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The ALPINE-ALMA [CII] Survey: nature, luminosity function and star formation history of continuum non-target galaxies up to $z \approx 6$

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ABSTRACT

Aims. We present the detailed characterisation of a sample of 56 sources serendipitously detected in ALMA Band-7, as part of the ALMA Large Program to INvestigate CII at Early Times (ALPINE). These sources, detected in COSMOS and ECDFS, have been used to derive the total infrared luminosity function (LF) and to estimate the cosmic star formation rate density (SFRD) up to $z \approx 6$.

Methods. We have looked for counterparts of the ALMA sources in all the available multi-wavelength (from HST to VLA) and photometric redshift catalogues. We have also made use of deeper UltraVISTA and *Spitzer* source lists and maps to identify optically dark sources with no matches in the public catalogues. We have used the sources with estimated redshift to derive the 250- μm rest frame and total infrared (8–1000 μm) LFs from $z \approx 0.5$ to 6.

Results. Our ALMA blind survey allows us to push further the study of the nature and evolution of dusty galaxies at high- z , identifying luminous and massive sources to redshifts and faint luminosities never probed before by any far-infrared surveys. The ALPINE data are the first ones to sample the faint-end of the infrared LF, showing little evolution from $z \approx 2.5$ to $z \approx 6$, and a “flat” slope up to the highest redshifts (i.e., $4.5 < z < 6$). The SFRD obtained by integrating the luminosity function remains almost constant between $z \approx 2$ and $z \approx 6$, and significantly higher than the optical/UV derivations, showing an important contribution of dusty galaxies and obscured star formation up to high redshifts. About 16% of all the ALPINE serendipitous continuum sources are found to be optically and near-IR dark (7 show a counterpart only in the mid-infrared and no HST or near-infrared identification, while 2 are detected as [C II] emitters at $z \approx 5$). The 7 HST+near-infrared dark galaxies with mid-infrared counterpart are found to contribute for about 15% of the total SFRD at $z \approx 5$ and to dominate the high-mass end of the stellar mass function at $z > 3$.

Conclusions.

Key words. galaxies: evolution – galaxies: high-redshift galaxies: luminosity function – cosmology: observations – submillimeter: galaxies

1. Introduction

Our current knowledge of the cosmic star-formation rate density (SFRD) at high redshift ($z > 3$) is based mostly on galaxy samples selected in the ultra-violet (UV) rest-frame (e.g., Bouwens et al. 2015; Oesch et al. 2018), whose bolometric star formation rates (SFRs) are not measured, but rather inferred through uncertain dust-correction techniques, and which are not necessarily representative of the whole galaxy population (e.g., missing strongly obscured massive systems with high dust content).

Since the discovery of the Cosmic Infrared Background (CIB, representing the cumulative emission reprocessed by dust from all the galaxies throughout the cosmic history of the Universe; e.g., Lagache et al. 2005) at the end of the 1990s by the COBE satellite (Puget et al. 1996; Hauser et al. 1998), and its resolution into discrete, rapidly evolving, far-infrared (far-IR) and sub-millimetre (sub-mm) sources by deep extragalactic surveys performed with the Infrared Space Observatory (ISO) and the Submillimetre Common-User Bolometer Array (SCUBA) on the JCMT, many searches have focused on deriving how much star formation activity in the early Universe is obscured by dust. These dusty star forming galaxies, also called "submillimetre galaxies" (SMGs; e.g., Smail et al. 1997, Hughes et al. 1998; Barger et al. 1998; Blain et al. 2002), are characterised by large far-IR luminosities ($10^{12} L_{\odot}$) and stellar masses ($M > 7 \times 10^{10} M_{\odot}$; e.g. Chapman et al. 2005, Simpson et al. 2014), extremely high star formation rates (SFRs, $\geq 100 M_{\odot} \text{ year}^{-1}$; e.g., Swinbank et al. 2014) and large gas reservoirs ($> 10^{10} M_{\odot}$; e.g., Bothwell et al. 2013, Béthermin et al. 2015). Despite them being rare and luminous objects, typically located around $z \sim 2-2.5$ (e.g., Chapman et al. 2003, Wardlow et al. 2011), their tremendous SFRs make them substantial contributors to the SFRD at Cosmic Noon, i.e., $1 < z < 3$ (e.g., Casey et al. 2013). However, the fraction of dust-obscured star formation, which is traced by *Herschel* up to $z \approx 3$ (e.g., Gruppioni et al. 2013, Magnelli et al. 2013), is still unknown at higher redshifts.

One of the problems is the difficulty in identifying the SMGs because of the coarse angular resolution of single-dish telescopes and the faintness of the optical/UV counterparts. The few SMGs that have been identified at $z > 4$ trace only the bright tail of the SFR distribution (e.g., Capak et al. 2011; Walter et al. 2012; Riechers et al. 2011, 2013, 2017; Marrone et al. 2018) and are unlikely to represent the bulk of the population. Moreover, most of the SMGs have photometric or spectroscopic observations that likely place them at $z < 3$ (Brisbin et al. 2017).

The Atacama Large Millimetre/submillimetre Array (ALMA) has now opened a breach in the wall, allowing us to refine our understanding of dusty galaxies at high redshifts by unveiling less extreme galaxies, between massive SMGs and normal star forming galaxies, through superb sensitivity and high spatial resolution surveys in the sub-mm/mm domain. This can be achieved thanks to the recently explored ability of ALMA to reveal serendipitously detected galaxies in blind extragalactic surveys.

The ALMA deep surveys performed by Dunlop et al. (2017), Walter et al. (2016) and Aravena et al. (2016), probing to very faint fluxes over small areas ($< 5 \text{ arcmin}^2$), and the wider (covering few tens of arcmin^2) and shallower (to $\sim 100-200 \mu\text{Jy}$) surveys by Hatsukade et al. (2018) and Franco et al. (2018), have enabled us to uncover faint (sub-)mm populations at $z > 4$, with infrared luminosities (L_{IR} , between 8 and $1000 \mu\text{m}$) $\lesssim 10^{12} L_{\odot}$ (e.g., Yamaguchi et al. 2019). An important product of these surveys is the discovery of a population of ALMA galaxies that are undetected even in the deepest optical and near-infrared (near-

IR, i.e., $\approx 1-3 \mu\text{m}$) images with Hubble Space Telescope (HST). These galaxies, called "HST-dark", are often identified in the mid-Infrared (mid-IR), in deep *Spitzer*-IRAC 3.6 or $4.5\text{-}\mu\text{m}$ images (e.g., Franco et al. 2018; Wang et al. 2019; Yamaguchi et al. 2019), although, despite them being unlikely spurious ALMA detections (e.g., Williams et al. 2019; Romano et al. 2020), some remain undetected even in IRAC maps. The HST-dark galaxies tend to be serendipitously found also in CO line scan surveys (see, e.g., Riechers et al. 2020 finding two of them at $z > 5$), possibly with space densities higher than expected even at the bright end of the CO LFs. These results indicate the existence of a prominent population of dusty star-forming galaxies at $z > 4$, fainter than the confusion limit of the single-dish sub-mm surveys that discovered the SMGs, but with much larger space densities, providing a significant contribution to the SFRD at high- z , even higher than that of the UV-bright galaxies at the same redshifts (e.g., Rodighiero et al. 2007; Williams et al. 2019; Wang et al. 2019).

