The emergence of passive galaxies in the early Universe

Article (Accepted Version)

Santini, P, Castellano, M, Merlin, E, Fontana, A, Fortuni, F, Kodra, D, Magnelli, B, Menci, N, Calabrò, A, Lovell, C C, Pentericci, L, Testa, V and Wilkins, S M (2021) The emergence of passive galaxies in the early Universe. Astronomy and Astrophysics, 652. A30 1-20. ISSN 0004-6361

This version is available from Sussex Research Online: http://sro.sussex.ac.uk/id/eprint/111955/

This document is made available in accordance with publisher policies and may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher's version. Please see the URL above for details on accessing the published version.

Copyright and reuse:
Sussex Research Online is a digital repository of the research output of the University.

Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable, the material made available in SRO has been checked for eligibility before being made available.

Copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.
The emergence of passive galaxies in the early Universe

P. Santini¹, M. Castellano¹, E. Merlin¹, A. Fontana¹, F. Fortuni¹, D. Kodra², B. Magnelli³, N. Menci¹, A. Calabrò¹, C. C. Lovell⁴, L. Pentericci¹, V. Testa¹, and S. M. Wilkins⁵

1 INAF - Osservatorio Astronomico di Roma, via di Frascati 33, 00078 Monte Porzio Catone, Italy
2 Department of Physics and Astronomy and PITT PACC, University of Pittsburgh, Pittsburgh, PA 15260, USA
3 Argelander-Institut für Astronomie, Universität Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany
4 Centre for Astrophysics Research, School of Physics, Astronomy & Mathematics, University of Hertfordshire, Hatfield AL10 9AB
5 Astronomy Centre, Department of Physics and Astronomy, University of Sussex, Brighton, BN1 9QH, UK

Received ....; accepted ....

ABSTRACT

The emergence of passive galaxies in the early Universe results from the delicate interplay among the different physical processes responsible for their rapid assembly and for the abrupt shut-down of their star formation activity. Investigating the individual properties and demographics of early passive galaxies will then improve our understanding of these mechanisms. In this work we present a follow-up analysis of the $z > 3$ passive galaxy candidates selected by Merlin et al. (2019) in the CANDELS fields. We begin by first confirming the accuracy of their passive classification by exploiting their sub-mm emission to demonstrate the lack of ongoing star formation. Using archival ALMA observations we are able to confirm at least 61% of the observed candidates as passive. While the remainder lack sufficiently deep data for confirmation, we are able to validate the entire sample in a statistical sense. We then estimate the Stellar Mass Function (SMF) of all 101 passive candidates in three redshift bins from $z = 5$ to $z = 3$. We adopt a stepwise approach that has the advantage of taking into account photometric errors, mass and selection completeness issues, and the Eddington bias without any a-posteriori correction. We observe a pronounced evolution in the SMF around $z = 4$, indicating that we are witnessing the emergence of the passive population at this epoch. Massive ($M > 10^{11} M_\odot$) passive galaxies, only accounting for a small ($< 10\%$) fraction of galaxies at $z > 4$, become dominant at later epochs. Thanks to a combination of photometric quality, sample selection and methodology, we overall find a higher density of passive galaxies than previous works. The comparison with theoretical predictions, despite a qualitative agreement (at least for some of the models considered), denotes a still incomplete understanding of the physical processes responsible for the formation of these galaxies. Finally, we extrapolate our results to predict the number of early passive galaxies expected in surveys carried out with future facilities.

Key words. Galaxies: evolution - Galaxies: high-redshift - Galaxies: luminosity function, mass function - Methods: data analysis

1. Introduction

It has become evident, in the last 10-15 years, that massive passive galaxies were already in place at earlier and earlier epochs (e.g. Cimatti et al. 2004; Saracco et al. 2005; Labbé et al. 2005; Kriek et al. 2006; Grazian et al. 2007; Fontana et al. 2009; Straatman et al. 2014; Navarri et al. 2014; Schreiber et al. 2018b, 2018c, 2019; Merlin et al. 2018, 2019; Carnall et al. 2020; Shahidi et al. 2020). The very existence of massive galaxies with suppressed star formation at $z > 3$ poses serious challenges to theoretical predictions, that struggle to reproduce intense enough star formation rates (SFR) at even higher redshift to assemble such large stellar masses ($> 10^{10} - 10^{11} M_\odot$), and prevent further gas collapse at least until the epoch of observation (Fontana et al. 2006; Vogelsberger et al. 2014; Feldmann et al. 2016; Merlin et al. 2019; Shahidi et al. 2020). Despite the difficulties associated with their search, substantially due to their faintness in the UV rest frame commonly used to select high-redshift galaxies, as well as with their spectroscopic confirmation, studying and deeply understanding these systems will help us shed light on their rapid formation process and similarly rapid quenching mechanism.

This paper is the fourth in a series. In our first work (Merlin et al. 2018) we presented an accurate and conservative technique to single out passive galaxies at high redshift by means of SED fitting with a probabilistic approach. We selected 30 $z > 3$ candidates in the GOODS-S field. Passive galaxy candidates, while being relatively easy to select from photometric surveys once the technique is established, need to be confirmed by other means. This is usually achieved through spectroscopic observations. However, spectroscopy becomes particularly difficult and time consuming at $z > 3$, where only few candidates have been confirmed so far (Glazebrook et al. 2017; Schreiber et al. 2018b; Tanaka et al. 2019; Valentino et al. 2020; Forrest et al. 2020). In our second work (Santini et al. 2019, S19 hereafter), we used a complementary approach, and looked for evidence of lack of star formation as seen in the sub-mm regime to confirm the passive classification of the high-$z$ candidates selected in GOODS-S. At that time, we could confirm only 5% of the targets on an individual basis adopting conservative assumptions, and validated the sample as a whole in a statistical sense. In our third work (Merlin et al. 2019, M19 hereafter), we extended the search for passive galaxies to the entire CANDELS sample, and selected 102 $z > 3$ candidates over the five fields. In the present work, we first confirm the passive nature of these candidates adopting the method presented in S19 and taking advantage of the richer ALMA archive (that includes observations that were still proprietary at the time of our previous work). We then analyse the emergence and mass growth of...
selected by M19 in the five CANDELS fields. Candidates have
cation of the star formation, that is set to zero thereafter. Despite
a period of constant star formation followed by an abrupt trun-
csumed “top-hat” star formation histories (SFH), character ized by
used Bruzual & Charlot (2003) stellar population models and as-
technique, fully described in Merlin et al. (2018). Briefly, we
z
2.1. The selection of high-z passive candidates
We briefly summarize here the major characteristics of the CAN-
DELs data set and the strategy adopted to select passive galaxies,
and refer the reader to the relevant publications for further
details.

The Cosmic Assembly Near-infrared Deep Extragalactic
Legacy Survey (CANDELS: Koekemoer et al. 2011
Grogin et al. 2011; PIs: S. Faber and H. Ferguson) is the largest
(902 orbits) HST program ever approved, and it has observed
the distant Universe with the WFC3 and ACS cameras. It has
targeted 5 fields, covering a total area of ∼ 1000 sq. arcmin. The
multiwavelength photometric catalogues have been publicly
released and are fully described in the relevant accompanying
papers (Guo et al. 2013 for GOODS-S, Barro et al. 2019 for
GOODS-N, Galametz et al. 2013 for UDS, Stefanon et al.
2017 for EGS and Navarri et al. 2017 for COSMOS). For
GOODS-S we used an improved catalogue including three
more bands (WFC3 F140W, VIMOS B and Hawki-K, from the
HUGS survey, Fontana et al. 2014) and improved photometry
on the Spitzer bands thanks to new mosaics (IRAC CH1 and
CH2, by R. McLure) and new software (all four channels
released and are fully described in the relevant accompanying
catalogues).

We adopted the photometric redshifts from the latest CAN-
DELs estimates (Kodra 2019), to be presented in Kodra et al.
in prep.). These improve upon the original released ones pre-
presented in Dahlen et al. (2013), and are based on a combination
of four independent photo-z probability distribution functions
(unless spectroscopic redshifts are available), using the minimum
Frechet distance combination method.

2.1 The selection of high-z passive candidates
The present work is based on the z > 3 passive galaxy sample
selected by M19 in the five CANDELS fields. Candidates have
been identified by means of an ad-hoc developed SFH fitting
technique, fully described in Merlin et al. (2018). Briefly, we
used Bruzual & Charlot (2003) stellar population models and
assumed “top-hat” star formation histories (SFH), characterized by
a period of constant star formation followed by an abrupt trunc-
ation of the star formation, that is set to zero thereafter. Despite
being over-simplified, these analytic shapes manage to mimic the
rapid timescales available for quenching at high redshift, com-
parable to the age of the Universe (at variance with standard
exponential models, that require at least ∼ 1 Gyr to reach quies-
cence). Moreover, the adoption of “top-hat” SFHs improves over
a standard UVJ selection since the fit is able to identify recently
quenched sources, still showing blue U − V colours.

In addition of being fit in their passive phase (i.e. with zero
SFR), candidates also need to pass conservative selection criteria
based on the probability P(χ^2) of the χ^2 resulting from the fitted
solution. In the end, in order to be classified as passive, galaxies
need to fulfill the following criteria:
- H < 27;
- 1σ detection in K, IR1 and IR2 bands;
- z_{phot} > 3;
- \text{SFR}_{\text{cen}} = 0;
- P(\chi^2_1) > 30\% \text{ and } P(\chi^2_{SFR}) < 5\%.

The last requirement ensures that the best-fit passive solution has
a high probability P(\chi^2_1) and at the same time that no plausible
(i.e. with P(\chi^2_{SFR}) > 5\%) star-forming solutions exist.

We ended up with a sample of 102 galaxies (the so-called
“reference” sample in M19, i.e. that obtained without inclusion
of emission lines in the fit). Candidates are distributed quite
inhomogeneously across the fields: 33 in GOODS-S, 36
in GOODS-N, 16 in UDS, 13 in EGS, 4 in COSMOS. The variance
across the fields cannot be entirely explained by cosmic
variance, but probably reflects the different photometric prop-
ties of the five catalogues. In particular, they differ in the depth
of the K and IRAC bands (see M19). All candidates have red-
shift lower than 5 except one source in GOODS-N (z_{phot} ∼ 6.7,
discussed in M19). In the following, we restrict to the 3 < z < 5
sample, made of 101 galaxies. The final list of passive candidates is
presented in Tables 1A to 1A.3.

Among our passive galaxies, 4 are flagged as X-ray detected
AGNs in GOODS-S (one of which is a confirmed AGN, see

![Fig. 1. Redshift distribution of the 3 ≤ z < 5 passive candidates used in
the present analysis. Different colours show the counts in the various
fields (see legend). The black open histogram shows the total sample.](image)
M19), 3 in GOODS-N and 2 in EGS. Two of the AGN candidates in GOODS-S are also detected by Herschel (see Santini et al. [2019]), likely due to the emission of the host dust heated by the central nucleus. We believe the AGN candidates are therefore obscured, or at least not bright Type 1 AGNs. AGN emission does not significantly affect the estimate of the stellar mass for obscured AGNs, as demonstrated by Santini et al. [2012]. For this reason, we did not exclude AGNs from the sample.

Fig. 1 shows the redshift distribution of our passive candidates, colour-coded according to the field they belong to. The majority of them are below redshift 4, but the distribution shows a non negligible tail to higher redshift (12 galaxies at $4 < z < 5$).

### 2.2. Stellar masses

Stellar masses have been estimated by SED fitting the observed near-UV-to-near-IR photometry, up to $5.5 \mu m$ rest-frame, to libraries built on Bruzual & Charlot (2003) stellar population synthesis models.

For passive galaxies they have been obtained from the fit with “top-hat” SFHs without including emission lines, as discussed in Sect. 2.1. The grid in stellar ages, burst duration, metallicities and dust extinction is detailed in M19 (see their Appendix A).

To test the reliability of the inferred stellar masses we explored the possibility that our candidates host an on-going dusty burst, misinterpreted as an old stellar population in our fit. We therefore built a stellar library by combining an old, unobscured or moderately obscured burst finished by at least 100 Myr with a star formation episode on-going since 50 Myr. We fit our GOODS-S candidates with this 2-component library and found very similar stellar masses, with a median $M_{\text{tophat}}/M_{\text{2comp}}$ of 0.96 and semi interquartile range of 0.12. We also found that in 29 out of 33 candidates the fit prefers solutions with purely old stellar populations, and that in the remaining 4 sources the young stellar population contributes by no more than 20% in mass. This very same result is found by fitting mock galaxies that are purely passive, indicating that in a small fraction of objects (13%) the fit is limited by parameter degeneracy.

