard $\tau$-models. The same SED-fitting technique has been used in several previous studies (Fontana et al. 2004, 2006; Grazian et al. 2006; Maiolino et al. 2008; Santini et al. 2012; Dahlen et al. 2013; Castellano et al. 2014, 2016) and it is similar to that adopted by other groups in the literature (e.g. Dickinson et al. 2003; Ilbert et al. 2013); however, the adoption of the abruptly quenched SFH is novel.

As described above, the TH library consists of a grid of models with constant SFR for a time $t_{burst}$, after which the SFR is set to zero. The models have been created using Bruzual & Charlot (2003, BC03) libraries and adopting a Salpeter (1955) IMF. Ages are computed from the onset of SFR, which means that any model is star-forming from age $= 0$ to age $= t_{burst}$, and passive for age $> t_{burst}$. Only ages less than the age of the Universe at a given redshift are allowed. The burst duration $t_{burst}$ spans several values (0.1, 0.3, 0.6, 1.0, 2.0 and 3.0 Gyr) as well as metallicities ($Z/Z_{\odot} =$ 0.2, 0.4, 1). For each value of $t_{burst}$, dust is included adopting C00 or Small Magellanic Cloud (Prevot et al. 1984) attenuation curves, limited within the following physically motivated values:

(i) $0 < \text{age} \leq t_{burst}$: $0 < E(B-V) \leq 1$
(ii) $\text{age} > t_{burst}$: $0 < E(B-V) \leq 0.2$

(this choice mimics the expected drop of dust content in a quenched galaxy after the end of the star-forming activity). The full library consists of ~3.13 millions models, and the quasi-logarithmic step in age results in a larger number of star-forming models (~78 per cent indeed have age $< t_{burst}$).

Another important ingredient in computing the SED of high-$z$ galaxies is the proper inclusion of emission lines, that can contribute significantly to the observed $K$-band and IRAC fluxes (e.g. Nayyeri et al. 2014; Pacifici et al. 2015). As first presented in Castellano et al. (2014), the contribution from nebular emission has been inserted in *zphot* following Schaerer & de Barros (2009). Briefly, nebular emission is directly linked to the amount of hydrogen-ionizing photons in the stellar SED (Schaerer & Vacca 1998) assuming an escape fraction $f_{esc} = 0.0$. The ionizing radiation is converted in nebular continuum emission considering free-free, free-bound, and H two-photon continuum emission, assuming an electron temperature $T_e = 10\,000$ K, an electron density $N_e = 100\ \mathrm{cm}^{-3}$, and a 10 per cent helium numerical abundance relative to hydrogen. Hydrogen lines from the Lyman to the Brackett series are included considering case B recombination, while the relative line intensities of He and metals as a function of metallicity are taken from Anders, Fritze-von Alvensleben & de Grijs (2003).

However, the computation from first principles of this contribution is not easy, and it has not been tested on large spectroscopic samples. For this reason we choose to adopt two different paths: we build models both without emission lines, as done in most of the published analysis so far, as well as including emission lines, as described above. We will analyse our sample separately with both libraries.

The crucial output parameters of the fit are the SFR, which must be equal to zero in passive candidates, and (equivalently) the galaxy age, that must be compared with the duration of the SF activity: for ages shorter than $t_{burst}$, the galaxy is star-forming – these models can be described reasonably well both as starburst galaxies with a relatively small amount of dust (i.e. the usual Lyman Break Galaxies) and more reddened galaxies – while for ages definitely larger than $t_{burst}$ these models describe galaxies that are passively evolving, with a negligible amount of star-formation activity.

### 4.2 The selection criteria

We performed our search for passive galaxies in the GOODS-South field starting from the $H$-detected catalogue, and using the photometric data described in Section 2. First of all, we selected all the sources in G13 having $H160 < 27$, with simultaneous $1\sigma$ detection in Ks (Hawk-I), IRAC 3.6 and IRAC 4.5 μm bands. We also excluded from the selection any source with defects or unclear classification (relying on the CANDELS flagging). Finally, we added the K/IRAC-detected sources to the list. On this sample, we have performed the SED-fitting process described above.

The selection is done using the information contained in the probability $p(\chi^2)$ of any fitted model. The probability $p(\chi^2)$ is simply computed as the probability that the observed $\chi^2$ (computed on all bands) is due to normally distributed errors (the number of free parameters used in the calculation is actually $N - 1$, with N the available number of bands for each object, as 1 degree of freedom is used to normalize the spectrum). Similarly to what has been done in several previous works (e.g. Papovich, Dickinson & Ferguson 2001; Fontana et al. 2009; Santini et al. 2015), the procedure to estimate the $\chi^2$ is iterative. The $\chi^2$ of each object is first evaluated on its photometry, and then the uncertainties on the observed bands are all increased by a constant factor, in order to have the $\chi^2$ of the best-fitting solution equal to 1. This boost of the photometric uncertainties (that does not change the choice of the best-fitting solution) is used to take into account the limitations of the template models, that may lead to relatively large $\chi^2$ (the average $\chi^2$ is indeed ~3) despite an overall good fit. We note that this approach is particularly conservative, as it widens significantly the allowed parameter space, and hence the possibility that a given object is classified as both passive and star-forming. Uncertainties on all the other relevant physical quantities in the fit are computed in the same way.

Our proposed method uses the probability $p(\chi^2)$ by requiring that the following two conditions are fulfilled:

(i) no star-forming solutions with a probability higher than a fixed threshold $p_{SF}$ exist;
(ii) the best-fitting solution is characterized by an age larger than the duration of the burst $t_{burst}$, and must have a probability $p \geq 30$ per cent.

The first of these two criteria enforces the reliability and credibility of the candidates by requiring that no plausible star-forming solution alternative to the best-fit one exists; in practice, this is obtained by looking at the probability $p(\chi^2)$ of every model inside our multiparameter grid (that includes dusty-star forming models as well as passive ones). We explicitly note that our criterion is based on the absolute value of the probability $p(\chi^2)$, not on the density of the resulting models in the parameter space, as the latter would be indeed heavily altered by the (arbitrary) sampling of the models along the (many) free parameters.

To assess the value of $p_{SF}$, we used a set of dedicated simulations, proceeding as follows. We created a mock catalogue using the TH library, consisting of ~2500 star-forming models having $H$ magnitudes of 23, 24 and 25. Each of these models was then replicated 10 times adding observational noise, consistently with the scatter of the distribution observed in each CANDELS pass-band; the full catalogue therefore consisted of 25 000 mock objects. Then, we used the TH library to fit these models. Around 1200 of them turned out to have a passive best-fit, showing that the effect of noise and models degeneracy can turn a star-forming observed source into a passive fit, with some 5 per cent of chances. Our goal was therefore to make sure that the chosen criteria are stringent enough to avoid that any of these sources is confirmed as passive after the probabilistic selection. Unsurprisingly, these objects also had a non-zero probability of being fitted with a star-forming solution, although with a worst $\chi^2$ than the passive best-fitting one; we found that the lowest probability of a star-forming solution is 12 per cent. Considering that the simulation is an idealized case and in real photometric catalogues the uncertainties due to blending or varying depth must be taken into account, we decided to apply a more conservative threshold of $p_{\rm SF} = 5$ per cent.

As we show in the following, the effects of this first condition depend dramatically on the range of redshifts allowed in the error analysis. On the other hand, the second condition is significantly affected by the inclusion of the emission line in the spectral library. We list below the different samples resulting from the application of these alternatives.

### 4.2.1 The selected reference sample

The first fit has been performed keeping the redshift fixed at the CANDELS value (i.e. spectroscopic redshifts when available, photometric redshifts otherwise, the latter obtained as a median of nine independent photo-$z$'s determinations; see Dahlen et al. 2013). For all our objects, this corresponds to the photometric redshift, as they are too faint to be observed spectroscopically.

We therefore apply our SED-fitting technique to fit all the objects at $z_{\rm CANDELS} > 3$, utilizing the TH models *without emission lines* and applying the selection criteria described above.