Very faint ALMA fluxes were also reached by surveys of serendipitously detected sources in targeted observations (i.e., non pure blind surveys), that were able to constrain the faint end of the sub-mm/mm galaxy source counts, estimate their contribution to extragalactic background light, study their nature and possibly detect dark galaxies (e.g., Hatsukade et al. 2013; Ono et al. 2014; Carniani et al. 2015; Oteo et al. 2016; Fujimoto et al. 2016).

Here we present the identification, multi-wavelength characterisation and luminosity function of a sample of 56 sources, serendipitously detected in continuum at ~ 860 and $\sim 1000 \mu\text{m}$ (ALMA Band 7), within the *ALMA Large Program to INvestigate CII at Early Times* (ALPINE, PI: LeFèvre; see Le Fèvre et al. 2019; Faisst et al. 2020; Béthermin et al. 2020)¹ survey fields. ALPINE is a 70 hours ALMA survey in band 7, specifically designed to measure singly ionised Carbon ([C II] at $158 \mu\text{m}$) emission and any associated far-IR continuum for 118 main sequence galaxies at $4.4 < z < 5.9$ (representative in stellar mass and SFR of the star-forming population at $z \approx 5$; see Le Fèvre et al. 2019; Faisst et al. 2020). The programme, completed in February 2019, will allow us for the first time to build a coherent picture of the baryon cycle in galaxies at $z > 4$, by connecting the internal ISM properties to their well-characterised stellar masses and SFRs (from a wealth of ancillary photometric and spectroscopic data, already in hand). All the ALPINE pointings are located in the Extended Chandra Deep Field South (ECDFS; Giacconi et al. 2002) and Cosmic Evolution Survey (COSMOS; Scoville et al. 2007), thus benefit from a wealth of ancillary multi-wavelength photometric data (from UV to far-IR), making ALPINE one of the currently largest panchromatic samples to study the physical properties of normal galaxies at high- z .

Besides the main targets, in the ALPINE pointings a blind search for serendipitous line and/or continuum emitters in 24.9 arcmin^2 have been performed, providing two independent catalogues of emission lines (Loiacono et al., in preparation) and continuum (Béthermin et al. 2020) detections. For the continuum sources, we have performed identification in all the catalogues and deep images available in the COSMOS and ECDFS fields, we have constructed spectral energy distributions (SEDs), estimated photometric redshifts when unavailable from the literature, derived the $250\text{-}\mu\text{m}$ rest-frame and total IR ($8-1000 \mu\text{m}$) luminosity functions and the contribution of dusty galaxies to the cosmic SFRD up to $z \approx 6$.

¹ <https://cesam.lam.fr/a2c2s/>

The ALPINE sample of non-target objects detected in continuum will be briefly described in Section 2, the identification process and results will be presented in Section 3, while the luminosity function results will be discussed in Section 4. In Section 6 we present our conclusions.

Throughout the paper, we use a Chabrier (2003) stellar initial mass function (IMF) and adopt a Λ CDM cosmology with $H_0=70$ km s⁻¹ Mpc⁻¹, $\Omega_m=0.3$, and $\Omega_\Lambda=0.7$.

2. The ALPINE non-target continuum detections

The ALMA ALPINE observations were carried out in Band-7 during Cycle 5 and Cycle 6, and were completed in February 2019. Each target was observed for ~30 minutes of on-source integration time, with the phase center pointed at the UV position of the sources. One spectral window was centred on the [C II] expected frequencies, according to the spectroscopic redshifts extracted from the UV-spectra, while the other side-bands were used for continuum measurements only. The data were calibrated using the Common Astronomy Software Applications package (CASA; McMullin et al. 2007), version 5.4.0 and the continuum maps were obtained by collapsing the line-free channels in all the spectral windows (see Bethermin et al. 2020).

The ALMA observational strategy/setup, the details of the data reduction and the method adopted to extract continuum flux density information from ALPINE data and to select a complete sample of serendipitous sources, are comprehensively discussed in Bethermin et al. (2020). In the following paragraphs we summarise the main steps. The data-cubes were imaged using the *tclean* CASA routine down to a flux threshold of 3σ (σ being the standard deviation measured in a non-primary-beam-corrected map after masking the sources). A natural weighting of the visibilities was applied in order to maximise the point-source sensitivity and to optimise the measurement of the integrated properties of the ALPINE targets. The continuum maps were obtained by excluding the channels contaminated by the lines of the target sources and those of a few off-center serendipitously detected continuum sources with lines. In fact, in order to avoid possible contamination of the continuum flux by the flux of lines, spectra were extracted for all the non-target sources and new tailored continuum maps were produced by masking the potential line-contaminated channels, then remeasuring the continuum flux (correction varying from 58% to a negligible fraction of the flux density).

The average synthesized beam size is 1.13×0.85 arcsec² (size varies with frequency and array configuration, i.e., between 5.2 and 6 kpc at $4.4 < z < 6$). The continuum sensitivity also varies with the frequency, for this reason the continuum sources have been extracted on signal-to-noise (SNR) maps, by searching for local maxima above a given threshold using the *find_peak* routine of *astropy*. As revealed from simulations shown in Bethermin et al. (2020), the threshold above which we obtain a purity of 95% corresponds to a SNR=5 outside the central region of 1 arcsec radius (expected to contain the ALMA continuum flux of the ALPINE targets). We call *target sample* the sources extracted in the 1-arcsec central regions and *non-target* the objects found outside of this area. In this paper we focus only on the *non-target* sources.

The final sample of non-target sources detected in continuum at $S/N > 5$ in ALMA band-7 consists of 56 sources, of which 3 in the ECDFS and 53 in COSMOS, extracted over a total area of 24.92 arcmin² (excluding the circle of 1 arcsec radius around the central ALPINE targets). The number of expected spurious

sources in this sample is ≤ 3 , while the completeness is a function of the flux density and the size of each source (see Bethermin et al. 2020), as discussed in Section 4. One of the ECDFS sources has been detected in two different (slightly overlapping) ALPINE pointings, therefore it has a flux measurement in both channels, i.e., 860 μ m and 1000 μ m. Details on the flux measurement and uncertainties are provided in Bethermin et al. (2020).