For the whole galaxy population we adopted exponentially declining models ($\tau$-models) to parameterize the SFH. The library has been built as done in previous works (e.g. Fontana et al. [2004], Santini et al. [2009], Grazian et al. [2015]); metallicities range from $Z = 0.02Z_\odot$ to $Z = 2.5Z_\odot$; $0 < E(B-V) < 1.1$ with a Calzetti et al. (2000) or Small Magellanic Cloud (Prevot et al. 1984) extinction curve, left as a free parameter; the timescale for the exponentially declining SFH ranges from 0.1 to 15 Gyr; the age (defined as the time elapsed since the onset of star formation) varies within a fine grid and, at a given redshift, is set lower than the age of the Universe at that redshift.

The mass distributions of passive candidates and of the whole population in the redshift intervals used in the present analysis are shown in Fig. 2.

While being very effective in selecting quiescent galaxies at high redshift, the adoption of “top-hat” models does not have a strong impact on stellar masses. This confirms the results of Santini et al. [2015], who found that the stellar masses are stable against the choice of the SFH parameterization and differences in the metallicity/extinction/age parameter grid sampling. However, as we discussed in our previous work, while the stellar mass is on average a relatively stable parameter, it can vary for some peculiar sub-classes of objects for which a different SFH parameterization is necessary, such as passive galaxies at high redshift.

Fig. 3 shows a comparison between stellar masses obtained with $\tau$-models and with “top-hat” models, for the whole population in the redshift range of interest (gray shaded histogram) and for the passive candidates (black open histogram). Despite being slightly skewed towards larger $M_{\tau}/M_{\text{tophat}}$ ratios ($< \log M_{\tau}/M_{\text{tophat}} > = 0.06$ and 0.09 for the passive and global population, respectively), the distributions are peaked at unity, and the mean value is well within the standard deviation of the distribution (0.10 and 0.16, respectively). The latter is also smaller than the average error bar associated with the estimate of the stellar mass ($\sim 0.4$ dex for the entire $M > 10^8M_\odot$, $\sim 0.2$ dex at $M > 10^{10}M_\odot$). We conclude that the two stellar mass estimates are in good agreement for the large majority of sources. A systematics however appears for the passive candidates, whose distribution of $\log M_{\tau}/M_{\text{tophat}}$ shows a secondary peak at $\sim 0.2$ dex. This feature is entirely due to candidates with stellar mass...
below $10^{10.5} M_\odot$, that show a broad (or slightly bimodal) distribution between 0 and 0.2 dex. The objects showing the largest standard deviation of the two distributions.

3. Confirmation of the passive nature of the candidates from their sub-mm emission

One powerful possibility to validate the passive classification of photometrically selected candidates is to measure their FIR and/or sub-mm emission, used to exclude on-going star formation. This method allows us to avoid possible degeneracies between dusty star-forming and old passive solutions in the optical fit. In M19 we cross-matched our sample with Herschel catalogues. For the GOODS fields we took advantage from the new, deep ASTRODEEP catalogues by Wang et al. (in preparation), which combine data from PEP (Lutz et al. 2011) and GOODS-Herschel (Elbaz et al. 2011) surveys and from the HerMES survey (Oliver et al. 2012) for the SPIRE bands. For COSMOS and EGS we used PEP-PACS catalogues and HerMES-SPIRE ones (Roseboom et al. 2010, 2012). For the UDS field we used HerMES catalogues for both cameras. As discussed in our previous work, with the exception of two sources in GOODS-S (GOODS-10578 and GOODSS-3973), which are likely obscured AGNs (see discussion in Merlin et al. 2013, S19, M19 and in Sect. 3.2.1), no clear evidence for FIR emission was found. This test is however limited by poor sensitivity at these redshifts and high level of confusion. For this reason, we attempted to extract more information out of Herschel maps by stacking. We stacked all sources at 100 and 160 $\mu$m, offering the best compromise between depth and angular resolution among all Herschel bands. We did not measure any flux above the noise level in any of the five fields individually nor in the combination of them. We note, however, that the depth of stacked Herschel maps, resulting into a typical limiting SFR of $\sim 100$ (600) $M_\odot$/yr from 100$\mu$m (160$\mu$m), is not sufficient to reject mild levels of SFR in these galaxies. For this reason we opted for ALMA data to confirm the passive solutions of our candidates.

We took advantage of the rich ALMA archive, and extended the very same analysis described in S19 to the entire CANDELS sample of high-$z$ passive candidates. In the following, we summarize the main steps and present the new results. We refer the reader to S19 for further details.

3.1. ALMA archival observations

Out of the five CANDELS fields, only three are accessible by ALMA (GOODS-S, UDS and COSMOS). This reduces the number of candidates over which the validation method can be attempted to 53. A search in the ALMA archive returned observations in Band 6 and 7 for 41 of them. Nine candidates in UDS and three candidates in COSMOS were observed in Band 7, with one of the latter also observed in Band 6. 21 and 19 candidates in GOODS-S have been observed in Band 6 and 7, respectively, with 11 observed in both bands. Band 3 and 4 observations, available for a fraction of the sources, give less stringent constraints and have not been used.

We produced images with $\geq 0.6$ arcsec spatial resolution using “natural” weightings and $uv$-tapers when needed. In this way, we could assume that sources are unresolved (see justification and references in S19), and maximize the sensitivity to detection. We note that given the native angular resolution of the data, the maximum recoverable scale is $>1.5$ arcsec (0.75 arcsec in a couple of cases). Assuming an homogenous surface brightness, this results into a physical scale of $>10$ kpc ($\sim 5$ kpc) at the redshifts of our sources. The typical size of $z > 2$ sources measured by Fujimoto et al. (2017) on ALMA Band 6 and 7 images ($R_c < 3$ kpc, with an average value of $\sim 1$ kpc) makes us confident that the emission of our targets is not filtered-out by the reduction process.

The sub-mm flux was read directly on the map (in units of Jy beam$^{-1}$) as the value of the pixel at the position of the source. The associated uncertainty was taken as the standard deviation of all pixels with similar coverage, after excluding the position of the candidate and potential other sources in the image (see S19). In order to avoid astrometry issues, if the source is detected at more than $3\sigma$, we replaced the value of the flux at the centre with the maximum value within the beam; if, on the other hand, the source is undetected, we used the mean flux within the beam. We finally stacked sources observed more than once in the same Band by averaging the fluxes measured from different programs weighting them with the associated errors (the final sensitivity per beam was inferred as the standard error on the weighted mean).

The achieved median sensitivity is 0.17 mJy in Band 6 and 0.25 mJy in Band 7 (with a semi interquartile range of scatter among the various sources of $\sim 0.07$ in both cases). Only one of the 41 sources is detected at $>3\sigma$ level (GOODSS-3973, $S_{870\mu m} = 0.74 \pm 0.18$ mJy). Six sources are barely above the noise level (at 1-2 $\sigma$ level). We report in Tables 2 and 3 the ALMA flux in the most stringent band. No significant detection is found even after stacking all observations in the same Band (including the only detected source), either over the entire redshift range or in bins of redshift ($3 < z < 4$ and $4 < z < 5$).
3.2. Method

Sub-mm fluxes were converted into estimates of (or in most cases upper limits on) the SFR by fitting them to a number of IR templates. We considered the average SMG SEDs of Michałowski et al. (2010) and Pope et al. (2008), the two average SEDs fitted by Elbaz et al. (2011) for Main Sequence and starburst galaxies, and the full libraries of Charry & Elbaz (2001), Dale & Helou (2002) and Schreiber et al. (2018a). The latter library has the dust temperature $T_d$ as free parameter, whose choice highly affects the inferred SFR. We considered two templates, one with $T_d = 25 K$, as conservatively expected for quiescent galaxies (Gobat et al. 2018; Magdis et al. 2021) and one with light-weighted $T_d = 40 - 50 K$, as predicted by the redshift evolution of the dust temperature parameterized by Schreiber et al. (2018a). We assumed $R_{SB} = \text{SFR}/\text{SFR}_{SB} = 1$. As done in S19, in the following we adopted the template of Michałowski et al. (2010) as reference model. We converted the inferred total infrared luminosity between 3 and 1100 $\mu$m adopting the calibration of Kennicutt & Evans (2012), adjusted to a Salpeter IMF using their conversion factor. The SFR was calculated at the redshift of the candidates and at any given redshift between 0 and 6. For the majority (10 out of 12) of the candidates observed both in Band 6 and 7, we used the former, as the data turned out to be deeper in terms of the resulting SFR. The median limiting SFR is $\sim 43 M_{\odot}/yr$ ($\sim 55 M_{\odot}/yr$ at $z > 4$), with a semi interquartile range of $\sim 15 M_{\odot}/yr$. The inferred SFRs are listed in Tables [A.1] to [A.3]. We note that any possible contribution from evolved stellar populations to the FIR luminosity would decrease the inferred SFR, and therefore would make our results even stronger.

As discussed in S19, the spread in the inferred SFR among different templates is not negligible (it may span even a decade when fitting to the longest wavelength Band 6 data). As a consequence, the exact value of the SFR is subject to this systematics. However, as discussed in S19, the spread in the inferred SFR among different templates is not negligible (it may span even a decade when fitting to the longest wavelength Band 6 data). As a consequence, the exact value of the SFR is subject to this systematics. However, although we discuss the results based on the reference model of Michałowski et al. (2010), we note that our conclusions are solid against the choice of the IR templates.

We used two approaches to validate the passive solutions of the optical fit.

3.2.1. Validation of individual candidates

To make sure that our candidates were not erroneously best fitted by passive templates, we checked whether the alternative star-forming solutions are compatible or not with ALMA results. To this aim, we compared the SFR inferred from ALMA data, or in most cases the 3$\sigma$ limits on the SFR, as a function of redshift to any plausible (i.e. with associated $\chi^2$ probability larger than 5%) star-forming solutions of the optical fit obtained at any redshift. The fit was indeed re-run with redshift set as a free parameter, instead of fixed to the best-fit one (where, by definition, there are no star-forming solutions with probability larger than 5%).

For 61% of the observed candidates (including the only detected source), ALMA constraints predict a SFR that, at any redshift, is below the optical solution (or in most cases no star-forming solutions exist at all). In other words, the very red colours of the candidates cannot be justified by a large amount of dust, but need to be explained by old stellar populations. This implies that the optical star-forming solutions are implausible, therefore supporting the passive best-fit. These sources are robustly and individually confirmed as passive at a 3$\sigma$ confidence level, and the result is unaffected by the choice of the IR template used to calculate the SFR (we note that even more sources would be confirmed adopting more conservative templates). The last column of Tables [A.1] to [A.3] indicates the candidates that have been individually confirmed. For the rest of the sample, ALMA upper limits are above the optical star-forming solutions, making the comparison inconclusive. Deeper sub-mm data would be needed to confirm (or reject) the passive nature of these sources. This comparison is graphically represented in Fig. 3 of S19 for the GOODS-S candidates of Merlin et al. (2018). The improvement in the fraction of validated candidates compared to S19 results is explained by two effects. In part, the adoption of updated redshifts for the search of passive galaxies leads to a more reliable selection. Most importantly, our previous work relies on the exceedingly conservative choice of adopting, for this test, the nebular line fit for all candidates, even for those selected without their inclusion.

Among the candidates that have been individually confirmed as passive are the two GOODS-S candidates GOODSS-10578 and GOODSS-3973 with associated Herschel (and MIPS) emission, the latter also detected by ALMA. Though it may at first be surprising, as fully discussed in Merlin et al. (2018), S19 and M19, these two sources are likely obscured AGNs, both of them being identified as X-ray emitters in the Chandra catalog of Cappelluti et al. (2016), and the former also confirmed as AGN by the MUSE deep data (Inami et al. 2017). Their IR emission is indeed likely associated with hot dust heated by the central AGN rather than cold dust heated by UV stars and tracing on-going star formation. As a matter of fact, according to the IR templates used to estimate the SFR (see Sect. [A.2] and S19), the mid-IR emission of these two sources is at least a factor of 10 (if not 100, depending on the chosen model) lower than expected based on ALMA flux. Similarly, the recent analysis of D’Eugenio et al. (2020) found four secure 24$\mu$m detections out of their 10 $\sim 3$ spectroscopically confirmed passive galaxies, with no FIR counterparts, three of which consistent with being AGN-powered. Based on a mean stack radio detection they derived similar limiting SFR as individually measured by us from ALMA data. Furthermore, Spitler et al. (2014) found six 24$\mu$m detections among their 26 massive quiescent (based on a UVJ selection) 3 $< z <$ 4 candidates, three of which showing signs of AGN. In conclusion, the presence of 24$\mu$m emission in passive candidates is not totally unexpected and likely associated with AGN activity.