This way, we single out 30 red and dead candidates. This approach is analogous to previous works (e.g. Fontana et al. 2009): we use models with no emission lines and perform the scan of star-forming alternative solutions only at the best-fitting photometric redshifts. For these reasons, in the following we will consider this set of objects our *reference sample*. These objects span a redshift range between 3.0 and 4.7, and have IRAC magnitudes $23 < m_{4.5} < 26$ (corresponding to stellar masses between $10^9$ and $2 \times 10^{11}$ M$_\odot$ in our fit). Five of them have $z_{\rm CANDELS} > 4$ (IDs 3912, 5592, 6407, 9209, 23626); these all have best-fitting masses larger than $10^{10}$ M$_\odot$. The 30 selected objects are $H$-detected (while none of the K/IRAC-detected additional sources passed our selection criteria). A full description of their physical best-fitting parameters is shown in Appendix A, along with their images in the CANDELS data set (Appendix B) and full SED and resulting best-fitting spectrum (Appendix C).

It is important to remark that the condition that the probability of star-forming solutions is less than $p_{\rm SF} = 5$ per cent has a dramatic effect of the selection of candidates. Indeed, the number of objects that have a formal best-fitting passive solution is much larger – namely 482 candidates (4 per cent of the whole G13 catalogue, and 94 per cent of all $z > 3$ galaxies). Most of these candidates are, of course, faint sources with detections at very few levels in the $K$ and IRAC bands whose fit is degenerate, i.e. that can be fitted nearly equally well by star-forming or passive solutions. Indeed, almost all of the objects in the final reference sample have observed $K$, IRAC 3.6 and 4.5 magnitudes $< 25$, with S/N, respectively, larger than 20, 10 and 6. Clearly, a robust analysis is possible only for galaxies well above the detection limit. This first example highlights the importance of the S/N in the credibility of the identification, on which we shall expand below.

Figure 2. Probability ($p(\chi^2)$, upper panels) and $E(B - V)$ (lower panels) as a function of [age $- t_{\rm burst}$] of all the possible solutions in the SED-fitting process, for three red and dead candidates in the reference sample (IDs 22085, 18180 and 7526, chosen as examples of three levels of robustness in the selection; see also Fig.; and the plot for the full TH sample is in Appendix D). The colours of the dots in the probability panels refer to the belonging of the source to the selection with (blue) or without (red) the inclusion of nebular lines. The dots (i.e. the models) are shaded as a function of their density. All the solutions have age $> t_{\rm burst}$, as required to be classified as passive in this approach. Galaxies excluded from the selection, on the other hand, have been fitted by at least one model with age $\leq t_{\rm burst}$, i.e. still star-forming, with a probability $p > 5$ per cent (not shown). [A colour version of this figure is available in the online version.]

In Fig. 2 we show the outcome of this procedure for three objects belonging to the reference sample (with additional information, to be explained in the next section); the whole sample is shown in Appendix D. For each object, we plot the probabilities of all the SED-fitting solutions (shaded as a function of their density), and the corresponding UV extinctions, as a function of the time passed from the end of the SF burst; the candidates have solutions with high probability and low extinction well after the quenching of the activity. The extinction tends to anti-correlate with time, because of the way our models are built, but also because a red object can be fitted with a young dusty model or with an old model without dust, so the two possibilities are somewhat degenerate and only the goodness of the fit (namely the $\chi^2$) can disentangle them.

### 4.2.2 Including the emission lines

We then repeated the analysis, but this time using the TH spectral models *including* emission lines.

In this case, we identify only 10 objects satisfying the selection criteria. As in the previous case, the requirement on the (low) probability of the star-forming solution is very effective in removing potential candidates at low S/N (we identify a total of 194 candidates with passive best-fitting solutions).

We remind here that the lines are computed self-consistently from the intensity of the ionizing flux in the spectrum, such that the resulting SED of a quiescent galaxy is by default identical to that obtained without emission lines. As a consequence, all the objects selected as passive in this 'emission lines sample' are also part of the reference sample by construction.

On the other hand, of the 20 candidates of the reference sample that are not included in the emission lines sample, 12 have a

Figure 3. Redshift versus mass distribution of the red and dead selections. Cyan points refer to objects having $z < 5.5$ and a passive best-fitting solution (both in the fit including emission lines and in the one without them), but excluded from the reference sample because of the existence of different, non-passive solutions with probability larger than 5 per cent; blue dots: reference sample (30 candidates surviving the probabilistic selection; the void squares mark the 10 sources selected also using the library including nebular lines emission); red stars: the two candidates surviving the $z$-free fitting. See the text for more details. [A colour version of this figure is available in the online version.]

star-forming best-fitting solution with emission lines (i.e. best-fit ages $< \tau_{\rm burst}$) with significant SFRs (typically 30–50 $M_\odot$/yr). The physical origin of this difference can be understood looking at the SEDs shown in Appendix C. The intense emission lines significantly affect the shape of the spectrum (as sampled by the broad-band filters) beyond 4000 Å, implying a weaker break and yielding a shallower slope in the rest-frame infrared region.

The remaining eight objects still have a best-fitting passive solution, but also an increased probability of having a star-forming solution, and hence do not pass our probabilistic selection criterion $p < 5$ per cent (see the table in Appendix A).

Looking at Fig. D1, one can see how in the emission lines sample (blue dots) four sources are likely to be passive since more than 100 Myr (IDs 2782, 18180, 22085, 23626), while the other six might have quenched their SF activity very recently. In the reference sample (red dots), most of the sources have solutions suggesting very recent quenching, while only four are more likely to be passive since more than 100 Myr (IDs 3973, 4503, 7526, 7688). This is interesting particularly when compared to the results of a standard selection using decaying SFH histories (see Section 5).

Fig. 3 shows the stellar masses and redshifts of the selected candidates. The emission lines sample sources (empty squares) are among the most massive objects in the reference selection (blue dots). This may be expected because the ambiguity between the passive and star-forming solution is increased by the somewhat lower S/N of the faintest among the 30 objects in the reference sample.

In principle, spectral templates including emission lines are expected to be a more accurate representation of the real spectra, and the intensity of such lines is expected to increase at high redshift, so that the 10 objects that are classified as passive even including the emission lines should be regarded as more reliable. However, the recipes adopted here to compute the emission lines from the SED have not been extensively tested or verified, especially in high redshift galaxies. In addition, most previous works adopted spectral models without emission lines, so that a proper comparison can be more appropriately performed considering the whole reference sample. Therefore, we keep it as our fiducial selection.

### 4.2.3 Free redshift selection

As already pointed out, the analysis described above assumes that the redshift is fixed at the CANDELS photometric estimate. However, for galaxies that have a very steep spectrum and are undetected in many of the optical images, the possibility of degeneracies among the spectral templates due to low S/N and poor sampling, and/or by the adoption of incorrect templates, may lead to substantial uncertainties in the photo-$z$ that need to be taken into account. To this aim, we repeat again the SED-fitting procedure on the reference sample, but leaving the redshift free to vary around the best-fitting CANDELS value in the whole redshift range where the probability $p(z)$ of having an acceptable fit is above 1 per cent.

We note that since the best-fitting photometric redshift has not been computed with the TH library, it is in principle possible that the best-fitting photometric redshift obtained using the TH library is different from the official CANDELS one. Reassuringly, we find that most of the candidates still have best-fit solutions with zero star formation activity, at redshifts similar to the CANDELS one.

However, most galaxies also have star-forming solutions at different (typically lower) redshifts, with $p > 5$ per cent. Only two galaxies, IDs 10578 and 22085, are left as reliable passive candidates, with no probable star-forming solutions at any redshift.

Of course, this does not mean that no other candidate is reliable as a ‘real’ passive object. Indeed, the consistency between the best-fitting solutions leaving $z$ free to vary and the one obtained at $z_{\rm CANDELS}$ is reassuring; furthermore, we will show in the next section that most of the objects in the reference sample have no detectable FIR emission, ensuring that most of them can be considered as robust red and dead candidates. Nevertheless, using the present-day state-of-the-art facilities and methods, it is still not possible to rule out the possibility that some low-redshift, dust-reddened star-forming objects are erroneously identified as high-redshift passive galaxies with 100 per cent certainty. The best we can do is try and reduce the risk of contamination using all the available information, e.g. checking the FIR fluxes, while waiting for even deeper data to come (see Section 6).