3. The nature of the ALPINE non-target sources

We take advantage of the great wealth of multi-wavelength ancillary data, catalogues, spectroscopic and photometric redshifts and deep images, available in the ALPINE fields (ECDFS and COSMOS; see, e.g., Faisst et al. 2020), to investigate the nature of the serendipitous sources detected in continuum by ALMA.

The ground-based photometry available in the ECDFS includes *U38*, *b*, *v*, *Rc*, and *I* broad-band filters from the Wide Field Imager on the ESO/2.2-m telescope, *U* and *R* bands from VIMOS on the ESO-VLT, near-IR filters *J*, *H*, and *Ks* from ISAAC on the ESO VLT, *J* and *Ks* data from WIRCam on the CFHT, and 14 intermediate-band filters from the Suprime-Cam on the Subaru telescope. In addition, a wealth of HST observations are available in the ECDFS field.

The photometric data available in the COSMOS field include *u*-band observations from MegaCam on CFHT, *B*, *V*, *r+*, *i+*, *z++* as well as 12 intermediate-band and 2 narrow-band filters from the Suprime-Cam on Subaru, *YHSC*-band from the Hyper Suprime-Cam on Subaru as well as near-IR bands *H* and *Ks* from WIRCam on CFHT and *Y*, *J*, *H*, and *Ks* from VIRCAM on the ESO-VISTA telescope. In terms of HST data, all but one ALPINE pointings in COSMOS are covered by ACS *F814W* observations (Koekemoer et al. 2007; Scoville et al. 2007), and CANDELS data in ACS and WFC3 bands (Grogin et al. 2011; Koekemoer et al. 2011), and several additional pointings in ACS and WFC3 bands.

The space-based photometry in both fields includes *Spitzer* data in the four IRAC bands (3.6, 4.5, 5.8 and 8.0 μ m) and in the MIPS 24- μ m band, and Herschel data in the PACS (100 and 160 μ m) and SPIRE bands (250, 350 and 500 μ m). A detailed summary and references of the different ground- and space-based data available in the two fields are presented in Faisst et al. (2020).

In the identification process, the basis catalogues to which we have first matched the ALMA non-target list are the 3D-HST catalogues (Brammer et al. 2012; Skelton et al. 2014; Momcheva et al. 2016) in both ECDFS and COSMOS, and the COSMOS2015 (Laigle et al. 2016), the super-deblended (Jin et al. 2018) and the DR4 UltraVISTA catalogues (McCracken et al. 2012; Moneti et al. 2019²) in COSMOS. Moreover, in COSMOS we have considered the IRAC catalogue based on Spitzer Large Area Survey with Hyper-Suprime-Cam data (SPLASH; Capak et al. 2012; Steinhardt et al. 2014).³

In the following sections we describe in detail the identification process of the ALPINE non-target continuum sources and the results obtained.

² <http://www.eso.org/rm/api/v1/public/releaseDescriptions/132>

³ The SPLASH maps are available, upon request, at <http://splash.caltech.edu/>

3.1. Source Identification

3.1.1. Catalogue Match

As a first step in the identification process of the ALPINE non-target sources, the ALMA list has been cross-matched with the multi-wavelength catalogues available from the literature in COSMOS and ECDFS. We have found a counterpart within 1 arcsec from the source position for all the 3 GOODS-S galaxies in the 3D-HST catalogue, and for 38 and 1 (3 in total, but 2 in common) of the COSMOS sources in the Laigle et al. (2016) and 3D-HST catalogues, respectively. Three additional COSMOS sources (39 in total, but 36 also in the COSMOS2015 catalogue) have been identified with galaxies in the super-deblended catalogue (at $\lambda \geq 24 \mu\text{m}$, but 2 also in the UltraVISTA DR4 catalogue) by Jin et al. (2018), plus other 3 only with IRAC/SPLASH objects (the fluxes were provided by M. Giullietti, private communication). By running Monte Carlo random shifts of the COSMOS15 catalogue we find an average number of spurious matches ≤ 2 , at an average distance of $\sim 0.7''$ from the ALMA sources. Since the great majority of the positional offsets between the ALMA sources and the catalogue counterparts are $< 0.4''$, with just 6 sources with an offset in the range $0.4''$ – $0.6''$, we can consider the false match rate as negligible. Moreover, as we will discuss later, we have visually inspected the ALMA contours over-plotted onto the images in all the available bands, for all the sources, in order to validate the match. We have therefore been able to photometrically identify 48 sources out of 56 (3/3 in ECDFS and 45/53 in COSMOS), leaving us with a sample of 8 galaxies with no counterpart in any of the available catalogues. Of these 8 sources, 2 have been identified as line emitters in the blind lines catalogue by Loiacono et al. (in preparation). Because the 2 serendipitously detected lines associated to unidentified continuum sources are in the same side-band of the [C II] $158\mu\text{m}$ emission of the ALPINE targets in the same pointings, they are likely [C II] as well (see e.g., Jones et al. 2020; Romano et al. 2020). This provided us a spectroscopic redshift estimate for 2 sources without any catalogue counterparts, leaving us with 6 sources with neither catalogue matches, or redshift estimates.

3.1.2. Images visual inspection

As a second step, we have inspected the images, from UV to sub-mm and radio, at the position of the ALMA sources, finding a likely faint counterpart (i.e., below the threshold imposed by the catalogues, at 2.5 – 4.5σ) in the IRAC/SPLASH maps (at $4.5 \mu\text{m}$) for 2 of the unidentified sources and in the MIPS $24\text{-}\mu\text{m}$ image for 1. By inspecting the images, we found 2 sources for which the optical counterpart from Laigle et al. (2016), though within 1 arcsec from the ALMA position, was slightly offset and likely not the true identification, as at longer wavelengths (i.e., Ks and IRAC bands) another source was appearing at the exact position of the ALMA galaxy. For these sources, only the long wavelength photometric data ($> 2 \mu\text{m}$, assumed to represent the true identification) were considered for constructing the spectral energy distribution (SED).

In the end, the number of sources with no obvious identification, either photometric nor spectroscopic, is 3, which is consistent with the number of expected spurious detections estimated through inverted map analysis (see Bethermin et al. 2020), which is indeed $2.8^{+2.9}_{-1.6}$. The signal-to-noise-ratios of these 3 unidentified sources are 6.7, 5.5 and 5.1: while the latter is likely a spurious detection, for the other two this conclusion is not so ob-

vious. To summarise, among the 56 continuum sources, 44 were identified in the optical and near-IR (38 COSMOS2015, 4 3D-HST, 2 UltraVISTA DR4), 7 only in the mid-IR (3 SPLASH, 1 super-deblended, 3 IRAC/MIPS images), 2 as [C II] emitters (with no photometric counterpart), while 3 remained unidentified (and could be spurious). The results of our identification process are summarised in Table 1.