3.2.2. Statistical validation of sample

Since the available ALMA data is not deep enough to draw any conclusion for 39% of the observed candidates, we tried to validate the passive nature of the entire sample in a statistical sense. To this aim, we adopted 1$\sigma$ limits in the following.

We first repeated the procedure described above on the stacked flux in Band 6 and 7, which is compared to the collection of star-forming solutions of all sources included in the stacks. We found that the sample is on average consistent with being passive (a group of solutions with low SFR values, below the ALMA limits, is observed in Band 7, but it can be ascribed to a minor fraction of sources, i.e. 10% of the stacked sample). Once again the result is robust against the uncertainty in modelling the IR SED. Indeed, only when adopting two of the models (Pope et al. 2008 and Schreiber et al. 2018a) with high dust temperature) the results are not conclusive, but again due to a minority of sources.

We then adopted an independent approach to verify how the SFR of the candidates compares with that of typical star-forming galaxies. We made use of the stellar mass inferred from the optical fit (a much more robust parameter than the SFR, as discussed
above; see also Santini et al. (2015) and of the sub-mm-based SFRs, and compared the position of the candidates on a SFR-stellar mass diagram with the location of the Main Sequence (MS) of star-forming galaxies. In Fig. 4 we show all candidates observed by ALMA divided into two redshift bins, compared with the observed (i.e. not corrected for the Eddington bias) MS inferred from HST Frontier Field data by Santini et al. (2017). We found that 59% of the candidates are located below the 1σ scatter of the MS (0.3 dex), while 39% and 27% are at least 2σ and 3σ below of the MS, respectively, i.e. in the region where one expects to find sources that have completely exhausted their star formation. The fraction of sources at least 1σ / 2σ / 3σ below the MS is in the range 39-80%/ 24-68%/ 2-41%, depending on the choice of the IR template (46-80%/ 34-68%/ 5-41%, respectively, if the most extreme template is ignored). We highlight on the figure the candidates that have been individually and robustly confirmed (Sect. 3.2.1). The majority of them are located below the MS. However, a fraction of the confirmed sources have less stringent constraints, placing them around the MS. We remind that, with the exception of one source with huge error bars extending down to the passive area of the diagram, the rest of the candidates around the MS only have upper limits on the SFR: the knowledge of their exact position is hampered by the available data, and they may in principle have much lower levels of SFR. The fact that some of them are individually confirmed as passive makes us confident that even the sources with shallow sub-mm constraints preventing their individual confirmation may actually be intrinsically passive.

We finally stacked sources in bins of stellar mass (orange symbols in Fig. 4). Once again, the stacking analysis supports the passive classification of the whole sample. Indeed, the stacked SFR is well below the MS, with the exception of the lowest mass bin in both redshift intervals, where available sub-mm data is not deep enough to reach the lower level of the typical SFR of low-mass galaxies. The only IR template unable to confirm the stacking results with high significance is the high dust temperature template of Schreiber et al. (2018), yielding a high-z/high-M stacked SFR only ≤ 1.3σ below the MS.

We note that, once the sample has been confirmed as passive, either for individual sources or statistically, ALMA fluxes can be fit with the IR passive template of Magdis et al. (2021). This template yields ~5 times lower SFR, and places 95% / 78% / 66% of the candidates 1σ / 2σ / 3σ below the MS (basically all sources with log M/M⊙ > 10.4 are at least 0.9 dex below the MS according to this template).

3.3. Conclusions

We used ALMA archival observations to confirm the passive nature of our candidates. By means of the (lack of) sub-mm emission, we could validate the passive classification for 61% of the candidates observed by ALMA at a 3σ confidence level. At the same time, based on the available data, we could not reject any of the candidates, and found that the sample is on average consistent with being correctly classified as passive. This result is solid against the large systematics associated with the choice of the IR template when computing the SFR from sub-mm emission. Only one model, the one characterized by the highest dust temperature, appears to be unable to statistically confirm the entire sample with high significance, but we note that this is the most extreme template, and the assumed temperature is at the highest envelope of the T_d distribution (Faisst et al. 2020, see also the extrapolation to high-z of the results of Magnelli et al. 2014 or Genzel et al. 2015).

Once again we confirmed the reliability and robustness of the photometric selection technique developed in Merlin et al. (2018) and M19. Assuming our technique to perform equally well on the sources unobserved by ALMA, in the following, we consider the entire sample of 101 3 < z < 5 passive galaxy candidates.

4. Determination of the galaxy Stellar Mass Function (SMF)

To estimate the Stellar Mass Function (SMF) we adopted the stepwise method, a non-parametric approach that has the advantage of not assuming an a-priori shape for the SMF (e.g. Takeuchi et al. 2009; Bouwens et al. 2008; Weigel et al. 2016). Instead, the stepwise estimate assumes that the SMF can be approximated by a binned distribution, where the number density Φ_{true} in each mass bin j is a free parameter.

In particular, we adopted the procedure presented in Castellano et al. (2010) (Sect. 6.2.2). We assumed a fixed, constant, reference density Φ_{ref} over the entire mass range and exploited a simulation to compute the distribution of observed stellar masses originating in each mass bin, as a consequence of percolation of sources across adjacent bins caused by photometric scatter or failure in the selection technique to isolate simulated passive galaxies. In order to take into account field-to-field variations in depth and selection effects, the simulations were run for each field separately, scaled to the relevant observed areas, and eventually summed to obtain the total number densities predicted in each mass bin. The intrinsic densities are expressed as Φ_{true} = w_j · Φ_{ref}, where w_j are the multiplicative factors to the reference density of the simulation. The intrinsic densities, hence the multiplicative factors, and relevant uncertainties, which best reproduce the observed number densities Φ_{obs} of our survey, were determined by inverting the linear system Φ_{obs} = \sum_j (S_{ij} Φ_{true}), where S_{ij} are the elements of the transfer...
function computed from the simulation (i.e. $S_{ij}$ is essentially the number of galaxies in the mass bin $i$ scattered from the bin $j$ and taking into account the sources missed by the selection). The bin size was chosen as a compromise between the need to have reasonable statistics in each bin and the desire to sample the shape of the SMF with good mass resolution.

Simulated masses were obtained by redshifting between $z = 3$ and $z = 5$ a subset of the synthetic spectra of the stellar libraries. The library parameters have been chosen in order to reproduce the observed mass-to-light ratios in the rest-frame $I$ band of the passive candidates and of the entire $3 \leq z < 5$ sample. For the passive sources we only considered passive templates. Each template has then been normalized to stellar masses between 9 and 12 in the logarithmic space. The final simulations are made of 32893 templates for the “top-hat” library and 43044 templates for the $r$-models library. The simulations were designed to reproduce both the average and the scatter of the observed S/N as a function of magnitude to provide the closest match between observed and simulated data, as done in Castellano et al. (2012). Differences in depth and therefore selection effects among the different fields are taken into account by running the simulation independently for each of them. In addition, the two GOODS fields have inhomogeneous coverage in the HST bands. While the difference in depth between the CANDELS wide and deep areas is accounted for by the scatter of the error-magnitude relation, this is not true for the ultradeep GOODS-S area (4.6 arcmin$^2$, Guo et al. 2013). For this reason, we treated the latter as a separate field, with its own simulation. For each field, synthetic fluxes have been obtained by convolving the synthetic templates with the filter response curves and have been perturbed with noise in a way to mimic the field properties in terms of depth. We then fitted these simulated catalogues and selected simulated passive galaxies in the very same way as done on real data. For the total population, we simply selected $H < 27$ galaxies. We verified that the resulting mass-to-light ratio distribution is in good agreement with the input one (this makes us confident that mass-to-light ratios are not substantially modified by observational errors).

Although the simulation covers stellar masses from $10^9$ to $10^{12}M_\odot$, in the following we will consider the SMF on a narrower range of masses. Indeed, the required corrections below $10^{10}M_\odot$ make the SMF very uncertain at these low masses. However, low mass bins need to be included in the procedure to consider the effect of the Malmquist bias, i.e. to account for low mass sources scattered to larger measured masses. The overall corrections applied to the observed counts are within a factor of 3, with the only exception of the lowest mass bin at $z > 3.5$, affected by a higher level of incompleteness, where the required correction is a factor of 5 and 10, respectively, at intermediate and high redshift.

The stepwise method has the advantage of taking into account mass completeness issues, incompleteness in the passive selection, photometric errors (i.e. the percolation of sources across adjacent mass bins), and the Eddington bias. The latter is naturally accounted for without any a-posteriori simulation. As shown by Davidzon et al. (2017), stepwise results show very good agreement with the standard $1/V_{\text{max}}$ method. As an additional test, we verified that the SMF computed with the stepwise approach on the GOODS-S sample, using the very same photometric catalogue, redshifts and sample selections of Grazian et al. (2019), nicely agrees with their $1/V_{\text{max}}$ points.

The cumulative area over which the SMF was calculated is 969.7 arcmin$^2$. Cosmic variance has been added using the QUICKCV code of Moster et al. (2011). It computes relative cosmic variance errors as a function of stellar mass, in bins very similar to the ones used by us, up to $10^{11.5}M_\odot$. For the largest mass bin, we adopted the value for the 11-11.5 logarithmic bin incremented by 50%. We verified that this particular choice does not significantly affect our results. Since cosmic variance not only depends on the total area surveyed but also on the survey geometry, following Driver & Robotham (2010), we reduced these relative errors by $\sqrt{N}$, where $N = 5$ is the number of non-contiguous fields of similar area.

Finally, Schechter functions have been fitted to the stepwise points and uncertainties.

As discussed in Sect. 2.1, we did not exclude AGN candidates from the sample. Anyhow, we verified that the exclusion of the 9 X-ray detected candidates among the passive sample (and similar exclusion from the total sample) does not change our results.

5. The SMF and the Stellar Mass Density of $3 \leq z < 5$ passive galaxies

The resulting SMF for the passive population, computed in three different redshift bins, is shown in Fig. 3 and reported in Table 1. We also show the best-fit Schechter functions and the associated 68% probability confidence regions. Due to the lack of constraints at low masses and larger uncertainties at high redshift, at $z > 3.5$ we fixed the value of slope $\alpha$ to its best fit value in the lowest redshift bin. The best fit Schechter parameters are listed in Table 2.

A strong evolution in the “knee” of the SMF ($M^*$) is observed around $z \sim 4$. For a better visualization of the evolution in the SMF we show in Fig. 6 the three redshift bins simultaneously. Despite the large associated uncertainties, we find a clear evolution in the passive galaxy population from $z = 5$ to $z = 3$. While both the stepwise points and the best-fit Schechter functions are very similar in the two lowest redshift bins, we observe a pronounced evolution beyond $z \sim 4$, indicating that we are witnessing the epoch of passivization of massive galaxies. While the lowest mass passive galaxies seem to be already in place at these redshifts, the largest structures have not had the time to form yet at $z > 4$. We note that this result is independent on the choice of the mass binning.

With the aim of understanding the relative abundance of passive galaxies, we computed the SMF for the entire population. The results are shown in Fig. 7 (gray stepwise points and gray Schechter fits). We also show several SMF for the entire galaxy population taken from the literature (Libert et al. 2013; Duncan et al. 2014; Grazian et al. 2015; Davidzon et al. 2017; McLeod et al. 2021). Different fields, photometric quality, sample selections, methodology and corrections for incompleteness are responsible for the large spread in the SMF observed at such high redshifts. For this reason, for a fair comparison with the passive population, instead of using a reference SMF from the literature we decided to recompose the SMF for all CANDELS $H < 27$ galaxies using the very same method applied to the passive candidates. We note that our estimates tend to be on the upper envelope of the distribution of the various results from the literature. This is a consequence of our choice to include AGN in the sample.