As a summary of the $z$-free selection and a final summary of the whole procedure, Fig. 4 shows the fitted SEDs of the same three sources already discussed in Fig. 2, which passed three different levels of our selection criteria: top to bottom, ID22085, which survived the $z$-free selection and is one of the two strongest red and dead candidates; ID18180, which passed the emission line selection but has a star-forming solution at a redshift different from the CANDELS one; and ID7526, a ‘standard’ object in the reference sample. In each panel, we plot the best-fitting model at $z = z_{\rm CANDELS}$ (which is always passive) as a red line, along with the best star-forming model at any redshift (blue line). The corresponding probability distributions can be inferred from the inner boxes.

### 4.3 Fir fluxes

To further reduce the risk of including dust-obscured star-forming solutions in the reference selection, we perform a sanity check on the *Herschel* images and catalogues described in Magnelli et al. (2013). The FIR images are shallower than the optical and NIR ones, but they can nevertheless provide a hint on the real nature of these objects; and indeed, detections in *Herschel* bands occur in

Figure 4. Fitted SEDs of the three candidates reported in Fig. in the reference sample, and compared probabilities of all the solutions (inner panel), in the free-$z$ fit. In each panel, the red line is the best passive solution at the CANDELS photometric redshift, and the blue line is the best star-forming solution (at a different redshift); the dots in the inner panel refer to the corresponding probabilities. Top: ID22085, a strong candidate surpassing all the selection criteria: the best star-forming solution (obtained at $z \sim 3.4$) has probability $p < 5$ per cent, so this object can safely be considered passive even letting its redshift freely vary in the fit. Middle: ID18180, despite having mostly passive solutions with very high probabilities, it also has a few star-forming solutions with $p > 5$ per cent (at $z \sim 3.1$), so it is formally excluded from the most stringent selection. Bottom: ID7526 (which is part of the reference sample, but fails the emission line fit selection) has many high-probability star-forming solutions at various redshifts. [A colour version of this figure is available in the online version.]

many cases of passive candidates detected with other methods (see Section 5).

We first perform a spatial cross-correlation between the $H$-band coordinates of the passive candidates and the 24 µm MIPS catalogue. We find that two among them, IDs 3973 and 10578, have very close counterparts (below 1 arcsec), while none of the remaining 28 have one within a radius of 3.0 arcsec (the FWHM of MIPS is 5.7 arcsec, but the catalogue has been obtained using IRAC 3.6 µm priors with FWHM $\sim$ 1.6 arcsec, so this minimum distance is enough to exclude the detection of 24 µm flux). We note that ID10578 is indeed one of the 'strongest' candidates in our reference sample, since it has survived the whole selection process, including the free-$z$ SED-fitting – meaning that no star-forming solution exists at any redshift with probability above 5 per cent. Emission is detected at the position of the two sources also at longer wavelengths (100, 160 and 250 µm) on the *Herschel* PEP-GOODS (Lutz et al. 2011) and HerMES (Smith et al. 2012) blind catalogues; however, possible associations become more common, given the increasing width of the PSFs: at 100 µm four sources have matches below the FWHM of $\sim$6.7 arcsec, at 160 µm 11 sources have matches below the FWHM of $\sim$11.0 arcsec, and at 250 µm 16 objects have a match below the FWHM of $\sim$18.1 arcsec. A visual inspection on the Herschel maps always hints at different possible objects as the origin of the detected fluxes, as many other $H$-detected galaxies lie close to the considered *Herschel* source, so that it is almost impossible to discern the actual origin of the FIR emission.

To further strengthen the analysis, we have also checked a new ASTRODEEP MIPS/*Herschel* catalogue by Wang et al. (2016), which is deeper than previous catalogues particularly in the SPIRE bands, and uses the G13 $H$-band detections as priors. Using this catalogue, it is therefore possible to directly link each source to its measured FIR flux. The two candidates identified above as having clear MIPS/*Herschel* counterparts are also recognized as FIR emitters in this new catalogue, while none of the other red and dead candidates is associated with a detectable *Herschel* source.

Finally, we checked a stack of the 28 non-associated sources thumbnails from the *Herschel* maps, finding no trace of detectable flux in any of the considered bands.

Summarizing, it is fair to conclude that there is no emission at 24 µm evidently linked to 28 out of 30 sources in the reference sample. Two objects instead clearly have FIR counterparts. In principle, this might be due to their wrong identification as passive in the SED-fitting process. However, as discussed above, the uncertainty in the classification dramatically worsens for objects with low S/N, while both the two galaxies are very bright (ID 3973 has $\mathrm{S/N}_H = 17.3$ and $\mathrm{S/N}_K = 49.9$, and ID 10578 has $\mathrm{S/N}_H = 166.8$ and $\mathrm{S/N}_K = 528.9$). A possible different explanation for their strong FIR emission might be the presence of a dust-obscured active galactic nucleus (AGN) hosted in a recently passivized galaxy. In this case, while the stellar content would yield a passive spectrum in the optical and NIR wavelengths, galactic dust absorbing and re-emitting part of the X radiation from the nuclei could cause the observed *Herschel* fluxes. To test this hypothesis, we check the *Chandra* catalogue by Cappelluti et al. (2016), which directly links X-ray emitters to the $H$-detected sources in G13. As it turns out, both the two sources are identified as X-ray emitters in the catalogue. Also, in our analysis they are fitted with a relatively high amount of extinction [$E(B-V) = 0.2$ for ID3973 and 0.3 for ID10578]. This leads to the interesting speculation that these two galaxies indeed seem to have recently become passive, but still retain an active radiating nucleus, and large amounts of dust which cause the observed FIR strong emission. For these reasons, we decide to keep the two sources in the reference

Figure 5. Number density of red and dead candidates with $\log[M/M\ ] > 10.6$ in the redshift bin $0.65 < \log(1 + z) < 0.72$, from this work (blue star: reference sample; magenta star: 'emission lines' selection), compared to the results by S14 (red squares). Our mass estimates are corrected to match the analysis by S14, who assumed a Chabrier IMF rather than a Salpeter IMF. See the text for more details. [A colour version of this figure is available in the online version.]

sample, although we are aware that red colours in the NIR/MIR wavelength range can be also typical of AGNs hosted in young, active galaxies (see e.g. Giallongo et al. 2015), while our SED libraries are solely based on stellar tracks.

### 4.4 Properties of the red and dead candidates

Four galaxies in the reference sample have been observed spectroscopically: IDs 4503 (Mobasher, priv. comm.), 9209 (Cassata et al. 2015), 10578 (Vanzella et al. 2008), 19505 (VANDELS, but the observations and analysis are not completed yet). In all the cases $z_{\rm spec}$ is close to $z_{\rm CANDELS}$, except for 10578 ($z_{\rm spec} = 3.89$, $z_{\rm CANDELS} = 3.06$). However, all of these spectra have poor-quality flags, so that they cannot be taken as strong constraints to our aims; the only exception might be ID19505, which shows a broad line at 5640 Å that can be interpreted as a strong Lyman- emission. This would imply $z_{\rm spec} = 3.6386$; fitting the observed photometric data at this redshift yields an SED which is very similar to the one at $z_{\rm CANDELS} = 3.33$, but with a worse $^2$, which would exclude the object from the selection.

Considering the area of the GOODS-South deep field ( 173 arcmin$^2$), the 30 passive candidates would imply a number density of 0.173 passive objects per arcmin$^{-2}$ at $z > 3$ and above the detection criteria. The corresponding total comoving number density in the redshift interval $3 \le z < 5$ is of $2.0 \times 10^{-5}$ Mpc$^{-3}$. Fig. 5 shows a comparison between the number density of passive high redshift objects inferred from these study and the one found by S14: applying their same mass selection criterion $M > 10^{10.6}$ M ,[3] and considering their redshift bin $0.65 \le \log(1 + z) < 0.72$, we find a number density of $1.0 \times 10^{-5}$ if we consider the whole reference sample, and of $6.0 \times 10^{-6}$ if we only include the emission lines selection. These densities are slightly lower than the $1.78 \times 10^{-5}$ value found by S14 – which is unsurprising given their more relaxed selection criteria – and are broadly consistent with the value found by Muzzin et al. (2013).