In Figure 1 we show some examples of different cases resulting from the identification process of the ALPINE continuum non-target sources: from *top left* to *bottom right* we plot the ALMA $> 3\sigma$ contours superimposed to the ALMA, HST/ACS-i, Subaru, UltraVISTA, IRAC, MIPS and radio VLA-1.4GHz images. Panel (a): object with multi-wavelength counterparts in all bands and photo- z from Laigle et al. (2016). Panel (b): object with near-IR to sub-mm identification and photo- z . Panel (c) optically+near-IR dark galaxy detected only in the SPLASH/IRAC- $4.5 \mu\text{m}$ image. Panel (d): unidentified source.

3.2. Spectral energy distributions and source properties

By using all the available photometric data in COSMOS and ECDFS, we have constructed the SEDs of all the ALPINE non-target sources with at least one photometric detection in addition to the ALMA one. In order to obtain also the complete mid- and far-IR coverage for our sources, the ALMA sample has been cross-matched with the *Spitzer* and *Herschel* catalogues in both the ECDFS and COSMOS fields (i.e., the PACS Extragalactic Probe Survey, PEP, Lutz et al. 2011, the *Herschel*-GOODS, H-GOODS, Elbaz et al. 2011, the *Herschel* Multi-tiered Extragalactic Survey, HerMES, Oliver et al. 2012, the super-deblended catalogue by Jin et al. 2018). In the COSMOS15 and super-deblended catalogues, the *Herschel* fluxes are already reported: we choose the values from the super-deblended catalogue, when available. No additional *Herschel* matches for sources not identified in these two catalogues have been found. In H-GOODS the *Herschel* fluxes have been obtained from IRAC priors, thus source blending should not be an issue.

For 3 sources for which a faint counterpart (below the catalogue threshold) is detected only in the IRAC or MIPS maps, we have obtained a magnitude measurement by performing aperture photometry directly on the images. Thus, for 2 sources we obtained IRAC fluxes at 3.6 and $4.5 \mu\text{m}$, while for 1 we derived only a MIPS $24\text{-}\mu\text{m}$ flux. For 5 sources (2 with just a line identification and no photometric counterparts and 3 with no counterpart at all – the latter possibly spurious detections) we could not construct any SEDs.

3.2.1. SED fitting

We made use of all the available multi-wavelength information (either detections or upper limits) to fit the SEDs of our sources, by means of the LE PHARE software (i.e., Arnouts et al. 2002; Ilbert et al. 2006), which performs a χ^2 fit to the data by considering different templates. We have considered the semi-empirical template library of Polletta et al. (2007), representative of different classes of IR galaxies and AGN, to which we added some templates modified in their far-IR part to better reproduce the observed *Herschel* data (see Gruppioni et al. 2010, 2013), and three starburst templates from Rieke et al. (2009). The final set of templates (32 in total) included SEDs of different types of galaxies, from ellipticals to starbursts, of AGN and of composite Ultra Luminous Infrared Galaxies (ULIRGs, containing both AGN and star forming galaxy), in the rest-frame wavelength in-

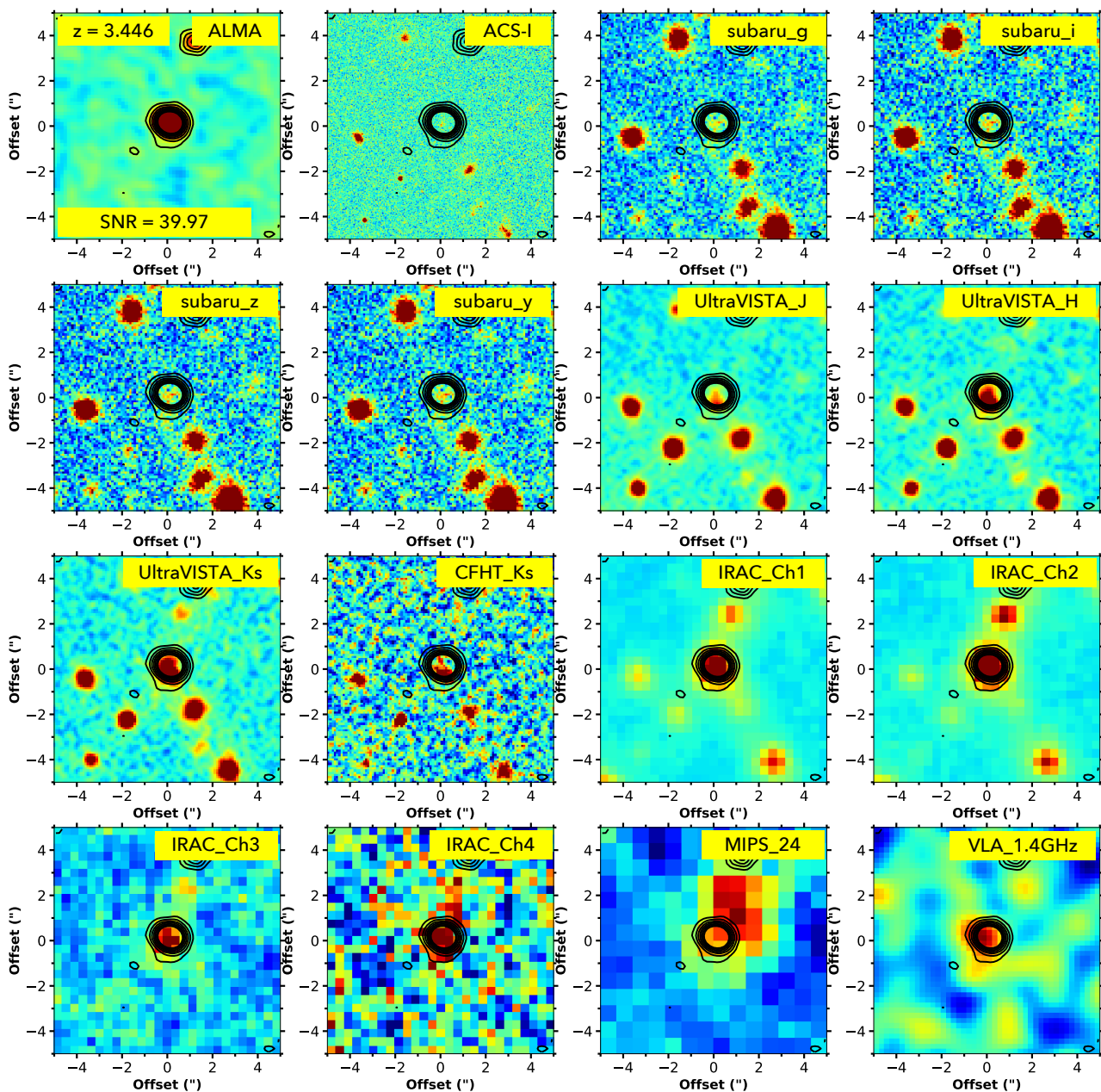


Fig. 1. Example of identification of ALPINE non-target continuum source: the postage stamps (from *top left* to *bottom right*) show the ALMA band-7 continuum map and the ALMA $\geq 3\sigma$ contours over-plotted to images from HST/ACS-i to radio VLA-1.4GHz (band specified in the top right corner). (a) - Object with multi-wavelength counterparts in all bands and photo- z from Laigle et al. (2016). – Continued in the next page.