While at $z < 4$ the massive tail of the SMF of passive and all galaxies are rather similar, they diverge below $\sim 10^{10}M_\odot$. The lower panels of Fig. 7 show the ratio between the passive and the global SMF ($\phi_{\text{pass}}/\phi_{\text{tot}}$). As expected, we observe a trend with stellar mass, with passive galaxies being more abundant at
we integrated the SMF from 10∗10 to 10∗10 M⊙ counted for by passive galaxies at different epochs by integrating the joint probability distribution function of the Schechter parameters. Blue open symbols and lines show the SMF for passive galaxies taken from the literature, scaled to a Salpeter IMF, in the same (or very similar) redshift bins [Ichikawa & Matsuoka 2017 as squares, [Davidzon et al. 2017 as dashed line and [McLeod et al. 2021 as dot-dashed line], and at slightly different redshifts [Muzzin et al. 2013 as triangles and [Girelli et al. 2019 as 6-points stars].

**Fig. 5.** SMF for passive galaxies in the five CANDELS fields. Black solid points show the stepwise results, with error bars accounting for Poissonian and cosmic variance uncertainties. Black curves show the Schechter fits and the coloured shaded areas indicate the regions at 68% confidence level considering the joint probability distribution function of the Schechter parameters. Blue open symbols and lines show the SMF for passive galaxies taken from the literature, scaled to a Salpeter IMF, in the same (or very similar) redshift bins [Ichikawa & Matsuoka 2017 as squares, [Davidzon et al. 2017 as dashed line and [McLeod et al. 2021 as dot-dashed line], and at slightly different redshifts [Muzzin et al. 2013 as triangles and [Girelli et al. 2019 as 6-points stars].

| log M/M⊙ | 3 < z < 3.5 | 3.5 < z < 4 | 4 < z < 5 |
|----------|-------------|-------------|-------------|
| 10.35    | 5.25 ± 1.76 | 4.29 ± 2.00 | 3.64 ± 1.74 |
| 10.85    | 4.24 ± 1.77 | 3.82 ± 1.19 | 0.99 ± 0.53 |
| 11.35    | 2.70 ± 0.84 | 1.84 ± 0.71 | 0.17 ± 0.18 |
| 11.85    | < 0.49      | < 0.53      | < 0.36      |

Table 1. Stellar Mass Function of passive galaxies as inferred from a stepwise method. 1σ uncertainties include Poissonian errors and cosmic variance.

high masses relative to the global population. While making a negligible fraction of the total population at ∼10¹⁰ M⊙, z < 4 passive galaxies become dominant at large stellar masses. Although the associated uncertainty is too large to estimate a precise fraction, passive galaxies could make up to ∼30% of the total galaxy population at M ∼ 10¹³ M⊙ and more than 50% at larger masses. We note, however, that while the passive SMF is nicely fitted by a Schechter function at stellar masses between 10¹⁰ and 10¹¹.5 M⊙, its shape is poorly constrained above this value. Due to the paucity of such sources, larger surveys are needed to better constrain the high-mass tail of the passive SMF. Consistently with the pronounced evolution around z ∼ 4, the fraction of massive galaxies earlier than this epoch is very low. Even at the highest masses, passive galaxies constitute no more than a few percent of the total galaxy population at z > 4.

We finally estimated the Stellar Mass Density (SMD) accounted for by passive galaxies at different epochs by integrating the best-fit Schechter functions reproducing their SMF. In order not to be affected by large extrapolations at low stellar masses, we integrated the SMF from 10¹⁰ M⊙ to 10¹³ M⊙. The results and associated 1σ uncertainties are shown in Fig. 8 as green points and shaded area (while the gray shaded region represents the global population).

An increase in the SMD of passive galaxies by a factor of 7 from z ∼ 5 to z ∼ 3 is observed. In the lower panel of Fig. 8 we show the passive fraction in terms of stellar mass density, i.e. the ratio between the passive and the total SMD (ρ°°/ρ°*). 20-25% of the total mass assembled by redshift ∼3 is accounted for by passive galaxies, while this fraction reduces to ∼5% at z > 4.

We verified that our results for the abundance of passive galaxies, in terms of their contribution to both the SMF and the SMD, remain unchanged when AGNs are excluded from the sample. They may instead be affected by the inclusion of HST-dark galaxies, z ≥ 3 red galaxies that are undetected on the H band image ([Huang et al. 2011; Caputi et al. 2012; Wang et al. 2016, 2019; Alcalde Pampliega et al. 2019]), whose abundance relative to the underlying H-detected red massive galaxy population increases with redshift and stellar mass. These objects are not included in our sample because of the H < 27 cut. They are taken into account by our simulation to some extent that is impossibly to quantify exactly, because of the difficulty of mimicking their observed mass-to-light ratio distribution, being them not contained in the CANDELS catalogs. We can estimate an upper limit to their additional contribution to the overall statistics of high-z quiescent galaxies by correcting our passive and global SMF according to the results of [Alcalde Pampliega et al. 2019]. They estimated the contribution of HST-dark galaxies to a mass-selected sample in bins of redshift and stellar mass, and estimated that 30% of them are quiescent or post-starburst galaxies. While the effect of including HST-dark would be negligible at z < 4, at the highest redshifts the passive and global SMFs would increase by ∼0.2-0.3 (−1) dex and ∼0.05 (−0.1) dex, respectively, at intermediate (high) masses. This would however leave our results on the abundance of passive galaxies relative to the global population almost unaffected, due to the already very low fraction of passive galaxies at z > 4. We note,
Fig. 6. Evolution in the SMF of passive galaxies from \(z = 5\) to \(z = 3\). Points, lines and shaded regions are as in Fig. 5.

anyway, that this is a conservative evaluation of the contribution of HST-dark galaxies to the passive fraction, because of the less stringent definition of quiescent/post-starburst galaxy of Alcalde Pampliega et al. (2019) compared to the one adopted by us.

Overall, we can conclude that we, despite the difficulties associated with the study of high-\(z\) passive galaxies, these sources are already in place in the young Universe. They make up a significant fraction (>50%) of massive (\(M \gtrsim 10^{11}-10^{11.5} M_\odot\)) galaxies up to \(z = 4\), and account for \(\sim 20\%\) of the total stellar mass formed by that time. On the contrary, only a few percent passive galaxies are observed earlier than this epoch. We are witnessing the emergence of the quiescent population, i.e. their passivization, in the redshift interval spanned by this work.

### 6. Comparison with the literature

#### 6.1. Comparison with previous observations

At variance with other aspects of galaxy evolution over which a large consensus exists by now, the study of high-\(z\) passive galaxies, and in particular the details such as their abundance, is still matter of debate, and current surveys have not found a final and joint solution yet. Early passive galaxies are rare sources, and several differences among the various analyses may be responsible for the variance among their results. Firstly, the photometric quality is crucial to detect these faint and elusive sources, and different filter combinations and depths affect the selection in a non straightforward way. Secondly, given the paucity of these sources, field-to-field variations may play an important role. Thirdly, different selection techniques may lead to different candidates, as discussed at length in M19. Finally, the methodology adopted to compute the SMF and the correction for observational incompleteness are essential ingredients in the analysis, as discussed in the following.

We compare here our findings with the few previous works that analyse the SMF of passive galaxies at similar redshifts. We plot on Fig. 5 the SMF of Davidzon et al. (2017) and Ichikawa & Matsuoka (2017), using the same redshift bins adopted by us, and the estimate of McLeod et al. (2021), covering a redshift space slightly larger than our first interval but equally centred at \(z \sim 3.25\). As for reference, we also plot the results of Muzzin et al. (2013) and Cirelli et al. (2019), although their SMF are estimated on redshift intervals not coincident with ours, making the comparison tricky. For this reason, we will not discuss their results in the following. As for Ichikawa & Matsuoka (2017) results, we sum their estimate for passive and recently quenched galaxies. For Davidzon et al. (2017) and McLeod et al. (2021) we plot their Schechter fits, which include the correction for the Eddington bias. All these works selected passive galaxies through a colour selection (based on either observed or rest-frame colours). All of them, except for McLeod et al. (2021) results, are based on the shallower COSMOS field.

Our SMF of passive galaxies at \(z \sim 3.25\) nicely agrees with that of McLeod et al. (2021) at intermediate mass, and is marginally 1\(\sigma\) consistent with it at the high mass end. This mismatch may be due to fluctuations in the relatively small area probed by us. Overall, although we find larger densities, given the different parent sample, sample selection and methodology, the consistency is more than satisfactory. The SMF measured by us at \(z \sim 3.25\) and \(z \sim 3.75\) are higher than those of Davidzon et al. (2017) by a factor of \(~4\) to \(~8\) at the peak and by more than a decade at larger masses. At \(z < 4\) the mismatch with Ichikawa & Matsuoka (2017) is a factor of \(~4\) at the peak, while the massive tail is marginally consistent with our results. The agreement with the latter study improves at \(z > 4\), where the two estimates are well consistent within the error bars.

In the lower panels Fig. 7 we compare the fraction of passive sources as a function of stellar mass (\(\phi_{\text{pass}}/\phi_{\text{tot}}\)) with previous works, less prone to the systematics associated with the various SMF. Once again, our results nicely agree with those of McLeod et al. (2021) at \(M < 10^{11} M_\odot\), but diverge at higher masses (though remain consistent within the error bars). They are also consistent within the uncertainties with those of Davidzon et al. (2017), while we observe higher fractions than Muzzin et al. (2013).

Literature results on the SMD of passive galaxies show a very large variance, spanning more than an order of magnitude at the redshifts probed by this work. Our results tend to be on the upper envelope of the ranges spanned by previous works, and are consistent with the analyses of McLeod et al. (2021), Straatman et al. (2014) and Shahidi et al. (2020) (Fig. 8). We note however that the integration limits are not always consistent. For example, McLeod et al. (2021) integrates down to a lower mass limit, but their lower SMD is likely explained by their steeper SMF at both low (mostly) and high stellar masses.

The integrated passive fraction (i.e. the ratio between the SMF of passive vs all galaxies, \(\rho_{\text{pass}}/\rho_{\text{tot}}\), shown in the lower panel of Fig. 8) is consistent with that reported by Muzzin et al. (2013) and McLeod et al. (2021) at \(z \sim 3\)–\(3.5\), Straatman et al. (2014) found a higher ratio of 34\%, still consistent with our estimate, with the difference likely explained by their higher integration limit (indeed, passive galaxies are more abundant at large stellar masses, as shown in Fig. 7). However, their higher value might also reflect their higher number density and could be explained by their shallower selection criterion (see discussion in M19). The constant decline in the quiescent fraction observed from the local Universe to high redshift could flatten at \(z \gtrsim 2\)–\(3\),
Table 2. Best-fit parameters and their 1σ uncertainties in the different redshift intervals derived from fitting the stepwise SF with a Schechter function. At \( z > 3.5 \), the Schechter slope \( \alpha \) has been fixed to the value in the lowest redshift bin. The second column indicates the numbers of galaxies in each redshift bin based on which the SMF is actually computed. The last column reports the corresponding mass density \( \rho \) obtained by integrating the SMF from \( 10^{10} M_{\odot} \) to \( 10^{13} M_{\odot} \).

| Redshift | N    | \( \alpha \)  | \( \log M^*/M_{\odot} \)  | \( \log \phi^*/\text{Mpc}^{-3} \)  | \( \log \rho_{10}/(M_{\odot}\text{Mpc}^{-3}) \) |
|----------|------|--------------|----------------|----------------|----------------|
| 3.0 - 3.5 | 58   | -0.81 ± 0.52 | 11.23 ± 0.38   | -4.44 ± 0.35   | 6.74\( ^{+0.39}_{-0.34} \) |
| 3.5 - 4.0 | 31   | -0.81         | 11.19 ± 0.20   | -4.51 ± 0.14   | 6.62\( ^{+0.28}_{-0.31} \) |
| 4.0 - 5.0 | 12   | -0.81         | 10.55 ± 0.22   | -4.52 ± 0.30   | 5.90\( ^{+0.43}_{-0.41} \) |