Figure 6. UVJ diagram for $z_{\rm CANDELS} > 3$ sources, computed adopting the standard -models to derive the rest-frame magnitudes. The passive selection region is defined by $(U - V) > 0.88 \times (V - J) + 0.59$, $(U - V) > 1.2$ and $(V - J) < 1.4$ (Whitaker et al. ). Yellow points are the whole sample of $z > 3$, Ks+3.6+4.5μm H-detected galaxies from G13. Cyan small dots refer to the objects having a passive best-fitting model, both with and without the inclusion of the emission lines in the TH library. Blue large dots are the 30 galaxies in the reference sample, with empty squares indicating the 10 sources selected also including nebular emission lines. The red stars refer to the candidates surviving the z-free selection. Finally, empty circles refer to the -model red and dead selection (sSFR < $10^{-11}$ yr$^{-1}$; Section 5). Not all the galaxies in the selections are visible because some models have very similar rest-frame properties and colours, so that the symbols overlap. [A colour version of this figure is available in the online version.]

## 5 COMPARISON WITH OTHER SELECTION CRITERIA

In this section we compare our results with those that can be obtained using other selection criteria (namely the rest-frame UVJ diagram and the observed VJL and iHM diagrams), and with those obtained in similar recent studies.

### 5.1 The *UVJ* selection

It is interesting to check which sources would be identified as passive using a more standard approach. To this aim, we started anew from the G13 catalogue, and perform the SED-fitting on the photometric data set, again keeping the official CANDELS redshifts, but now using a typical library of -models, without the inclusion of nebular lines. On this sample we tested both the standard UVJ criterion and a selection based on the specific SFRs.

Fig. 6 is a UVJ diagram in which, for the sake of clarity, we only plot the $z_{\rm CANDELS} > 3$ sources. In this plot we use the rest-frame colours obtained from the -model fitting. We display the position in the UVJ plane of the objects in our reference sample (blue dots; the 10 objects also selected with the library including nebular emission are highlighted with empty squares). Here we use the rest-frame colours of the best-fitting models; we checked that using colours computed interpolating the observed fluxes (shifted at the redshift of the source), e.g. using EAZY, yields qualitatively similar results, although with a larger scatter in the distribution. Reassuringly, it is clear that most of the objects that are selected as passive with the UVJ approach are also selected with our technique. However, some contamination is present, as a few objects fall inside this region but are not selected in our reference sample: these objects are discarded

---

[3] We apply a scaling factor of 0.24 dex (e.g. Santini et al. ) to take into account the fact that we adopt a Salpeter IMF rather than a Chabrier IMF as in S14.

in our case due to the existence of possible star-forming solutions with $p > 5$ per cent. In addition, a non-negligible number of our candidates in the reference sample fall outside (below) of the passive region, in the region where recently quenched sources are expected to lie (as discussed in Section 3). This confirms that the adoption of simple -models and colour criteria may fall short in singling out a complete sample of red and dead objects, and we therefore conclude that the choice of a more sounded SFH analytic shape like the top-hat we adopted in this study can have significant impact on the selection of realistic candidates of passively evolving objects at high redshift.

In the same Fig. 6, we also code the objects according to their estimated sSFR in the fit. We selected as red and dead candidates the objects having specific rates $\mathrm{sSFR} < 10^{-11}\,\mathrm{yr}^{-1}$: with this criterion, and again requiring $z_{\mathrm{CANDELS}} > 3$ and Ks+3.6+4.5 1 detection, we single out only 10 objects, marked as open circles in the figure. We notice that only 5 out of 10 are present in the TH selection: they are IDs 2782, 7526, 8785, 17749 and 18180. Their best-fitting values are similar to those obtained with the TH libraries. Snapshots showing the other five sources included in the selection and not in the reference TH selection are shown in Fig. E1; we note that ID 34275 is only clearly visible in the H-band image and might be a spurious detection from a close-by star, while IDs 2032, 5501, 22515 and 34636 have not been included in the TH selection despite having best fits as passive objects, because star-forming solutions with $p > 5$ per cent are present.

Interestingly, none of the five $z > 4$ red and dead candidates in the reference selection is identified as passive with the -models criteria. Two of them, IDs 3912 and 23626, are fitted as sources of 1.3 Gyr and 500 Myr, respectively, missing the selection because of estimated sSFR slightly higher than the chosen threshold ($6.3 \times 10^{-11}$ and $4.2 \times 10^{-11}\,\mathrm{yr}^{-1}$). The other three objects (IDs 5592, 6407, 9209) are fitted as young (age 800 Myr) star-forming sources with $\mathrm{sSFR} > 10^{-10}\,\mathrm{yr}^{-1}$. The $^{2}$ of the fits with the -models and the TH models are similar. Again, if our modelling is correct, all these are good examples of the kind of objects discussed in Section 3: young galaxies in the early Universe which have quenched their short SF activity abruptly, just before the time they are observed, and are identified as still (slightly) star-forming in a standard fit because of the limitation of the chosen fitting model.

Fig. 7 (top panel) displays the shifts in the UVJ diagram positions for the objects belonging to the reference sample, when fitted with different libraries of models. The shifts are typically small, of the order of 0.1–0.3 mag (generally consistent with the uncertainties in the relevant observed colours). Noticeably, they tend to affect the $V - J$ colour more than the $U - V$ colour. This is basically due to the fact that the fit is much more robustly constrained in the region of the observed visible and NIR (covered by the ACS and WFC3 bands), which straddle the rest-frame $U - V$ break at $z$ 3, than in the reddest part of the spectrum, since the two 5.6–8.0 μm IRAC bands have the poorest S/N. This allows larger variations in the $V - J$ colour, as shown by the two examples reported in the bottom panels of the same figure. We also note a systematic effect between the two libraries, as most of the candidates with a red $[U - V]_{\mathrm{rest}}$ have bluer $[V - J]_{\mathrm{rest}}$ using the TH than using the library, while galaxies with bluer $[U - V]_{\mathrm{rest}}$ are shifted towards redder $[V - J]_{\mathrm{rest}}$ colours – implying a shallower mid-IR profile in all cases, as it can be seen in the two SEDs examples. To definitively solve this ambiguity, deeper data longward of 3 μm are necessary; this anticipates the need for *JWST* observations, which will be the target of Section 6.

Figure 7. In the top panel we show the shifts on the UVJ diagram of the objects in the reference sample, when fitted with different libraries of models. Blue dots: exponentially declining ( ) library; red squares: TH library. The shifts are small ( 0.3 mag) and typically more pronounced in the $V - J$ colour. The bottom panels show two examples explaining the described trend: the fitted SEDs substantially coincide in the optical – NIR, but differ in the IRAC region. See the text for more details. [A colour version of this figure is available in the online version.]

## 5.2 Diagnostic planes with observed colours

Fig. 8 shows the result of the selections on diagnostic VIL and iHM observed colour–colour planes, which are the equivalent of the BzK diagram (Daddi et al. 2004) for selection of quiescent galaxies at $z$ 3 and $z$ 4. In each diagram, the upper right region (delimited by the diagonal solid line and the horizontal dashed line) is expected to be populated by passive sources. The grey dots are individual objects from the whole G13 catalogue, while red dots are galaxies having $z_{\mathrm{CANDELS}}$ in the interval of interest for the corresponding diagram. Larger filled dots are the reference sample sources, again colour-coded depending on their photo-$z$ (see the caption of the figure). While some of the selected objects lie in the passive region of the diagram, many others are found having slightly bluer observed colours. Therefore, a straightforward colour selection would exclude them from the sample (see Grazian et al. 2007, for similar discussions on the BzK selection).