Table 1. Summary of continuum source identification

Redshift	Photometry							
	TOT	COSMOS2015	3D-HST ^a	UVDR4	SPLASH	Super-deblended	Ad-hoc IRAC/MIPS	No ID
TOT	56	38	3+1 (3+3) ^b	2 (26) ^c	3 (42)	1 (39)	3	5
Catalogue	38	33	4	0	0	1	0	0
LE PHARE	10	2	0	2	3	0	3	0
[C II]	5	3	0	0	0	0	0	2
No z	3	0	0	0	0	0	0	3

Notes. (a) ECFDS+COSMOS.

(b) Values outside parentheses are the "new" identifications not included in other catalogues, while those between parentheses are the total number of sources identified in that catalogue.

(c) Twenty-four of the 26 galaxies found in the new UltraVISTA DR4 catalogue are also in COSMOS2015, while 2 in the super-deblended list.

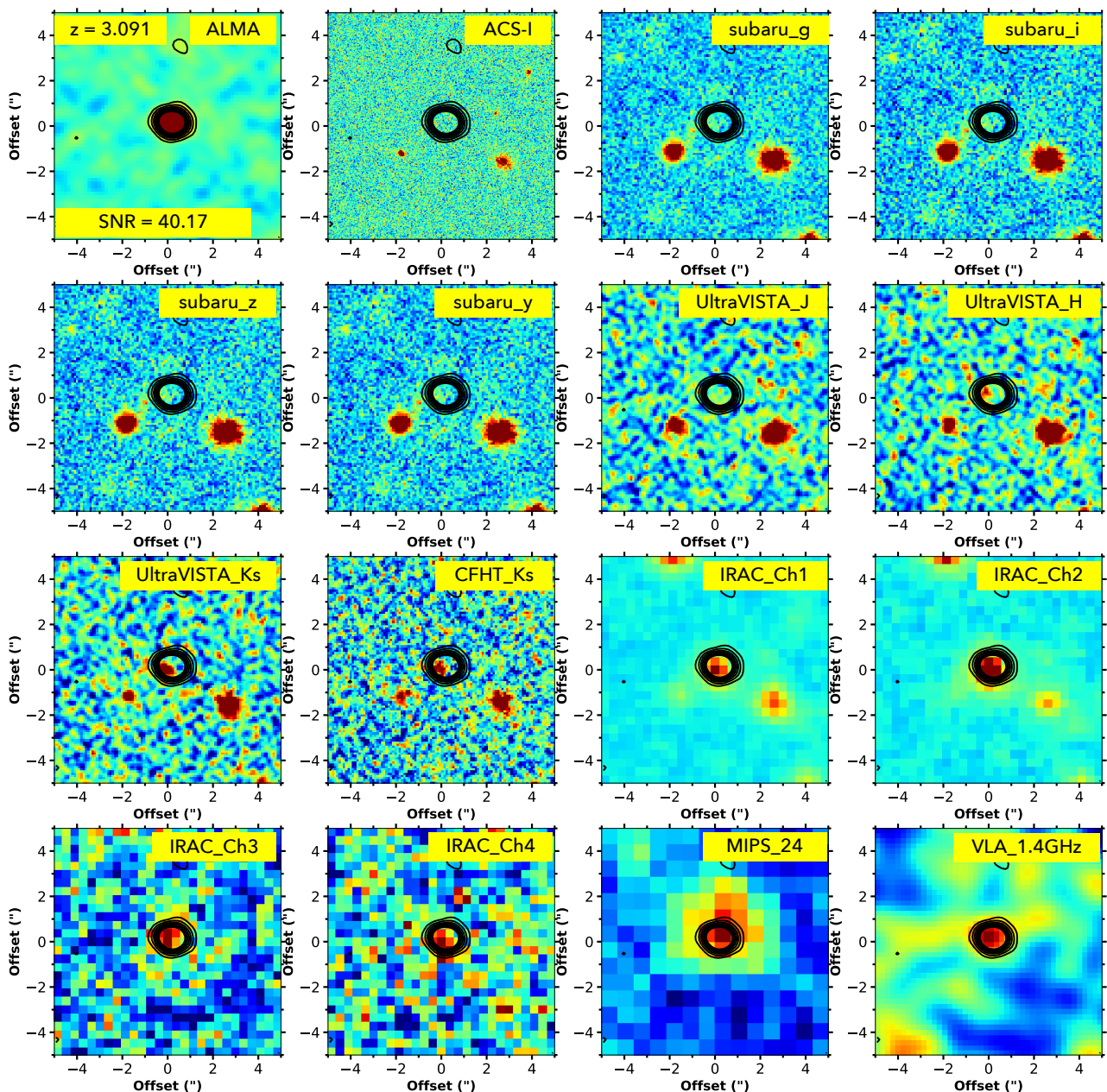


Fig. 1. – Continue: (b) - Object with no optical counterpart, but with multi-wavelength counterparts from near-IR to sub-mm and photo- z from Laigle et al. 2016).

interval 0.1–1000 μm . We allowed the code to apply different extinction values ($E(B-V)$) from 0.0 to 5) and extinction curves to the templates, in order to improve the fit. This increased the real number of possible templates. When performing the fit, the redshifts have been fixed to the spectroscopic or photometric values from the literature, or from [C II] line detection, when available. In most cases we found a good consistency between the photo- z from the literature and the best-fit SED obtained with our SED-fitting by fixing the redshift at that value. For the 7 sources with only a mid-IR counterpart, we attempted a photo- z estimate with LE PHARE, obtaining values of $z_{\text{phot}}^{\text{IR}}$ in the 2.2–6 range (with an average value $\bar{z}_{\text{dark}}=3.7$; see Section 3.3). In order to obtain a better determination of the total IR luminosity, we have simultaneously fit only the rest-frame 8-to-1000 μm range with additional far-IR template libraries included in LE PHARE (e.g., Chary & Elbaz 2001; Dale & Helou 2002; Lagache et al. 2004; Rieke

et al. 2009; Siebenmorgen & Krügel 2007), best-fitting the far-IR bump rather than constraining the whole SED from UV to mm (where optical/near-IR data always dominate the χ^2 , because of their smaller errors than those affecting the longer wavelength bands).