Fig. 7. Upper panels: SMF of passive candidates (black circles and curves, coloured shaded regions) vs all \( H < 27 \) galaxies (gray squares and curves, gray shaded regions). Shaded regions indicate the regions at 68% confidence level considering the joint probability distribution function of the Schechter parameters. Dark red curves show SMF from the literature in similar, but not identical, redshift bins (as indicated in the legend), all scaled to the same IMF: Ilbert et al. (2013) (long dashed), Duncan et al. (2014) (dot-long dashed), Grazian et al. (2015) (dotted), Davidzon et al. (2017) (dashed) and McLeod et al. (2021) (dot-dashed). Lower panels: Ratio of the passive and global Schechter functions. The shaded area and solid curve show the mass range where the comparison is meaningful (i.e. not affected by paucity of galaxies nor extrapolated due to the lack of observational data). We also show the passive fractions published by Davidzon et al. (2017) (narrow-spaced shaded area) and Muzzin et al. (2013) (wide-spaced shaded area), and the ratio between the passive and the total SMF of McLeod et al. (2021) (dot-dashed line).
Fig. 8. **Upper panel:** Evolution in the Stellar Mass Density of passive galaxies above $10^{10} M_\odot$ (green symbols and shaded area). As for comparison, we also plot the SMD of all $H_\text{\textless} 27$ galaxies integrated above the same mass limit (gray shaded region). In both cases, the shaded regions represent the 1$\sigma$ uncertainty. Results are compared to a number of literature works, as listed in the legend, both for passive galaxies (blue open symbols) and for the entire population (dark red open symbols and dot-dashed line). Literature estimates and their mass integration limits have been scaled to a Salpeter IMF, when needed. The dashed orange and dotted red lines are the SMD derived by integrating Star Formation Rate Density from Hopkins & Beacom (2006) and Madau & Dickinson (2014), respectively, assuming a constant recycle fraction of 28%. The solid blue line shows the prediction for the SMD in passive galaxies by Renzini (2016). Literature estimates and their mass integration limits have been scaled to a Salpeter IMF, when needed. The dashed orange and dotted red lines are the SMD derived by integrating Star Formation Rate Density from Hopkins & Beacom (2006) and Madau & Dickinson (2014), respectively, assuming a constant recycle fraction of 28%. The solid blue line shows the prediction for the SMD in passive galaxies by Renzini (2016). Lower panel: Ratio between the mass density of passive galaxies and of the overall galaxy population above $10^{10} M_\odot$ (green solid line and solid region). We also report the passive fractions in terms of mass densities measured by Muzzin et al. (2013) (triangles), Straatman et al. (2014) (squares), Ilbert et al. (2013) (7-point stars), McLeod et al. (2021) (pentagons), Mawatari et al. (2020) (5-point star) and predicted by Renzini (2016) (solid line).

At variance with the observations just discussed are the predictions of Renzini (2016). He estimated the SMD in passive and star-forming galaxies by combining the parameterization for the evolution in the Star Formation Rate Density from Madau & Dickinson (2014) with that of the sSFR (=SFR/M) for near MS galaxies of Peng et al. (2010), assuming a unitary slope for the MS. The obtained SMD for the passive population is a factor of 2 to 5 above our measurements. His prediction for the passive fraction, shown in the lower panel of Fig. 8, is also higher than our observational data by a similar factor. Indeed, in his empirical description, passive galaxies start dominating over the star-forming population at $z > 3$. We note, however, that these predictions are somewhat indirect, and rely on the assumptions mentioned above and on the consistency between measurements of SFR and stellar mass, as discussed in the paper. Moreover, the definition of passive galaxies is not entirely consistent with ours, as Renzini (2016) defines as passive all sources with sSFR $\ll$ sSFR$_{\text{MS}}$, including parts of star-forming galaxies such as quenched bulges and stellar halos, so a higher abundance of passive sources is expected. On the other side, his method has the advantage of not being affected by incompleteness in the selection of passive candidates.

Of Davidzon et al. (2017), they are consistent or below the SMF of McLeod et al. (2021), as expected, since they also correct for incompleteness; finally, compared to the results of Ichikawa & Matsuoka (2017), they are consistent at the highest redshift and only 1-2$\sigma$ above at $z < 4$. These findings are expected from the mismatch in the mere number of candidates found by Davidzon et al. (2017) and Ichikawa & Matsuoka (2017), compared to our sample, scaled by the relative areas. Indeed, the passive selection of Davidzon et al. (2017) and Ichikawa & Matsuoka (2017) encompasses $\sim 8 \times$ and $\sim 3.5 \times$, respectively, less candidates than ours ($\sim 1.4 \times$ less at the highest redshifts. Ichikawa & Matsuoka (2017). We also compared the uncorrected SMD of passive galaxies with literature results, and found that it is in line with the bulk of previous estimates. Overall, our higher SMF and SMD derive from a combination of a generally larger number of passive candidates and a more accurate correction for mass incompleteness, Eddington bias and incompleteness in the passive selection.
6.2. Comparison with theoretical predictions

To put our results in a broader context and understand how they fit the current theoretical scenario, we compared them with the predictions of one semi-analytic model (the PANDA model, Menci et al. 2014) and four hydrodynamic simulations (ILLUSTRIS-TNG100 and -TNG300, Pillepich et al. 2018b, Nelson et al. 2019, EAGLE, Schaye et al. 2015 and SIMBA Davé et al. 2019).

6.2.1. The models

The model of Menci et al. (2014) is an improved version of the semi-analytic model of Menci et al. (2006, 2008). It connects, within a cosmological framework, the baryonic processes (gas cooling, star formation, supernova feedback) to the merging histories of the dark matter haloes, computed by means of a Monte Carlo simulation. AGN activity is triggered by galaxy interactions and, in this latest version, by disk instability. The description of AGN feedback has been updated by implementing the 2-D modelling for the expansion of AGN-driven shocks (Menci et al. 2019). This model adopts a Salpeter IMF.

ILLUSTRIS-TNG100 and -TNG300 exploited the moving mesh code AREPO (Springel 2010) and simulated volumes of 100 and 300 co-moving Mpc on each side (110.73 and 302.63 Mpc3) with baryonic mass resolution of 1.4 × 106 and 1.1 × 107 M⊙, respectively. EAGLE is a set of simulations based on an updated version of the N-body Tree-PM smoothed particle hydrodynamics code GADGET-3 (Springel et al. 2005). We used the run EagleRefL0100N1504, that simulated a volume of 1003 Mpc3 with baryonic mass resolution of 1.81 × 106 M⊙. The SIMBA simulations utilize the Gizmo cosmological gravity plus hydrodynamics solver (Hopkins 2015, 2017), in its Meshless Finite Mass (MFM) version. It has a volume of (100/h)3 Mpc3, where h = 0.68, with baryonic mass resolution of 1.82 × 107 M⊙.

All these models include baryonic sub-grid physics to simulate star and black hole formation, stellar and AGN feedback, and metal enrichment. They assume Chabrier IMF, and have been scaled to a Salpeter one by multiplying the stellar masses by 1.74 (Salimbeni et al. 2009).

6.2.2. The selection of model passive galaxies

Accurately simulating the entire observational selection with a forward modelling approach is extremely time consuming and will be addressed in a future work (Fortuni et al. in prep.). We therefore here adopted a standard criterion to select model passive galaxies. One possibility would be to select passive galaxies based on their specific SFR, that is required to be lower than a given threshold. While a fixed cut of 10−11 yr−1 is widely adopted, it may be too conservative if applied to high redshift galaxies, as it does not take into account the evolution of the typical star formation rate. For this reason, we adopted the time-evolving criterion used by Pacifici et al. (2016), Carnall et al. (2019, 2020), as well as applied by Shahidi et al. (2020) on theoretical models, i.e. $\text{sSFR} < 0.2/t_U$, where $t_U$ is the age of the Universe at the galaxy redshift.

The ILLUSTRIS-TNG and EAGLE simulations release multiple estimates of stellar mass and SFRs, based on the physical region within which they are computed. We adopted the very same stellar masses and SFR as in our previous work (M19): for ILLUSTRIS-TNG they are defined within twice the half mass radius, best reproducing the observations (see M19,
Valentino et al. [2020] and Shahidi et al. [2020]: for the EAGLE model we considered the aperture which is closest to $4 \times R_{1/2, 100}$, where $R_{1/2, 100}$ is the half-mass radius computed within 100 kpc. For SIMBA we adopted the stellar masses and SFRs associated with all particles gravitationally bound to the dark matter halo, as these are the only available in the catalog. We note that the aperture choice over which stellar masses and SFRs are computed may have a significant effect on the selection of model passive galaxies, especially at $2 < z < 3$ and $M > 10^{10.5} M_{\odot}$, as shown by Donnari et al. [2020]. In the future, we plan to extend their work to higher redshifts, and analyze the impact of different definitions of quenched galaxies, apertures and averaging timescales for the SFR (Fortuni et al. in prep.).

6.2.3. The predicted SMF

We show the comparison of theoretical predictions for the SMF with observational results in Fig. 9. Error bars associated with the hydrodynamic simulations are based on Poissonian errors. In the semi-analytic model, the uncertainty is caused by the limited number of merger tree realizations, i.e. $\sqrt{N}/N$, where $N = 40$. For the semi-analytic model, we also consider a systematic uncertainty, that we summed in quadrature to the Poissonian one. Indeed, model predictions depend mainly on two quantities: the effective cooling time of gas inside the galactic dark matter potential wells, and the effectiveness of interactions triggering powerful starbursts at high redshifts. In the model, both of the above processes can be slightly tuned to improve the agreement with observations, provided that they remain consistent with the observed color distribution of local galaxies. This degree of freedom reflects into a factor $\sim 2.5$ systematic uncertainty associated with the prediction of the abundance of passive galaxies at high redshift ($z \geq 3$).

The model of Menci et al. [2014] predicts an overabundance of low-mass passive galaxies and underestimates the massive tail of the SMF over the entire redshift range probed by this work. This is a well known problem of galaxy formation models [Weinmann et al. 2012; Torrey et al. 2014; White et al. 2013; Somerville & Davé 2015]: in a CDM scenario, dwarf galaxies form first, hence are characterized by old stellar populations, and feedback effects effectively suppress their star formation. A partial solution to this problem has been implemented by Henriques et al. [2017] through a revised feedback model tuned to fit the observed passive fraction at $0 < z < 3$ (see also the comparison with the SMF for passive galaxies shown by Girelli et al. [2019]).

The overestimate of the low-mass tail is not observed in ILLUSTRIS-TNG, where it has been suppressed by the introduction of a minimum stellar wind velocity (the so-called wind velocity floor) (Pillepich et al. [2018a,b]). The ILLUSTRIS-TNG300 simulation performs in an excellent manner at $3 < z < 3.5$ and $\log (M/M_\odot) \gtrsim 10.7$ in a still satisfactory way at higher redshift and high $(\log (M/M_\odot) \sim 11 - 11.5)$ masses. However, it falls short of passive galaxies at low stellar masses compared to the observations. Donnari et al. [2020] reported a very low fraction of $M < 10^{10.3} M_\odot$ passive galaxies predicted by ILLUSTRIS-TNG300 at $0 < z < 3$. They concluded that the ILLUSTRIS-TNG model captures quite well the effect of AGN feedback in quenching massive galaxies ($10.5 < \log (M/M_\odot) < 11$), but needs some adjustment for the feedback mechanisms which regulate star formation in lower mass galaxies at high redshift (e.g. stellar feedback). The inability of reproducing high-$z$ passive galaxies (with the exception of the highest masses) is to be attributed to the still inefficient feedback. ILLUSTRIS-TNG100 very nicely reproduces the SMF of passive galaxies at $z < 3.5$ and $\log (M/M_\odot) \gtrsim 10.7$, and it underpredicts the number of passive galaxies at lower masses. In the intermediate (high) redshift interval, however, it only predicts the correct abundance of passive sources at intermediate (high) stellar masses. At the high mass end and intermediate redshifts, this could be due to the paucity of such systems, that can be under-represented in small simulated volumes (indeed, likely thanks to the larger volume, ILLUSTRIS-TNG300 is able to reproduce the massive tail of the SMF in the same redshift interval). With the exceptions of the mass and redshift bins where it predicts zero objects, ILLUSTRIS-TNG100 tends to overall predict a higher SMF than ILLUSTRIS-TNG300. This trend is also observed on the total SMF (Pillepich et al. [2018a]), and it is due to the combination of the limited numerical resolution (responsible for the lower number of particles exceeding the fixed density threshold above which stars can form) and volume effects.

An absence of massive passive galaxies as shown by TNG100 at intermediate redshifts is observed in the EAGLE and SIMBA simulations, both characterized by a similarly small volume. SIMBA predictions confirm the trend already outlined in M19, where it turned out to be the model showing the most serious underestimate of the number density of passive galaxies at all redshifts above $1 - 1.5$. While its predictions are similar to those of ILLUSTRIS-TNG300 at $z > 3.5$, it underestimates the SMF also at $z < 3.5$.