## 5.3 Comparison with previous samples

Another interesting comparison can be made with the results from previous published studies. Rodighiero et al. (2007) used the Giavalisco et al. (2004) multiwavelength imaging data to extract photometric data, performed a magnitude selection requiring no detection in HST bands, $K > 23.5$, and IRAC 3.6 μm $< 23.26$, and identified 20 objects as massive galaxies with high probability of being high-redshift, passive sources (with 14 of them also having

Figure 8. Diagnostic colour–colour diagrams. In both panels, grey dots are the whole G13 catalogue, and red dots are the sources having $z_{\rm CANDELS}$ in the interval of interest for the corresponding diagram: $2.5 < z < 3.5$ for the VJL plot (top panel), $3.5 < z < 4.5$ for the iHM plot (bottom panel). Black and blue dots are the reference sample red and dead candidates, respectively, having redshift within the interval of interest and outside it (arrows are upper limits). Empty squares and circles refer to the selection (Section 5), again, respectively, having redshift within the interval of interest and outside it. [A colour version of this figure is available in the online version.]

a lower redshift, dust-obscured star forming solution). We can now check the nature of those objects using our new deeper photometry. Using the H-detected catalogue, we can identify 18 out of 20 sources via spatial cross-correlation. As it turns out, none of these objects has a strong passive solution in our new analysis; the conclusion can be strengthened analysing the SEDs of these objects, even obtained with the library (they generally show very weak 4000 Å breaks, blue band detections and rising FIR flux), and by the cross-correlation with the 24 μm catalogue by Magnelli et al. (2013), with 12 out of 18 objects having an association with a 24 μm prior within 0.6 arcsec. Clearly the classification by Rodighiero et al. (2007) was heavily affected by the lower quality of the imaging data available at that time.

We then check the correspondence between our selection and two of the most recent similar works, S14 and N14. S14 use a UVJ criterion to single out six quiescent candidates in the GOODS-South field, which we cross-correlate with the G13 catalogue. Among these, three (CANDELS IDs 4503, 17749, 18180) belong to our reference sample as well, while the other three (IDs 5479, 6294 and 19883) have a star-forming best fit. Indeed, they are assigned rather high sSFR in the S14 fit too ($27.5 \times 10^{-11}$, $18.6 \times 10^{-11}$ and $4.47 \times 10^{-11}\,{\rm yr}^{-1}$, respectively); they are also flagged as probable AGNs in the Cappelluti et al. (2016) catalogue, and the first two are identified as AGNs by Xue et al. (2011) as well; they all have confirmed spectroscopic redshift consistent with the $z_{\rm CANDELS}$ we use (Szokoly et al. 2004).

N14 identify 16 evolved (post-starburst) galaxies using an $H - K$ colour selection to probe the 4000 Å break – a selection that in principle includes both star-forming and passive galaxies. Five objects in their selection also belong to our reference sample (IDs 2782, 7526, 12178, 17749, 18180). Of the other 11 objects in the N14 selection, 2 (IDs 9177 and 16671) have $z_{\rm CANDELS} < 3$, one (ID 6189) is a low-redshift ($z_{\rm CANDELS} = 0.6$) dust-obscured star-forming galaxy in the CANDELS catalogues while it is fitted as a passive $z = 4.0$ object by N14, and eight (IDs 4356, 4624, 9286, 10479, 12360, 13327, 18694 and 19195) have star-forming best fits in our analysis; five of them are also identified as AGNs in the catalogue by Cappelluti et al. (2016) (with three also included in the Xue et al. 2011 catalogue).

It is interesting to note that none of the previous cited works includes our best candidates, IDs 10578 and 22085, in their selections. S14 only include sources at $z > 3.4$, while ID10578 has $z_{\rm CANDELS} = 3.06$ and ID22085 has $z_{\rm CANDELS} = 3.36$. On the other hand, both galaxies fail N14 colour selection criteria ($Y - J$ versus [$H - Ks$]). In the case of ID22085, J105 band photometry is not available in the CANDELS GOODS-South data set (this actually shows one more point of strength of the SED fitting approach, in that the lacking of one band data does not compromise the whole study of one potentially interesting object); in ID10578, the object falls immediately outside the selection area of their colour–colour diagram.

## 6 LOOKING FORWARD: THE JWST PERSPECTIVE

As our study shows, there are still many sources of uncertainty that conspire to make the search for passive objects at $z > 3$ problematic and the selection uncertain: depending on the tightness of the selection criteria, one may end up with very different samples (e.g. in our case we can go from 30 to 2 objects). In particular, the spectral range centred on the 4000 Å break is crucial, both to determine with good accuracy the photometric redshift but especially to distinguish between the star-forming and passive objects at $z > 3$, inferring the spectral slope both below and above the 4000 Å break demands a good coverage of the whole wavelength range from J to the redder *Spitzer* bands, ideally up to 8 μm.

The *James Webb Space Telescope* appears to be perfectly suited to fill these gaps. The NIRCam and MIRI instruments[4] will include a large set of filters in the near- to mid-infrared wavelength range, allowing for a detailed photometric reconstruction of the mentioned important spectral features and, hopefully, for a much easier disentanglement between degenerate solutions from SED-fitting.

It is interesting to try a rough evaluation of the potential of the *JWST* capabilites in this context. To this aim, we have created a sample of synthetic spectra using our TH library. The full sample consists of 1686 simulated objects, of which 828 correspond to star-forming models (having age $\le t_{\rm burst}$), 230 have quenched the SF activity since less than 100 Myr, and 628 are red and dead (age $> t_{\rm burst} + 100$ Myr). Each of these spectra has been placed at redshifts from 3 to 7 (with the additional constraint that the age of the galaxy is not larger than the age of the Universe at that redshift) at steps of 0.1 in redshift. We then created observational catalogues corresponding to such models, reproducing both the filter sequence and depths of the CANDELS catalogue used in this work, as well as an idealized catalogue reproducing a possible survey executed with *JWST*. To this purpose we have replaced all the CANDELS filters redward of Y (included) with a combination of 12 *JWST*

---

[4] See the webpage for full information.

Figure 9. Comparison of the *UVJ* diagrams from mock observed catalogues, where the rest-frame magnitudes are obtained via SED-fitting using CANDELS (left panels) and *JWST* (right panels) filter sets. The mock catalogues have been created starting from the TH library of spectra, simulating 1686 objects including passive and star-forming galaxies, computing the observed fluxes in all the relevant bands rescaled to three reference magnitudes (each row in the figure corresponds to one of them – from top to bottom, $m_{4.5\,\mu\mathrm{m}} = 23$, 24 and 25), and including observational noise. In each panel, models having ongoing SF activity in the input library are plotted as blue stars, recently quenched objects as green squares, and passively evolving galaxies as red dots. The dashed lines define a 'green valley' used to quantify the contamination between the different samples. It is clear that the *JWST* pass-bands set removes almost completely the contamination in the fitted colours between the three different populations, which is severe in the CANDELS case. See the text for more details. [A colour version of this figure is available in the online version.]

bands (F090W, F115W, F150W, F200W, F277W, F356W, F444W, F560W, F770W, F1000W, F1130W and F1280W), as described in the MIRI and NIRCam documentation webpages. The resulting catalogue mimicks a survey executed (redward of F090) with *JWST* on the GOODS-S field, building upon the existent ACS data. In particular, we created three catalogues by normalizing the magnitudes to three reference values, $m_{4.5\,\mu\mathrm{m}} = 23$, 24 and 25, covering the magnitude range of our candidates. Noise has been added to these catalogues accordingly to the observed S/N versus magnitude relation in the CANDELS filters (see Castellano et al. 2012); in the *JWST*-simulated bands, we have assumed the depth expected in the case of an extragalactic survey for high redshift galaxies described in Finkelstein et al. (2015). For the three reddest *JWST* filters that were included there, we have computed the expected signal-to-noise ratio assuming a total exposure time per filter comparable to each of the other *JWST* filters.

These simulations are clearly simplified, since (a) they use the same library to compute the 'true' galaxy colours and to derive their photomeric redshifts and SED properties from the SED-fitting, and (b) because we ignore, on the one hand, the additional gain to the overall photometry that will be possible using the improved resolution of *JWST* compared to *Spitzer*, and on the other hand any possible complication due to the blending of sources and other systematics. Regardless of these limitations, these tests can give us a preview of the improvements that *JWST* will make possible.