For most of the continuum non-target ALPINE galaxies we could obtain a good fit to all the data points and a SED estimate: the majority (75%) are best reproduced by star-forming galaxy templates (though 55% of them are composite, i.e., star-forming galaxies containing an obscured or low-luminosity AGN), while the remaining 25% are fitted by type 1 or 2 AGN templates. We have checked by stacking on the X-ray images (Chandra) at the positions of the AGN and non-AGN samples, but no significant signal has been measured for either samples, although for the AGN-SED sources a 1.5σ positive signal was detected, against a negative signal for the non-AGN SEDs. We stress that for the 7

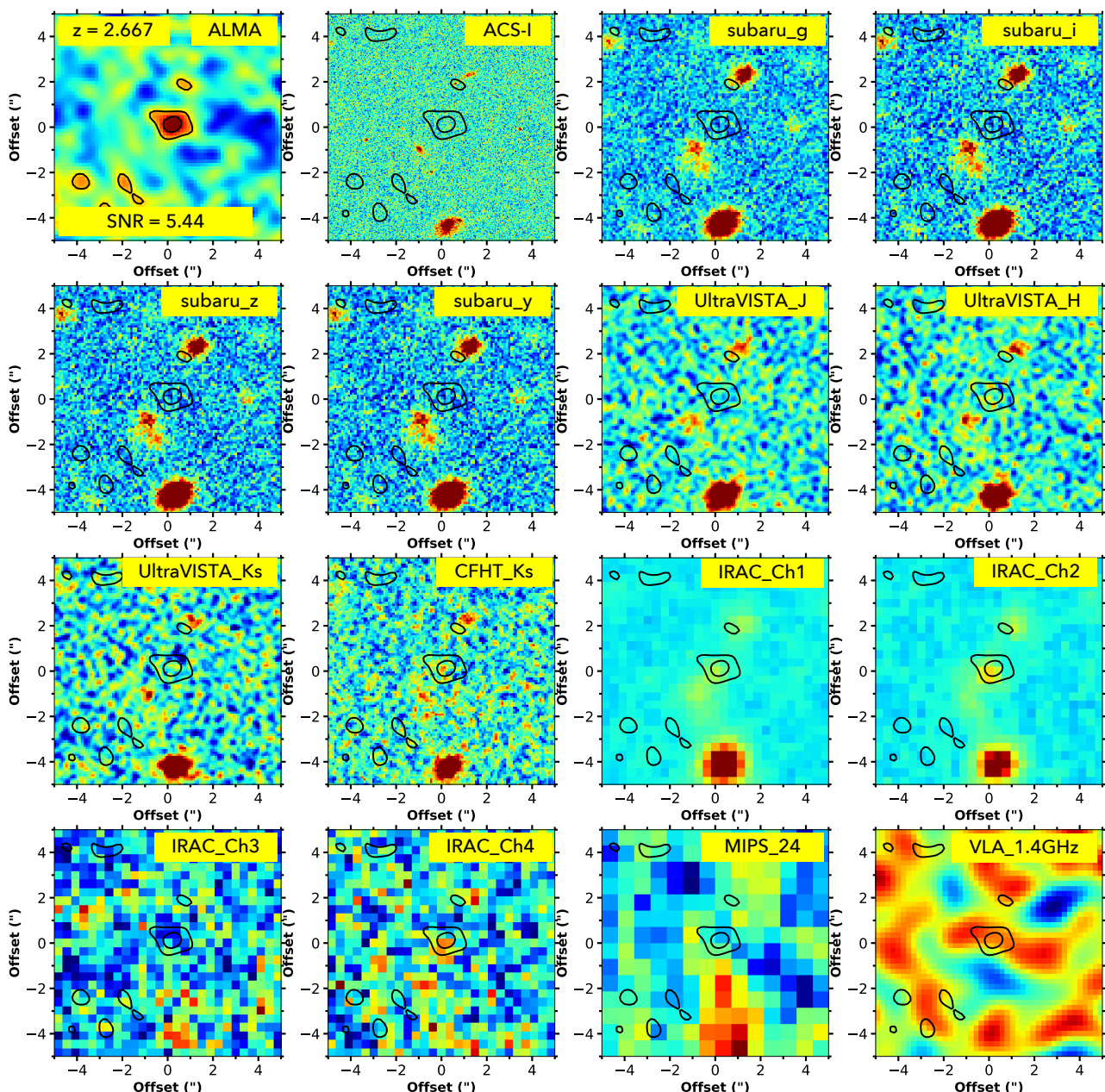


Fig. 1. – Continue: (c) - Optically dark galaxy detected only in the deep IRAC-SPLASH 4.5- μ m catalogue. The photo- z has been derived with LE PHARE using ALMA and IRAC data only.

sources detected only in the mid-IR (i.e., IRAC or MIPS bands), the SED-type and redshift are very uncertain and the relative results have to be taken only as indications.

In Figure 2 we show some examples of the observed SEDs and their best-fitting templates obtained from our analysis. The redshift distribution of the whole sample, including the spectroscopic and photometric redshifts from the literature, those from [C II] detection and those obtained with LE PHARE for the sources not in the COSMOS2015, super-deblended and 3D-HST catalogues, is shown in Figure 3. The 5 redshifts from [C II] are in a different colour, since we treated those sources separately in the LF analysis because, being at the same redshifts of the ALPINE targets at the centre of the ALMA pointing, they might be part of an overdensity, or in any case associated to the target. Indeed, at $z \approx 4.57$ a massive proto-cluster of galaxies located in the COSMOS field has been identified by Lemaux et al. (2018), therefore

some of our [C II] emitters might be part of it. Considering them as blindly detected sources might bias the LF calculation (see Loiacono et al. in preparation). These possible effects are discussed in Section 4.3.