The most interesting comparison is however with EAGLE: it very nicely reproduces the faint-end of the SMF, but it predicts no quiescent galaxies at $M \gtrsim 10^{11} M_\odot$. This was somewhat unexpected, as in M19 we showed that EAGLE was the only hydrodynamic model, among those considered, able to reproduce the number density of $M > 5 \times 10^{10} M_{\odot}$ passive galaxies at $z > 3.5$ (an equally lack of massive passive sources is obtained, as expected, when using the more conservative cut sSFR<$10^{-11}$ yr$^{-1}$, as in M19). It implies that the number density alone is not a powerful observable, as it does not encode information on the mass distribution of the sources. This results suggests that EAGLE might reproduce the abundance of high-$z$ passive galaxies thanks to an overprediction of lower mass sources. Our data, however, do not allow to reliably measure the SMF below $10^{10.5} M_\odot$ to test this hypothesis.

The lower panels of Fig. 9 show the passive fraction as a function of stellar mass. Some of the model analyzed match the observations at low masses, others show a good match at high masses, but none of them is able to reproduce the observed passive fraction over the entire mass range. The two ILLUSTRIS-TNG simulations are consistent with the data in the lowest redshift interval, but are below the observations at the low mass end. Similarly, they underpredict the passive fraction at higher redshift, with the exception of ILLUSTRIS-TNG100 that is consistent with the observations at $3.5 < z < 4$ and $\log (M/M_\odot) \sim 10.7$. Conversely, over the entire redshift range probed, the predictions of EAGLE and of the model of Menci et al. [2014] agree with the observations at low masses, but no, or very few, passive galaxies are predicted at high masses. SIMBA predicts a very low fraction of passive galaxies roughly over the entire mass range.

6.2.4. The predicted SMD

Figure 10 shows the comparison between the observed and predicted SMD. For both models and data the SMD has been computed above $10^{10.1} M_\odot$. The semi-analytic model of Menci et al.
epochs overpredicts the observed SMD due to its steep shape at low masses, dominating the integral. Consistently with the comparison of the SMF, the two ILLUSTRIS simulations reproduce the SMD of passive galaxies at \( z \approx 3 \), but underpredict it at higher redshifts. While the passive SMD according to SIMBA is always below the observations, EAGLE is marginally consistent at \( z \approx 3 \) and nicely agrees with the data at \( z > 4 \). Indeed, despite its inability to reproduce the most massive passive galaxies, the SMD is dominated by the low mass ones, and EAGLE turns out to be the only model among those considered able to nicely predict the faint-end of the passive SMF at the highest redshifts. The lower panel of the same figure shows the ratio between the passive and total SMD. ILLUSTRIS-TNG100 very nicely reproduces the observed trend, and EAGLE is consistent within the uncertainties. ILLUSTRIS-TNG300 and SIMBA predict a fraction of mass in passive galaxies consistent with the observations at \( z < 3.5 \). Given the large observational uncertainty, the model of Menci et al. (2014) as well as ILLUSTRIS-TNG300 and SIMBA at \( z > 3.5 \) are consistent with the data, although they systematically predict a negligible fraction of mass density accounted for by passive galaxies.

6.2.5. Conclusions

Overall, we observe a significant variation between the different models, despite their predictions roughly agree for the local SMF. In particular, the fact that none of the model analyzed is able to reproduce the observed passive galaxies over the entire mass and redshift range suggests that these passive derive from a subtle combination of several physical processes. Analyses like ours will allow the validation of model recipes in a new and seemingly powerful way. In any case, the inability of the models to correctly reproduce the observed high-\( z \) passive galaxies denotes a still incomplete understanding of the physical mechanisms responsible for the formation of these galaxies, their rapid assembly and abrupt suppression of their star formation, and for galaxy evolution in general.

7. Predictions for future surveys

We extrapolated our SMFs to predict the intrinsic number of high-\( z \) passive galaxies expected in surveys carried out with future facilities, depending on their depth (\( H \) band limiting magnitude) and their area. Basically, from the typical observed mass-to-light ratio of our candidates as a function of their observed magnitude, we converted the limiting flux into a limiting stellar mass. We then integrated the SMF at the different redshifts above this limiting mass and rescaled to the relevant survey area.

We note that the number of galaxies predicted by extrapolating the SMF is by definition larger than the number of candidates one will be able to select due to incompleteness in the actual surveys. As we discuss below, the availability of ancillary photometry, especially longward of the \( H \) band, and the choice of the specific selection technique will affect the actual number of candidates.

The calculation is based on two main assumptions. The first one is that the observed mass-to-light ratio (\( \log M - H \)) vs \( H \) band magnitude relation, well fitted by a linear slope at magnitudes brighter than 27, shows the same trend at fainter values. The second assumption is that the SMF, that we measure above \( 10^{10} M_\odot \), can be safely extrapolated to lower masses (we note that the faint-end slope was only fitted to the data in our lowest redshift bin, and it was kept fixed at higher redshifts). Both assumptions affect the predictions at magnitude deeper than 27, which is the magnitude cut of our selection. Indeed, \( H=27 \) roughly corresponds to \( 10^{10} M_\odot \), where our SMFs are still safely based on the observations and do not suffer from strong uncertainties associated with their extrapolation. Predictions for surveys deeper than \( H=27 \) should therefore been taken with caution.

Another important issue to be taken into account is that the selection function for high-\( z \) passive galaxies is not simply based on the depth of the observations in the \( H \) band, but it depends in a complex way on the depth in other filters, in particular the \( K \) and IRAC CH1 and CH2 bands, as described in Sect. 2.1 and fully discussed in M19. This implies that, although future telescopes are expected to survey large sky areas down to very deep limiting \( H \) band fluxes, additional data will be needed to properly select the high-\( z \) passive galaxies predicted to be found in the observed sky regions. The selection efficiency will indeed crucially depend on the availability of ancillary data. Our predictions can therefore be considered as upper limits to the expected number of candidates that will be detected by the future telescopes under consideration.

Keeping all these caveats in mind, the results of our calculation are shown in Fig. 11 and reported in Table 3. Given the large uncertainties associated with our SMFs, we only report the 68\% confidence level intervals on the predicted number of passive galaxies. Since the slope of the SMF has been fixed at \( z > 3.5 \), the associated confidence regions are narrower than at lower redshift, and so are the uncertainties on our predictions.

We first compared the expected number of passive sources in an area equal to the CANDELS one down to \( H=27 \) to the number of candidates actually observed. As expected, the number of selected passive galaxies is lower than our predictions by a factor of \( <2-5 \). As discussed above, this mismatch is explained by the incompleteness in the observed sample. It is larger at higher redshift due to the higher level of incompleteness, for a given mass limit.

Besides a CANDELS-like survey, we considered the JWST Advanced Deep Extragalactic Survey (JADES), Euclid and the
Based on our predictions, given the scarcity of passive galaxies in the young Universe, the surveyed sky area turns out to be the key feature to perform statistical studies of this class of sources, more than thanks to the observing depth. Thanks to its much larger area, the Euclid Deep survey, despite expected to be 1.5 and 3 magnitude shallower, will provide more candidates than the Medium and Deep surveys, respectively, carried out with the Nancy Grace Roman Space Telescope. The Euclid Wide survey will further improve the statistics by a factor of ~100, and by four orders of magnitude compared to what is now possible. We remind, however, that we are simply predicting the number of candidates expected in a given sky area down to a given flux limit, and not our capability in selecting them. As discussed above, ancillary, deep enough data are needed at longer wavelength to complement optical/near-IR observations. Spitzer data from the SIMPLE survey (Damen et al. 2011) over the Extended CDF-South (~ 0.5 deg²) and especially from the Euclid/WFIRST Spitzer Legacy Survey (covering 20 deg², proposals IDs #13058 and #13153, PI P. Capak) will be of great help, but will not cover the entire sky areas that will be observed by Euclid and Roman. This will allow us to only detect a fraction of the predicted number of high-z passive candidates.

Despite its small field of view, hence the relatively small areas surveyed, in the next future JWST will be the only instrument that will allow a self-standing selection of high-z passive galaxies, thanks to its red filters (> 2μm) that will complement the H band observations to a similar depth. JWST will allow a much cleaner selection of the candidates (see Merlin et al. 2018), an easier and faster spectroscopical confirmation, and it will extend the selection to even higher redshift thanks to its redder filters compared to CANDELS.

1  https://www.cosmos.esa.int/web/jwst-nirspec-gto/jades

Nancy Grace Roman Space Telescope. JADES is a JWST GTO program, imaging with NIRCam 46 and 190 arcmin² down to a limit of AB=30.6 and 29.6, respectively for the Deep and Medium survey, in the GOODS-S and GOODS-N fields. The Euclid Deep and Wide surveys will scan 40 and 15000 deg² down to a limiting depth of H=24 and H=26 (Laureijs et al. 2011), respectively. For the Nancy Grace Roman Space Telescope, we considered an UltraDeep survey reaching H=30 over 1 deg² (Koekemoer et al. 2019) and approximate depths of ~28.9 and ~27.5 over ~8.5 and ~9 deg² for a Deep and a Medium survey, respectively (Houssell et al. 2018).

Note that for a Medium survey, in the GOODS-S and GOODS-N fields. The JADES Medium survey, in the GOODS-S and GOODS-N fields. The JADES Medium survey, in the next future JWST will be the only instrument that will allow a self-standing selection of high-z passive galaxies, thanks to its red filters (> 2μm) that will complement the H band observations to a similar depth. JWST will allow a much cleaner selection of the candidates (see Merlin et al. 2018), an easier and faster spectroscopical confirmation, and it will extend the selection to even higher redshift thanks to its redder filters compared to CANDELS.

Table 3. Predicted number of passive galaxies at different redshifts expected at different flux limits, corresponding to different mass limits, in the areas surveyed by future facilities. The range in square brackets encompasses the 1σ uncertainty in the predicted number caused by the uncertainties in the Schechter fits to the SMF (see text).

| Survey          | Area [deg²] | $H_{lim}(5\sigma)$ | log $M_{lim}/M_\odot$ | $N_{z=3-5}$ | $N_{z=4-5}$ | $N_{z=6-5}$ |
|-----------------|------------|--------------------|------------------------|-------------|-------------|-------------|
| JADES Deep      | 0.013      | 30.6               | 9.1                    | [5 – 45]    | [5 – 10]    | [5 – 20]    |
| JADES Medium    | 0.053      | 29.6               | 9.4                    | [15 – 130]  | [15 – 35]   | [10 – 65]   |
| Roman UltraDeep | 1          | 30                 | 9.3                    | [30 – 280]\times10\(^1\) | [25 – 70]\times10\(^1\) | [20 – 135]\times10\(^1\) |
| Roman Deep      | 5          | 28.9               | 9.5                    | [15 – 100]\times10\(^2\) | [10 – 30]\times10\(^2\) | [10 – 55]\times10\(^2\) |
| Roman Medium    | 9          | 27.5               | 9.9                    | [20 – 100]\times10\(^2\) | [20 – 45]\times10\(^2\) | [10 – 55]\times10\(^2\) |
| Euclid Deep     | 40         | 26                 | 10.3                   | [70 – 270]\times10\(^2\) | [55 – 140]\times10\(^2\) | [25 – 120]\times10\(^2\) |
| Euclid Wide     | 15000      | 24                 | 10.8                   | [10 – 40]\times10\(^5\) | [10 – 25]\times10\(^5\) | [40 – 725]\times10\(^5\) |

Fig. 11. Predicted number of passive galaxies at different redshifts expected at different flux limits in the areas surveyed by future facilities (see Table 3). The plotted range accounts for the uncertainty in the Schechter fits to the SMF (see text). The coloured boxes are the number of candidates actually observed in CANDELS (this work). We note that the predictions are by definition larger than the number of observed candidates due to incompleteness in the actual surveys.

![Diagram](image-url)
8. Summary

In this paper, we present a follow-up analysis of the passive galaxy candidates selected at $z > 3$ in the CANDELS fields by M19 through an accurate and ad-hoc developed SED fitting technique. After confirming their passive nature by means of their sub-mm emission, probing the lack of on-going star formation, we study the Stellar Mass Function (SMF) of the passive population at $3 < z < 5$. We summarize our results in the following.

We started by searching the ALMA archive for observations of our candidates. We found data for $77\%$ of the sources located in the fields accessible by ALMA. Following the method presented in our previous work (S19), based on the comparison between ALMA predictions and the outcome of the SED fitting analysis, we could confirm the accuracy of the passive classification for $61\%$ of the candidates on an individual basis at a $3\sigma$ confidence level. Since the available data is not deep enough to confirm or reject the rest of the candidates, we validated the population as being on average passive in a statistical sense, through stacking and by comparison with the location of the Main Sequence of star-forming galaxies at the same redshifts.