We have repeated on these simulated catalogues the same analysis that we did on real data. We first fitted catalogues with our SED-fitting code, and then computed the rest-frame properties at the photometric redshift. For simplicity, we show here the results obtained in the *UVJ* plane, for the CANDELS-like and the *JWST*-like catalogues separately. They are shown in Fig. 9, for all objects having $3 < z_{\mathrm{phot}} < 7$. In each panel, models having ongoing SF activity in the input library are plotted as blue stars, recently quenched objects as green squares, and passively evolving galaxies as red dots. The results on the CANDELS simulated data show that there is a strong contamination in the fit, as many passive and star-forming galaxies end up in the same regions of the *UVJ* diagram. For example, one can define a 'green valley' as the region of the diagram for which $V - J > 0.5$ and $0.88 \times [V - J] + 0.44 < U - V < 0.88 \times [V - J] + 0.69$ (see the dashed lines in Fig. 9): considering the three data sets with reference magnitudes $m_{4.5\,\mu\mathrm{m}} = 23$, 24 and 25, the CANDELS simulation, respectively, yields 3.6, 7.2 and 10.0 per cent star-forming galaxies erroneously falling within or above the green valley; conversely, the passive models falling within or below the green valley in the three cases are 3.0, 16.7 and 31.4 per cent.

This contamination increases (as expected) when input galaxies are fainter. This simulation confirms that the identification of passive galaxies in the CANDELS data set is potentially prone to misidentification due to the still inadequate depth of the photometry.

Conversely, the situation is much more defined using the *JWST* filters: the three populations are robustly fitted and separated, with almost no contamination even down to the faintest magnitudes (the observed 'arched' distributions on the diagram derive from the input true colours, which the fitted ones closely resemble). This is an exciting demonstration of the future capabilities with the new instrument.

It is interesting to note that some red objects again fall outside the passive region of the diagram, as discussed in the previous sections: this shows again how the *UVJ* colour selection can be prone to the risk of missing objects that have quenched their SF activity in recent times, even using a much more accurate photometric data set.

## 7 SUMMARY AND CONCLUSIONS

In this paper we have presented the methods and results of a study aimed at searching passive galaxies in the early Universe. The summary of the work is the following.

(i) We search for high-redshift, red and dead (i.e. passively evolving) galaxies in the GOODS-South field, using an updated version of the Guo et al. (2013) photometric catalogue that includes CANDELS HST fluxes, HUGS Ks data, and new IRAC images and improved photometric measurements (Section 2). We pre-select *H*-detected objects having *K*s, IRAC 3.6 and 4.5 μm 1 detection, and $z_{\mathrm{CANDELS}} > 3$. We also add a new sample of 178 *K*/IRAC-detected sources from Boutsia et al. (in preparation) and Wang et al. (2016).

(ii) We then analyse this selection using dedicated top-hat libraries for SED-fitting. We assume that a single star formation event took place and abruptly stopped in the past, followed by passive evolution ever since, and we fit the observed fluxes with models having different values for the duration of the burst, the UV extinction and the metallicity. The selection criterion is based on two stringent requirements: the selected objects must have at least one passive model solution (i.e. SFR = 0 and age larger than the burst duration) with $p(\,^2) > 30$ per cent, and do not have any star-forming solution with a probability $p(\,^2) > 5$ per cent.

(iii) We first use a library without nebular lines emission and only consider the CANDELS redshifts. This way we select 30 candidates, all of which are *H*-detected (see Figs B1 and C1).

(iv) Including nebular lines in the top-hat library used for the SED-fitting procedure, only 10 of these candidates survive the probabilistic selection process: in many cases, the lines weaken the fitted continuum redward of the 4000 Å break, yielding a star-forming best-fit; in other cases, the probabilistic approach causes the exclusion of galaxies with alternative solutions.

(v) If we repeat the analysis letting the redshift free to vary around the best-fitting value, only two galaxies (IDs 10758 and 22085) retain their passive status as the only robust solution. All the other objects show alternative star-forming solutions (at different redshifts) with a probability $p(\,^2) > 5$ per cent.

(vi) Since it is not possible to completely rule out strongly obscured star-forming solutions for any of the selected sources (see Fig. D1), as a basic sanity check we perform a cross-correlation of the reference sample with the 24 μm catalogue by Magnelli et al. (2013), on *Herschel* PEP-GOODS (Lutz et al. 2011) and HerMES (Smith et al. 2012) blind catalogues, and on Wang et al. (2016) new catalogue based on *H*-detected priors. Two objects in our selection are associated with strong FIR emitters. Interestingly, they are also identified as optical counterparts of X-ray emitters (Xue et al. 2011; Cappelluti et al. 2016); we therefore speculate that they might be recently quenched galaxies, hosting a dust-obscured AGN. No other object in the reference sample has a clear association with an FIR source.

(vii) By means of a direct selection on the full G13 catalogue using a standard exponential-models fit with BC03, we then identify, for comparison, 10 sources as $z > 3$ passive candidates (we require sSFR $< 10^{-11}$ yr$^{-1}$). Five objects are in common between this selection and the reference sample (IDs 2782, 7526, 8785, 17749, 18180).

A clear outcome of our analysis is that the selection of passive galaxies, at least in the considered range of redshifts, is still prone to significant uncertainties, due to the limitations in the assumptions used in the SED fitting models and the relatively modest S/N of the objects. Nevertheless, considering the weakest among our selection criteria, we can at least derive an upper limit for the number density of these objects, finding 0.173 arcmin$^{-2}$ (or 2.0 × $10^{-5}$ Mpc$^{-3}$ for $3 < z < 5$).

The limitations in the SED modelling hampers our chances to derive robust physical information on the selected sample. Ages are poorly constrained, and thus so are the SF rates necessary to assemble such objects. We can try some educated guess on the minimum sSFR of the selected sources (assuming isolated evolution, i.e. no mergers) by taking their estimated stellar masses, and dividing them by the age of the Universe at the time the SF activity ceased (minus 300 Myr, to crudely exclude the dark ages), in the TH best-fitting models (we consider the fit without nebular lines, for simplicity). This yields a typical lower threshold for the sSFR of 7 × $10^{-10}$ yr$^{-1}$, which is fairly consistent with the observed values of main-sequence star-forming galaxies, in the same redshift and mass regimes (e.g. Salmon et al. 2015; Schreiber et al. 2017). This is the sSFR estimated at the end of the activity, i.e. when the mass has been completely assembled; we note that, since in our scheme the rate of star formation of the models is constant before the quenching, if we had observed the galaxies during the star formation phase they would have been classified as starbursts, because having lower stellar mass they would be above the Main Sequence M − M relation.

By means of a dedicated simulation, we have shown how *JWST* will yield a major improvement in this perspective, allowing for a much more effective detachment of high-*z* passive objects from dust-obscured low-*z* ones, thanks to an effective coverage of crucial regions of the observed spectra – namely, the 4000 Å break and the 20 μm rest-frame regions.

A thorough testing against theoretical expectations for the number density and properties of these kind of objects, at the considered redshifts, is compelling and recommended.

## ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 312725. We thank the anonymous referee for the useful comments and suggestions, which greatly helped to improve the paper.