3.2.2. Redshift distribution

In the paper by Bethermin et al. (2020), the redshift distribution is presented and discussed only for the “secure” identifications, i.e., the 38 sources with a counterpart in the catalogues. In this work we use all the redshifts, also the more uncertain ones, considering a total of 53 out of 56 sources. The redshift distribution obtained for the whole sample of 53 sources is shown in Figure 3 (black empty and blue-filled histogram in the *top* and *bottom* panel, respectively). We note that the total redshift distribution has a broad peak in the $z \approx 1.5$ – 3.5 range (with a low-

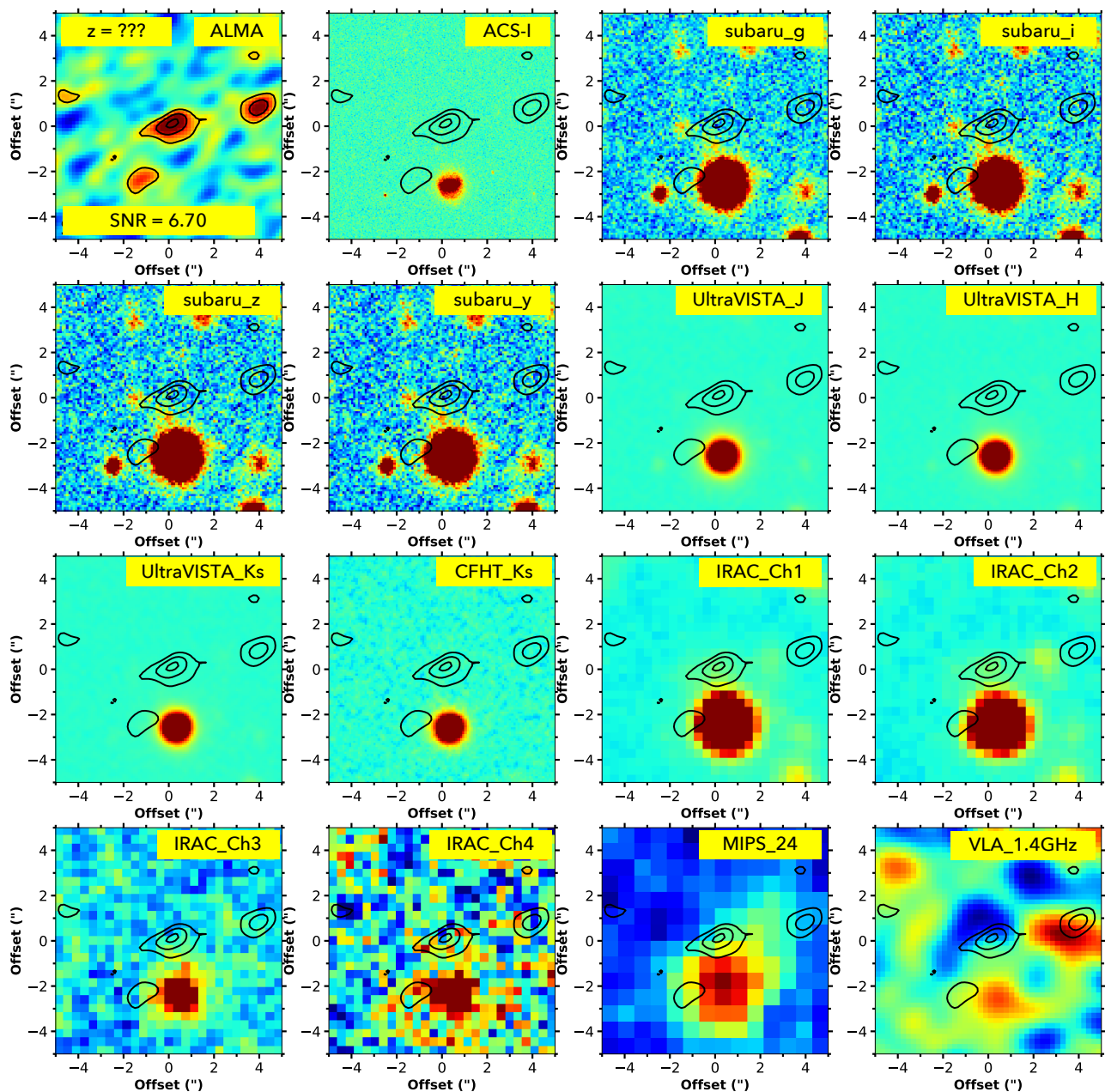


Fig. 1. – Continue: (d) - ALPINE serendipitous source with no obvious identification in any bands.

significance dip at $z \sim 2$), followed by a secondary peak at $z \sim 5$ and a tail up to $z \sim 6$. The secondary peak at $z \sim 5$ is mostly due to the sources "associated" to the ALPINE targets (i.e., with a line in the same ALMA side-band; deep-pink histogram in the *top* panel), although the higher redshift tail is made by sources apparently not related to the targets.

The median redshift of the total distribution is $z_{med} \approx 2.84 \pm 0.16$ ($z_{med} \approx 2.66 \pm 0.18$ excluding the sources at the same z of the targets, green-dashed distribution), similar to that found by Franco et al. (2018) in a $2\text{--}3 \times$ larger (69 arcmin^2) and shallower (to 0.7 mJy) ALMA survey at 1.1 mm in GOODS-S ($z_{med} \approx 2.9$), although the number of blindly detected objects in our ALPINE pointings is larger (56 against 20). The size of our continuum survey is similar to that of the ASAGAO Survey (26 arcmin^2 ; Hatsukade et al. 2018), although our number of detections is more than twice larger (i.e., we detect 56 sources above 5σ against 25 in ASAGAO). However,

we must note that our sources are selected in two different side-bands, and the 1.1 mm one goes about a factor of 2 deeper than the ASAGAO survey at the same wavelength. We refer to Bethermin et al. (2020) for a more detailed discussion about the redshift distribution of the ALPINE continuum non-target sources and the comparison with other ALMA survey works.

3.2.3. Mass

We have used the LE PHARE code and the Bruzual & Charlot (2003) libraries to estimate the stellar masses of our sources. We stress that the stellar masses derived for the HST and near-IR dark galaxies are extremely uncertain, given the few photometric points available (although we made use of all the 3σ upper limits to constrain the masses). We therefore can take the results only as indication. We find that our galaxies are massive, but slightly less extreme than those detected by Franco et al. (2018), although the