Once again (see S19), we confirmed the reliability and robustness of the photometric selection technique developed in Merlin et al. (2018). Assuming that it performs equally well on the sources for which no sub-mm information is available, we computed the SMF over the entire sample of $101$ $3 < z < 5$ passive candidates using a stepwise approach. The latter has the advantage of taking into account photometric errors, mass completeness issues and the Eddington bias, without any a-posteriori correction.

We analysed the evolution in the SMF from $z = 5$ to $z = 3$ and compared it with the SMF of the total population. Despite the large associated uncertainties, we observe a strong evolution in the SMF around $z \sim 4$, indicating that we are witnessing the emergence of the passive population at this epoch, i.e. we are looking at the epoch at which these galaxies become passive. Consistently, we observe an increase in the abundance of passive galaxies compared to the overall population at the same redshift. While quiescent galaxies are always below $10\%$ at low ($M \leq 10^{10}M_\odot$) stellar masses, they can make a large fraction of the entire population (up to or more than $50\%$) at $M > 10^{10}M_\odot$ and $z < 4$. On the other hand, their abundance remains low ($\lesssim 10\%$) at $z > 4$. Integrating over $M > 10^{10}M_\odot$, passive galaxies account for $\sim 20 - 25\%$ of the total stellar mass density at $z \sim 3 - 4$, and only $\sim 5\%$ at earlier epochs. Current uncertainties on these numbers are however very large and prevent more accurate conclusions.

We compared our results with the literature, and found a factor of 4 to 10 more passive sources than most previous observations, with the exception of a couple of works consistent with our results within the uncertainties, at least in some of the redshift bins. This is due to a combination of $a)$ the better quality of the CANDELS observations, $b)$ the very accurate selection technique developed by Merlin et al. (2018), that include recently quenched galaxies often missed by colour-colour selections, and $c)$ the method adopted to calculate the SMF, that intrinsically accounts for mass and selection incompleteness, as well as for the Eddington bias. We also compared our results with theoretical predictions. We found an overall agreement with at least some of the models considered, but also clear mismatches, denoting a still incomplete understanding of the physical processes responsible for the formation of these galaxies and for galaxy evolution in general.

The analysis of passive galaxies in the high redshift Universe will be greatly improved by future facilities. JWST observations will improve their selection, and thanks to its spectroscopical capabilities will allow a faster confirmation as well as a deeper investigation of their physical processes. On the other hand, wide field surveys with Euclid and the Nancy Grace Roman Space Telescope, complemented with ancillary optical and IR data, will be crucial to improve the statistical analysis of these rare sources. Depth, redder filters and area will all combine to reduce the uncertainties currently affecting this kind of studies.

Acknowledgements. We thank the anonymous referee for the thorough and careful review of the manuscript. This paper makes use of the following ALMA data: 2012.1.00869.S, 2012.1.00173.S, 2013.1.00718.S, 2013.1.01292.S, 2013.1.01118.S, 2015.1.00242.S, 2015.1.00543.S, 2015.1.01074.S, 2015.1.00099.S, 2015.1.00870.S, 2015.1.00379.S, 2015.1.01495.S, 2016.1.01079.S. The IllustrisTNG simulations were undertaken with compute time awarded by the Gauus Centre for Supercomputing (GCS) under GCS Large-Scale Projects GCS-ILLU and GCS-OVAR on the GCS share of the supercomputer Hazel Hen at the High Performance Computing Center Stuttgart (HLRS), as well as on the machines of the Max Planck Computing and Data Facility (MPCDF) in Garching, Germany. We acknowledge the Virgo Consortium for making their simulation data available. The EAGLE simulations were performed using the DiRAC-2 facility at Durham, managed by the ICC, and the PRACE facility Curie based in France at TGCC, CEA, Brüyères-le-Châtel. We also thank Romain Davé for help in using the SIMBA simulation data.

References

Alcalde Pampliega, B., Pérez-González, P. G., Barro, G., et al. 2019, ApJ, 876, 135
Barro, G., Pérez-González, P. G., Cava, A., et al. 2019, ApJS, 243, 22
Bouwens, R. J., Illingworth, G. D., Franx, M., & Ford, H. 2008, ApJ, 686, 230
Bruzual, G. & Charlot, S. 2003, MNRAS, 344, 1000
Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682
Cappelluti, N., Comastri, A., Fontana, A., et al. 2016, ApJ, 823, 95
Caputi, K. I., Dunlop, J. S., McLure, R. J., et al. 2012, ApJ, 750, L20
Carnall, A. C., McLure, R. J., Dunlop, J. S., et al. 2019, MNRAS, 490, 417
Carnall, A. C., Walker, S., McLure, R. J., et al. 2020, MNRAS, 496, 695
Castellano, M., Fontana, A., Grazian, A., et al. 2012, A&A, 540, A39
Castellano, M., Fontana, A., Paris, D., et al. 2010, A&A, 524, A28+26
Chary, R. & Elbaz, D. 2001, The Astrophysical Journal, 565, 562
Cimatti, A., Daddi, E., Renzini, A., et al. 2004, Nature, 430, 184
Dahlen, T., Mobasher, B., Faber, S. M., et al. 2013, ApJ, 775, 93
Dale, D. A. & Helou, G. 2002, ApJ, 576, 159
Damen, M., Labbé, I., van Dokkum, P. G., et al. 2014, ApJ, 727, 1
Davé, R., Álvarez-Acúñá, M., Narayanan, D., et al. 2018, MNRAS, 486, 2827
Donnari, M., Pillepich, A., Nelson, D., et al. 2020, subm. to MNRAS, [arXiv:2008.00004]
Donnari, M., Pillepich, A., Nelson, D., et al. 2020, subm. to MNRAS, [arXiv:2002.02767]
Driver, S. P. & Robotham, A. S. G. 2010, MNRAS, 407, 2131
Duncan, K., Conselice, C. J., Mortlock, A., et al. 2014, MNRAS, 444, 2960
Elbaz, D., Dickinson, M., Hwang, H. S., et al. 2011, A&A, 533, A119
Faiss, A. L., Fudamoto, Y., Oesch, P. A., et al. 2020, MNRAS, 498, 4192
Feldmann, R., Hopkins, P. F., Quataert, E., Faucher-Giguère, C.-A., & Kereš, D. 2016, MNRAS, 458, L14
Fontana, A., Dunlop, J. S., Paris, D., et al. 2014, A&A, 570, A11
Fontana, A., Pozzetti, L., Donnarumma, I., et al. 2004, Astronomy & Astrophysics, 424, 23
Fontana, A., Santini, P., Grazian, A., et al. 2009, A&A, 501, 15
Förster, B., Annunziatella, M., Wilson, A., et al. 2020a, ApJ, 890, L1
Förster, B., Marsan, Z. C., Annunziatella, M., et al. 2020b, ApJ, 903, 47
Fujimoto, S., Ouchi, M., Shibuya, T., & Nagai, H. 2017, ApJ, 850, 83
Galametz, A., Grazian, A., Fontana, A., et al. 2013, ApJS, 206, 10
Genzel, R., Tacconi, L. J., Lutz, D., et al. 2015, ApJ, 800, 20
Girelli, G., Bolzonella, M., & Cimatti, A. 2019, A&A, 632, A80
Glazebrook, K., Schreiber, C., Labbé, I., et al. 2017, Nature, 544, 71
Gobat, R., Daddi, E., Magdis, G., et al. 2018, Nature Astronomy, 2, 239
Grazia, A., Fontana, A., Santini, P., et al. 2015, A&A, 575, A96
Graziano, A., Salimbeni, S., Pentericci, L., et al. 2007, Astronomy & Astrophysics, 465, 393
Gronin, N. A., Kocevski, D. D., Faber, S. M., et al. 2011, ApJ, 197, 35
Appendix A: List of passive galaxy candidates

We list in Tables A.1 to A.5 the passive candidates selected by Merlin et al. (2019) and used in this work (we do not include one source at \( z = 6.7 \) as outside the redshift range probed) to compute the passive SMF. We report their redshift, \( H \) band magnitude and stellar masses. Tables A.1, A.2, and A.3 show the candidates in GOODS-S, UDS and COSMOS, respectively, and also report the sub-mm fluxes and inferred (limits on the) SFR for the sources having ALMA archival observations in Band 6 and 7. Tables A.4 and A.5 are for the GOODS-N and EGS fields, unobservable with ALMA. We refer the reader to Table B.1 of Merlin et al. (2019) for candidate positions, best-fit ages and time since quiescence.
| ID              | z   | $H$ [mag] | Stellar mass log $(M/M_\odot)$ | ALMA band | ALMA flux [mJy/beam] | SFR$_{M10}$ [$M_\odot$/yr] | SFR$_{M_{21}}$ [$M_\odot$/yr] | Confirmed (Y/N) |
|----------------|-----|-----------|-------------------------------|-----------|----------------------|-----------------------------|-----------------------------|------------------|
| GOODSS-2608    | 3.72| 26.03     | $9.58^{+0.11}_{-0.06}$        | 7         | 0.01±0.13            | <20                         | <5                          | N                |
| GOODSS-2717    | 3.03| 23.98     | $11.12^{+0.19}_{-0.08}$       | –         | –                    | –                           | –                           | –                |
| GOODSS-2782    | 3.58| 24.94     | $10.86^{+0.04}_{-0.05}$       | 7         | 0.05±0.11            | <23                         | <5                          | Y                |
| GOODSS-3718    | 3.85| 24.91     | $10.33^{+0.01}_{-0.06}$       | –         | –                    | –                           | –                           | –                |
| GOODSS-3897    | 3.12| 24.64     | $10.28^{+0.01}_{-0.06}$       | 7         | -0.05±0.50           | <74                         | <16                         | Y                |
| GOODSS-3912    | 3.90| 26.86     | $10.55^{+0.09}_{-0.13}$       | 6         | -0.07±0.17           | <43                         | <8                          | N                |
| GOODSS-3973    | 3.63| 25.42     | $11.23^{+0.08}_{-0.10}$       | 7         | 0.65±0.18            | 95±26                       | 23±6                        | Y                |
| GOODSS-4202    | 3.31| 26.06     | $9.66^{+0.04}_{-0.13}$        | –         | –                    | –                           | –                           | –                |
| GOODSS-4503    | 3.59| 24.07     | $11.14^{+0.03}_{-0.07}$       | 7         | -0.03±0.29           | <42                         | <10                         | Y                |
| GOODSS-4587    | 3.75| 25.84     | $9.74^{+0.12}_{-0.07}$        | 6         | -0.08±0.17           | <43                         | <8                          | N                |
| GOODSS-4949    | 4.82| 25.54     | $10.00^{+0.03}_{-0.01}$       | 6         | -0.07±0.23           | <55                         | <13                         | N                |
| GOODSS-5934    | 4.86| 25.81     | $9.83^{+0.01}_{-0.02}$        | 6         | 0.13±0.17            | <72                         | <17                         | N                |
| GOODSS-6407    | 4.81| 25.32     | $10.23^{+0.08}_{-0.07}$       | 6         | -0.11±0.17           | <42                         | <10                         | N                |
| GOODSS-7526    | 3.32| 25.98     | $10.54^{+0.10}_{-0.25}$       | 7         | 0.11±0.12            | <34                         | <7                          | Y                |
| GOODSS-7688    | 3.40| 25.83     | $10.37^{+0.08}_{-0.24}$       | 6         | 0.23±0.22            | 58±56                       | 11±10                       | Y                |
| GOODSS-8242    | 3.24| 25.31     | $9.84^{+0.01}_{-0.01}$        | 6         | 0.17±0.23            | <102                        | <19                         | N                |
| GOODSS-8785    | 3.85| 26.50     | $10.55^{+0.13}_{-0.23}$       | 6         | -0.37±0.22           | <56                         | <11                         | N                |
| GOODSS-9209    | 4.49| 24.75     | $10.96^{+0.01}_{-0.01}$       | 6         | -0.05±0.16           | <41                         | <9                          | Y                |
| GOODSS-10578   | 3.06| 22.63     | $11.52^{+0.01}_{-0.19}$       | 6         | 0.13±0.09            | 35±24                       | 6±4                         | Y                |
| GOODSS-12178   | 3.29| 25.15     | $10.68^{+0.08}_{-0.12}$       | 6         | 0.13±0.17            | <77                         | <14                         | Y                |
| GOODSS-13394   | 3.29| 24.90     | $10.06^{+0.01}_{-0.04}$       | 6         | 0.06±0.22            | <72                         | <13                         | Y                |
| GOODSS-15457   | 3.50| 25.56     | $9.67^{+0.06}_{-0.06}$        | 6         | 0.02±0.03            | <16                         | <3                          | N                |
| GOODSS-16506   | 3.38| 25.44     | $9.72^{+0.13}_{-0.02}$        | 6         | 0.01±0.02            | <8                          | <1                          | N                |
| GOODSS-16526   | 3.15| 24.62     | $10.13^{+0.01}_{-0.01}$       | 7         | 0.00±0.34            | <50                         | <11                         | Y                |
| GOODSS-17749   | 3.70| 25.25     | $10.98^{+0.10}_{-0.06}$       | 6         | 0.11±0.08            | 29±20                       | 5±4                         | Y                |
| GOODSS-18180   | 3.65| 25.13     | $10.91^{+0.09}_{-0.04}$       | 6         | 0.08±0.08            | 21±20                       | 4±3                         | Y                |
| GOODSS-19301   | 3.59| 26.38     | $10.13^{+0.06}_{-0.18}$       | 6         | 0.01±0.08            | <25                         | <5                          | Y                |
| GOODSS-19446   | 3.27| 24.48     | $10.25^{+0.01}_{-0.01}$       | 6         | 0.04±0.09            | <33                         | <6                          | Y                |
| GOODSS-19505   | 3.59| 24.36     | $10.72^{+0.01}_{-0.01}$       | 6         | 0.00±0.04            | <14                         | <2                          | Y                |
| GOODSS-19883   | 3.57| 24.50     | $11.20^{+0.03}_{-0.06}$       | 7         | 0.30±0.25            | 44±36                       | 10±9                        | Y                |
| GOODSS-22085   | 3.47| 25.13     | $10.68^{+0.05}_{-0.08}$       | –         | –                    | –                           | –                           | –                |
| GOODSS-22610   | 3.33| 24.81     | $10.05^{+0.06}_{-0.03}$       | 7         | 0.08±0.24            | <46                         | <10                         | N                |
| GOODSS-23626   | 4.75| 25.57     | $10.89^{+0.06}_{-0.06}$       | 7         | 0.17±0.30            | <76                         | <23                         | N                |