## REFERENCES

Anders P., Fritze-von Alvensleben U., de Grijs R., 2003, Ap&SS, 284, 937
Ashby M. L. N. et al., 2015, ApJS, 218, 33
Brammer G. B., van Dokkum P. G., Coppi P., 2008, ApJ, 686, 1503
Brammer G. B. et al., 2009, ApJ, 706, L173
Bruzual G., Charlot S., 2003, MNRAS, 344, 1000
Calzetti D., Armus L., Bohlin R. C., Kinney A. L., Koornneef J., Storchi-Bergmann T., 2000, ApJ, 533, 682
Cappelluti N. et al., 2016, ApJ, 823, 95
Cassata P. et al., 2015, A&A, 573, A24
Castellano M. et al., 2012, A&A, 540, A39
Castellano M. et al., 2014, A&A, 566, A19
Castellano M. et al., 2016, A&A, 590, A31
Ciesla L. et al., 2016, A&A, 585, 43A
Cimatti A. et al., 2004, Nature, 430, 184
Daddi E., Cimatti A., Pozzetti L., Hoekstra H., Röttgering H. J. A., Renzini A., Zamorani G., Mannucci F., 2000a, A&A, 361, 535
Daddi E., Cimatti A., Renzini A., 2000b, A&A, 362, L45
Daddi E., Cimatti A., Renzini A., Fontana A., Mignoli M., Pozzetti L., Tozzi P., Zamorani G., 2004, ApJ, 617, 746
Daddi E. et al., 2005, ApJ, 626, 680
Dahlen T. et al., 2013, ApJ, 775, 93
Dickinson M., Papovich C., Ferguson H. C., Budavári T., 2003, ApJ, 587, 25
Feldmann R., Quataert E., Hopkins P. F., Faucher-Giguère C.-A., Kereš D., 2017, MNRAS, 407, 1050
Finkelstein S. L., Dunlop J., Le Fevre O., Wilkins S., 2015, preprint ( )
Fontana A., D'Odorico S., Poli F., Giallongo E., Arnouts S., Cristiani S., Moorwood A., Saracco P., 2000, AJ, 120, 2206
Fontana A. et al., 2004, A&A, 424, 23
Fontana A. et al., 2006, A&A, 459, 745
Fontana A. et al., 2009, A&A, 501, 15
Fontana A. et al., 2014, A&A, 570, A11
Giallongo E. et al., 2015, A&A, 578, A83
Giavalisco M. et al., 2004, ApJ, 600, L93
Grazian A. et al., 2006, A&A, 449, 951
Grazian A. et al., 2007, A&A, 465, 393
Grazian A. et al., 2015, A&A, 575, A96
Grogin N. A. et al., 2011, ApJS, 197, 35
Guo Y. et al., 2013, ApJS, 207, 24
Ilbert O. et al., 2013, A&A, 556, A55
Koekemoer A. M. et al., 2011, ApJS, 197, 36
Labbé I. et al., 2005, ApJ, 624, L81
Labbé I. et al., 2015, ApJS, 221, 23
Laidler V. G. et al., 2007, PASP, 119, 1325
Lutz D. et al., 2011, A&A, 532, A90
Magnelli B. et al., 2013, A&A, 553, A132
Maiolino R. et al., 2008, A&A, 488, 463
Marchesini D. et al., 2010, ApJ, 725, 1277
Merlin E., Chiosi C., Piovan L., Grassi T., Buonomo U., Barbera F. L., 2012, MNRAS, 427, 1530
Merlin E. et al., 2015, A&A, 582, A15
Merlin E. et al., 2016, preprint ( )
Mobasher B. et al., 2005, ApJ, 635, 832
Muzzin A. et al., 2013, ApJ, 777, 18
Nayyeri H. et al., 2014, ApJ, 794, 68
Pacifici C. et al., 2015, MNRAS, 447, 786
Papovich C., Dickinson M., Ferguson H. C., 2001, ApJ, 559, 620
Patel S. G., Holden B. P., Kelson D. D., Franx M., van der Wel A., Illingworth G. D., 2012, ApJ, 748, L27
Pozzetti L., Mannucci F., 2000, MNRAS, 317, L17
Prevot M. L., Lequeux J., Prevot L., Maurice E., Rocca-Volmerange B., 1984, A&A, 132, 389
Rodighiero G., Cimatti A., Franceschini A., Brusa M., Fritz J., Bolzonella M., 2007, A&A, 470, 21
Rosati P., Stanford S. A., Eisenhardt P. R., Elston R., Spinrad H., Stern D., Dey A., 1999, AJ, 118, 76
Salmon B. et al., 2015, ApJ, 799, 183
Salpeter E. E., 1959, ApJ, 129, 608
Santini P. et al., 2012, A&A, 538, A33
Santini P. et al., 2015, ApJ, 801, 97
Schaerer D., de Barros S., 2009, A&A, 502, 423
Schaerer D., Vacca W. D., 1998, ApJ, 497, 618
Schaye J. et al., 2015, MNRAS, 446, 521
Schreiber C., Pannella M., Leiton R., Elbaz D., Wang T., Okumura K., Labbé I., 2017, A&A, 599, A134
Silk J., Mamon G. A., 2012, Res. Astron. Astrophys., 12, 917
Smith A. J. et al., 2012, MNRAS, 419, 377
Sommariva V. et al., 2014, A&A, 571, A99
Stefanon M., Marchesini D., Rudnick G. H., Brammer G. B., Whitaker K. E., 2013, ApJ, 768, 92
Straatman C. M. S. et al., 2014, ApJ, 783, L14
Szokoly G. P. et al., 2004, ApJS, 155, 271
van Dokkum P. G. et al., 2004, ApJ, 611, 703
Vanzella E. et al., 2008, A&A, 478, 83
Vogelsberger M. et al., 2014, MNRAS, 444, 1518
Wang T. et al., 2016, ApJ, 816, 84
Whitaker K. E. et al., 2011, ApJ, 735, 86
Whitaker K. E. et al., 2013, ApJ, 770, L39
Wiklind T., Dickinson M., Ferguson H. C., Giavalisco M., Mobasher B., Grogin N. A., Panagia N., 2008, ApJ, 676, 781
Williams R. J., Quadri R. F., Franx M., van Dokkum P., Labbé I., 2009, ApJ, 691, 1879
Wuyts S. et al., 2007, ApJ, 655, 51
Xue Y. Q. et al., 2011, ApJS, 195, 10

## APPENDIX A: PHYSICAL PROPERTIES OF THE SELECTED SAMPLE OF RED AND DEAD CANDIDATES

Table A1. Physical properties of the red and dead candidates belonging to the reference sample, as obtained from their best fit with the TH library without emission lines. $\mathrm{ID}_{\mathrm{CANDELS}}$ is the identification number in the G13 catalogue, $z_{\mathrm{CANDELS}}$ is the official CANDELS redshift. $\chi^2_{\mathrm{reduced}}$ is the normalized (reduced) $\chi^2$ of the best fit. The SFR is always zero, by definition. The table lists first the two most robust candidates, which have passed all the selection criteria including the free-$z$ fit; second, the other 8 objects, identified as passive in the emission line fit as well (see Table A2); finally, the remaining 20 objects in the reference sample.

| $\mathrm{ID}_{\mathrm{CANDELS}}$ | $z_{\mathrm{CANDELS}}$ | $\chi^2_{\mathrm{reduced}}$ | Age (Gyr) | Stellar mass ($10^9$ M$_\odot$) |
|---|---|---|---|---|
| 10578 | 3.06 | 1.97 | $0.63^{+0.37}_{-0.31}$ | $239.70^{+108.80}_{-54.40}$ |
| 22085 | 3.36 | 1.26 | $0.61^{+0.97}_{-0.30}$ | $44.25^{+17.08}_{-12.31}$ |
| 2717 | 3.04 | 1.13 | $1.58^{+0.00}_{-0.97}$ | $162.70^{+56.80}_{-69.01}$ |
| 2782 | 3.47 | 0.94 | $0.71^{+0.88}_{-0.40}$ | $69.95^{+16.27}_{-26.15}$ |
| 3912 | 4.08 | 1.32 | $1.25^{+0.05}_{-0.94}$ | $36.27^{+25.08}_{-15.79}$ |
| 8785 | 3.98 | 0.72 | $0.91^{+0.39}_{-0.59}$ | $38.96^{+17.36}_{-15.65}$ |
| 9209 | 4.55 | 1.61 | $0.41^{+0.74}_{-0.21}$ | $91.51^{+27.69}_{-44.79}$ |
| 17749 | 3.73 | 0.63 | $0.90^{+0.40}_{-0.39}$ | $108.80^{+30.20}_{-51.19}$ |
| 18180 | 3.61 | 1.36 | $0.91^{+0.39}_{-0.50}$ | $90.11^{+22.29}_{-37.97}$ |
| 23626 | 4.64 | 1.05 | $0.41^{+0.69}_{-0.11}$ | $75.91^{+28.89}_{-25.90}$ |
| 2608 | 3.58 | 1.36 | $0.63^{+0.42}_{-0.43}$ | $4.51^{+1.23}_{-1.83}$ |
| 3897 | 3.14 | 1.12 | $0.36^{+0.69}_{-0.16}$ | $11.86^{+10.14}_{-1.82}$ |
| 3973 | 3.67 | 1.84 | $0.91^{+0.39}_{-0.30}$ | $186.10^{+16.40}_{-85.20}$ |
| 4503 | 3.52 | 3.74 | $1.10^{+0.20}_{-0.80}$ | $142.70^{+38.20}_{-59.61}$ |
| 4587 | 3.58 | 2.55 | $0.41^{+0.85}_{-0.21}$ | $5.48^{+4.34}_{-1.72}$ |
| 5592 | 4.45 | 1.05 | $0.36^{+0.79}_{-0.16}$ | $30.16^{+17.90}_{-16.22}$ |
| 6407 | 4.74 | 1.31 | $0.36^{+0.69}_{-0.16}$ | $15.98^{+11.26}_{-3.71}$ |
| 7526 | 3.42 | 0.60 | $0.90^{+0.68}_{-0.58}$ | $36.24^{+17.89}_{-17.45}$ |
| 7688 | 3.35 | 0.69 | $0.61^{+0.97}_{-0.31}$ | $22.76^{+12.09}_{-11.71}$ |
| 8242 | 3.18 | 1.17 | $1.00^{+0.58}_{-0.69}$ | $6.55^{+1.97}_{-2.25}$ |
| 9091 | 3.30 | 2.22 | $0.36^{+0.90}_{-0.16}$ | $2.81^{+2.69}_{-0.81}$ |
| 10759 | 3.07 | 1.38 | $0.63^{+0.95}_{-0.62}$ | $0.91^{+1.17}_{-0.64}$ |
| 12178 | 3.28 | 1.02 | $1.10^{+0.20}_{-0.79}$ | $41.20^{+16.64}_{-10.46}$ |
| 15457 | 3.41 | 1.98 | $0.36^{+0.69}_{-0.16}$ | $4.39^{+2.90}_{-0.63}$ |
| 16506 | 3.34 | 3.68 | $0.36^{+0.69}_{-0.16}$ | $5.06^{+3.62}_{-0.67}$ |
| 19301 | 3.60 | 2.85 | $1.10^{+0.20}_{-0.90}$ | $11.58^{+7.36}_{-5.39}$ |
| 19446 | 3.25 | 2.89 | $1.00^{+0.58}_{-0.80}$ | $20.07^{+3.37}_{-10.73}$ |
| 19505 | 3.33 | 1.20 | $0.63^{+0.57}_{-0.43}$ | $46.63^{+6.19}_{-15.00}$ |
| 22610 | 3.22 | 0.74 | $0.63^{+0.63}_{-0.43}$ | $9.49^{+4.40}_{-3.09}$ |
| 26802 | 3.45 | 1.75 | $0.63^{+0.95}_{-0.43}$ | $4.67^{+2.45}_{-1.92}$ |

Table A2. Physical properties of the 10 red and dead candidates passing the probabilistic selection including nebular lines emission in the fit. $\mathrm{ID}_{\mathrm{CANDELS}}$ is the identification number in the G13 catalogue, $z_{\mathrm{CANDELS}}$ is the official CANDELS redshift. $\chi^2_{\mathrm{reduced}}$ is the normalized (reduced) $\chi^2$ of the best fit. The SFR is always zero, by definition. The table lists first the two most robust candidates, which have passed all the selection criteria including the free-$z$ fit; then, the other eight objects identified as passive in the emission line fit.

| $\mathrm{ID}_{\mathrm{CANDELS}}$ | $z_{\mathrm{CANDELS}}$ | $\chi^2_{\mathrm{reduced}}$ | Age (Gyr) | Stellar mass ($10^9$ M$_\odot$) |
|---|---|---|---|---|
| 10578 | 3.06 | 1.97 | $0.63^{+0.37}_{-0.47}$ | $239.60^{+108.70}_{-83.80}$ |
| 22085 | 3.36 | 1.26 | $0.61^{+0.97}_{-0.59}$ | $44.23^{+17.04}_{-33.61}$ |
| 2717 | 3.04 | 1.13 | $1.58^{+0.00}_{-0.97}$ | $162.50^{+56.70}_{-62.89}$ |
| 2782 | 3.47 | 0.94 | $0.71^{+0.88}_{-0.40}$ | $69.90^{+16.26}_{-26.12}$ |
| 3912 | 4.08 | 1.32 | $1.25^{+0.05}_{-0.94}$ | $36.26^{+25.07}_{-15.78}$ |
| 8785 | 3.98 | 0.72 | $0.91^{+0.39}_{-0.59}$ | $38.95^{+17.35}_{-15.65}$ |
| 9209 | 4.55 | 1.61 | $0.41^{+0.74}_{-0.40}$ | $91.49^{+27.61}_{-77.82}$ |
| 17749 | 3.73 | 0.63 | $0.90^{+0.40}_{-0.39}$ | $108.80^{+30.10}_{-51.29}$ |
| 18180 | 3.61 | 1.36 | $0.91^{+0.39}_{-0.50}$ | $90.04^{+22.26}_{-38.04}$ |
| 23626 | 4.64 | 1.05 | $0.41^{+0.69}_{-0.11}$ | $75.88^{+28.92}_{-25.89}$ |

## APPENDIX B: SNAPSHOTS OF THE TH CANDIDATES

Figure B1. Snapshots of the 30 passive candidates selected in the reference sample, obtained with the TH library. Left to right: ACS B435 + V606 + I814 stack, WFC3 J125, WFC3 H160, Hawk-I Ks, IRAC 3.6 + 4.5 μm stack, IRAC 5.8 + 8.0 μm stack. [A colour version of this figure is available in the online version.]

Figure B1 – continued

Figure B1 – continued

## APPENDIX C: SEDS OF THE TH REFERENCE SAMPLE CANDIDATES

Figure C1. SED-fitting for the objects in the reference sample. Shown is the best fit using the TH libraries with $z = z_{\rm CANDELS}$, with (red line) and without (black line) the inclusion of nebular emission; in many cases the two fits almost coincide, so the two lines are superposed. The physical parameters of the best-fitting models are reported on the bottom of each plot, with colours (blue or black) corresponding to the considered fit. [A colour version of this figure is available in the online version.]

Figure C1 – continued

Figure C1 – continued

Figure C1 – continued

Figure C1 – continued

## APPENDIX D: PROBABILITY AND EXTINCTION OF ALL THE MODEL SOLUTIONS OF THE TH CANDIDATES

Figure D1. Probability and dust extinction as a function of [age − $t_{burst}$] for all the possible solutions in the SED-fitting process, for all the candidates in the TH selection. For each candidate, indicated by its ID, two panels are shown. In the upper one, dots represent the probability $p(\chi^2)$ of each model solution; the colours of the dots refer to the belonging of the source to the selection with (blue) or without (red) the inclusion of nebular lines; the dots themselves are shaded as a function of their density. The lower one shows the corresponding values of the $E(B - V)$. All the solutions have age > $t_{burst}$, as required to be classified as passive in this approach. Galaxies excluded from the selection, on the other hand, have been fitted by at least one model with age < $t_{burst}$, i.e. still star-forming, with a probability $p > 5$ per cent (not shown). [A colour version of this figure is available in the online version.]

## APPENDIX E: SNAPSHOTS OF THE -MODELS CANDIDATES

Figure E1. Snapshots of the five passive candidates selected with the -models library which are not present in the reference sample. Left to right: ACS B435 + V606 + I814 stack, WFC3 J125, WFC3 H160, Hawk-I $K_s$, IRAC 3.6 + 4.5 μm stack, IRAC 5.8 + 8.0 μm stack. [A colour version of this figure is available in the online version.]

This paper has been typeset from a TEX/LATEX file prepared by the author.