Table A.1. Passive galaxy candidates at $3 < z < 5$ in the GOODS-S field.
Table A.2. Passive galaxy candidates at $3 < z < 5$ in the UDS field.

| ID          | $z$  | $H$  | Stellar mass log $(M/M_\odot)$ | ALMA band | ALMA flux [mJy/beam] | SFR$_{M_{10}}$ [M$_\odot$/yr] | SFR$_{M_{21}}$ [M$_\odot$/yr] | Confirmed (Y/N) |
|-------------|------|------|---------------------------------|-----------|----------------------|-----------------------------|-----------------------------|-----------------|
| UDS-1244    | 3.79 | 24.80| 11.14$^{+0.01}_{-0.12}$        | 7         | -0.17$\pm$0.36      | <52                         | <13                         | N               |
| UDS-2571    | 3.70 | 25.14| 10.84$^{+0.07}_{-0.13}$        | 7         | -0.05$\pm$0.55      | <81                         | <20                         | N               |
| UDS-4332    | 3.18 | 24.78| 11.25$^{+0.17}_{-0.07}$        | 7         | -0.07$\pm$0.24      | <36                         | <7                          | Y               |
| UDS-5720    | 3.16 | 24.28| 11.44$^{+0.01}_{-0.09}$        | -         | -                    | -                           | -                           | -               |
| UDS-7779    | 3.14 | 24.42| 11.01$^{+0.17}_{-0.12}$        | -         | -                    | -                           | -                           | -               |
| UDS-8682    | 3.46 | 25.11| 10.87$^{+0.09}_{-0.13}$        | -         | -                    | -                           | -                           | -               |
| UDS-8689    | 3.22 | 23.51| 11.24$^{+0.02}_{-0.01}$        | -         | -                    | -                           | -                           | -               |
| UDS-10086   | 3.09 | 24.63| 10.50$^{+0.09}_{-0.05}$        | -         | -                    | -                           | -                           | -               |
| UDS-10430   | 4.13 | 25.54| 11.02$^{+0.11}_{-0.14}$        | 7         | 0.03$\pm$0.26       | <42                         | <11                         | N               |
| UDS-11532   | 4.21 | 24.93| 10.25$^{+0.09}_{-0.08}$        | -         | -                    | -                           | -                           | -               |
| UDS-12640   | 3.61 | 25.05| 10.66$^{+0.17}_{-0.07}$        | 7         | 0.00$\pm$0.34       | <50                         | <12                         | Y               |
| UDS-20843   | 3.73 | 24.16| 10.98$^{+0.06}_{-0.01}$        | 7         | -0.04$\pm$0.22      | <31                         | <8                          | Y               |
| UDS-23628   | 4.25 | 24.67| 10.92$^{+0.14}_{-0.01}$        | 7         | 0.05$\pm$0.35       | <60                         | <17                         | Y               |
| UDS-25688   | 3.08 | 23.10| 11.42$^{+0.02}_{-0.02}$        | 7         | 0.22$\pm$0.24       | <68                         | <14                         | Y               |
| UDS-25893   | 4.49 | 26.32| 11.37$^{+0.10}_{-0.08}$        | 7         | 0.01$\pm$0.34       | <54                         | <16                         | N               |
| UDS-32406   | 3.28 | 26.10| 10.27$^{+0.09}_{-0.06}$        | -         | -                    | -                           | -                           | -               |

Table A.3. Passive galaxy candidates at $3 < z < 5$ in the COSMOS field.

| ID          | $z$  | $H$  | Stellar mass log $(M/M_\odot)$ | ALMA band | ALMA flux [mJy/beam] | SFR$_{M_{10}}$ [M$_\odot$/yr] | SFR$_{M_{21}}$ [M$_\odot$/yr] | Confirmed (Y/N) |
|-------------|------|------|---------------------------------|-----------|----------------------|-----------------------------|-----------------------------|-----------------|
| COSMOS-2075 | 3.35 | 24.43| 10.67$^{+0.07}_{-0.14}$        | 6         | -0.04$\pm$0.06      | <20                         | <3                          | Y               |
| COSMOS-16676| 3.72 | 24.60| 11.51$^{+0.16}_{-0.14}$        | 7         | 0.50$\pm$0.20       | 72$\pm$29                  | 18$\pm$7                   | Y               |
| COSMOS-18286| 3.04 | 23.89| 11.37$^{+0.01}_{-0.14}$        | -         | -                    | -                           | -                           | -               |
| COSMOS-19502| 3.87 | 24.46| 11.07$^{+0.12}_{-0.09}$        | 7         | 0.04$\pm$0.18       | <32                         | <8                          | Y               |
| ID            | $z$  | $H$   | Stellar mass   |
|---------------|------|-------|----------------|
|               |      | [mag] | log ($M/M_\odot$) |
| GOODSN-13     | 3.01 | 23.87 | 10.04$^{+0.03}_{-0.01}$ |
| GOODSN-357    | 3.09 | 24.15 | 9.98$^{+0.10}_{-0.06}$ |
| GOODSN-1570   | 3.23 | 23.48 | 10.12$^{+0.08}_{-0.01}$ |
| GOODSN-2901   | 3.70 | 25.30 | 10.07$^{+0.16}_{-0.23}$ |
| GOODSN-4004   | 3.81 | 25.56 | 10.56$^{+0.06}_{-0.08}$ |
| GOODSN-4691   | 3.18 | 24.75 | 11.04$^{+0.18}_{-0.15}$ |
| GOODSN-5059   | 3.69 | 25.50 | 11.10$^{+0.12}_{-0.19}$ |
| GOODSN-5744   | 3.46 | 25.81 | 10.70$^{+0.16}_{-0.17}$ |
| GOODSN-6430   | 3.21 | 24.86 | 9.94$^{+0.01}_{-0.07}$ |
| GOODSN-6620   | 3.70 | 23.87 | 10.44$^{+0.03}_{-0.01}$ |
| GOODSN-7385   | 3.18 | 25.09 | 9.90$^{+0.08}_{-0.15}$ |
| GOODSN-9626   | 3.18 | 24.71 | 9.89$^{+0.07}_{-0.05}$ |
| GOODSN-10956  | 3.09 | 24.90 | 9.64$^{+0.16}_{-0.01}$ |
| GOODSN-11579  | 3.17 | 25.63 | 10.73$^{+0.16}_{-0.17}$ |
| GOODSN-12446  | 3.05 | 25.40 | 9.29$^{+0.01}_{-0.01}$ |
| GOODSN-13007  | 3.04 | 24.18 | 10.57$^{+0.06}_{-0.21}$ |
| GOODSN-13403  | 3.79 | 26.14 | 9.81$^{+0.09}_{-0.16}$ |
| GOODSN-13435  | 3.65 | 25.65 | 10.79$^{+0.13}_{-0.17}$ |
| GOODSN-13800  | 3.33 | 23.72 | 10.87$^{+0.06}_{-0.05}$ |
| GOODSN-14482  | 3.49 | 25.30 | 10.05$^{+0.10}_{-0.04}$ |
| GOODSN-15054  | 3.06 | 22.90 | 11.32$^{+0.04}_{-0.03}$ |
| GOODSN-16817  | 3.69 | 24.78 | 9.81$^{+0.10}_{-0.01}$ |
| GOODSN-18860  | 4.53 | 24.95 | 10.11$^{+0.12}_{-0.01}$ |
| GOODSN-19580  | 3.10 | 24.24 | 11.03$^{+0.09}_{-0.04}$ |
| GOODSN-20589  | 3.34 | 24.85 | 9.88$^{+0.11}_{-0.01}$ |
| GOODSN-21034  | 3.33 | 26.19 | 9.98$^{+0.07}_{-0.10}$ |
| GOODSN-21961  | 3.36 | 25.52 | 10.44$^{+0.13}_{-0.17}$ |
| GOODSN-22398  | 3.11 | 24.87 | 9.67$^{+0.01}_{-0.11}$ |
| GOODSN-24092  | 3.30 | 23.99 | 11.09$^{+0.06}_{-0.03}$ |
| GOODSN-24501  | 4.24 | 24.93 | 10.32$^{+0.13}_{-0.03}$ |
| GOODSN-24572  | 3.34 | 23.96 | 10.22$^{+0.05}_{-0.07}$ |
| GOODSN-25209  | 3.27 | 24.65 | 10.79$^{+0.05}_{-0.12}$ |
| GOODSN-27251  | 3.12 | 24.59 | 10.07$^{+0.01}_{-0.07}$ |
| GOODSN-28344  | 4.76 | 26.72 | 10.44$^{+0.14}_{-0.17}$ |
| GOODSN-35028  | 3.64 | 25.17 | 11.24$^{+0.08}_{-0.15}$ |

*Table A.4. Passive galaxy candidates at $3 < z < 5$ in the GOODS-N field.*
| ID          | $z$  | $H$ [mag] | Stellar mass $\log (M/\text{M}_\odot)$ |
|------------|------|-----------|-----------------------------------------|
| EGS-2490   | 3.10 | 24.41     | $10.59^{+0.02}_{-0.15}$                 |
| EGS-6539   | 3.44 | 23.84     | $11.14^{+0.01}_{-0.12}$                 |
| EGS-14727  | 3.05 | 22.88     | $11.19^{+0.09}_{-0.04}$                 |
| EGS-15868  | 3.61 | 23.61     | $11.02^{+0.11}_{-0.01}$                 |
| EGS-21351  | 3.61 | 25.03     | $10.91^{+0.06}_{-0.06}$                 |
| EGS-23036  | 3.57 | 25.48     | $10.57^{+0.04}_{-0.09}$                 |
| EGS-24177  | 3.42 | 23.58     | $11.33^{+0.06}_{-0.07}$                 |
| EGS-24356  | 3.43 | 24.30     | $11.04^{+0.05}_{-0.06}$                 |
| EGS-25724  | 3.80 | 25.34     | $10.89^{+0.09}_{-0.07}$                 |
| EGS-26762  | 3.28 | 24.92     | $10.29^{+0.09}_{-0.11}$                 |
| EGS-27491  | 3.34 | 24.35     | $10.99^{+0.05}_{-0.13}$                 |
| EGS-29547  | 3.14 | 24.30     | $10.94^{+0.06}_{-0.09}$                 |
| EGS-30675  | 3.01 | 24.43     | $10.70^{+0.03}_{-0.15}$                 |

*Table A.5.* Passive galaxy candidates at $3 < z < 5$ in the EGS field.