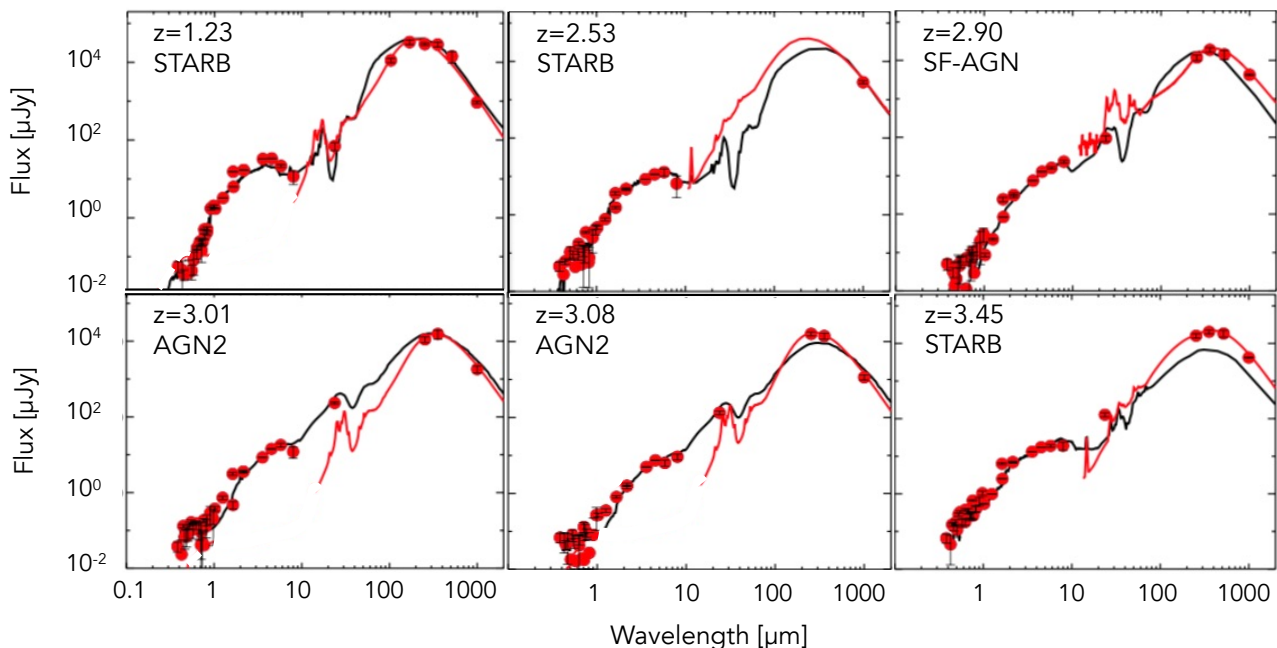


Fig. 2. Example of observed SEDs of the ALPINE continuum non-target sources with an identification and a photo- z in the available catalogues. The observed SEDs have been fitted with LE PHARE by fixing the redshift at the catalogue value: the best-fit template to all the data is shown in black, while the template best reproducing the IR data (i.e., from 8 to 1000 μm rest-frame, used to derive L_{IR}) is shown in red.

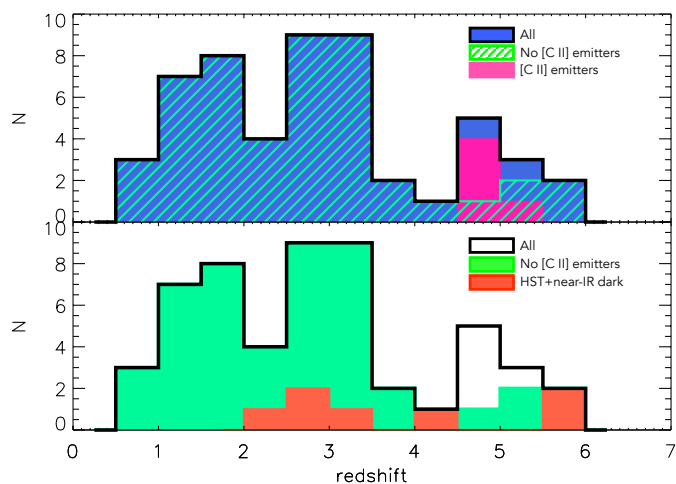


Fig. 3. Redshift distribution of the ALPINE non-target sources detected in continuum with an identification (black histogram, blue-filled in the *top* panel, empty in the *bottom* panel). In the *top* panel, the deep-pink histogram shows the 5 sources detected in [C II] at the same redshift of the ALPINE central targets, while the green dashed histogram shows the redshifts of the sources considered for the unbiased LF calculation (i.e., excluding the 5 [C II] emitters). In the *bottom* panel, we show the latter distribution as green filled, while the best-fit photometric redshifts of the 7 HST+near-IR dark galaxies are shown as red-orange filled histogram.

mass distribution extends up to masses as high as $\sim 4 \times 10^{11} M_{\odot}$ (see Figure 4). The median stellar mass of our distribution is $M^* \approx 9.8 \times 10^{10} M_{\odot}$, similar to the value of $1.1 \times 10^{11} M_{\odot}$ found by Franco et al. (2018).

3.3. Optically and near-IR dark galaxies

As mentioned in the previous section, of the 56 galaxies detected in our main catalogue, 12 (21%) do not present any obvi-

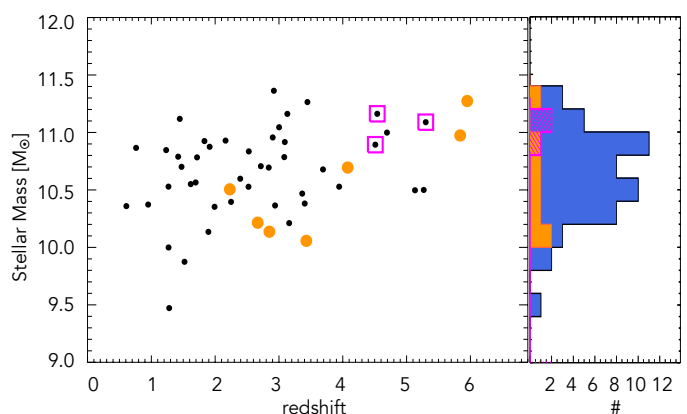


Fig. 4. Stellar mass versus redshift (*left*) and stellar mass histogram (*right*) for the ALPINE continuum non-target detections. The black filled circles and blue filled histogram show the distribution of the whole sample, while the orange circles and histogram show the locus occupied by the HST+near-IR dark sources. The magenta open squares and dashed-histogram show, for comparison, the locus of the sources identified with [C II] emitters at the same redshift of the ALPINE targets (note that the two without photometric counterpart are missing, since for them a mass estimate was impossible).

ous HST or near-IR (UltraVISTA, to $K_s \approx 24.9$; see McCracken et al. 2012, DR4; Moneti et al. 2019) counterparts. Six of these sources have been identified in the IRAC 3.6 or 4.5 μm bands and one in the MIPS 24- μm image, while 5 have no photometric counterpart at all. Two of these sources have been detected as line (likely [C II]) emitters by Loiacono et al. (in preparation), while 3 remain unidentified (compatible with the number of expected spurious sources based on simulations; see Bethermin et al. 2020). If we exclude the 3 likely spurious sources, we end up with a fraction of HST+near-IR dark galaxies among the ALPINE non-target continuum detections of $\approx 16\%$ (7 with

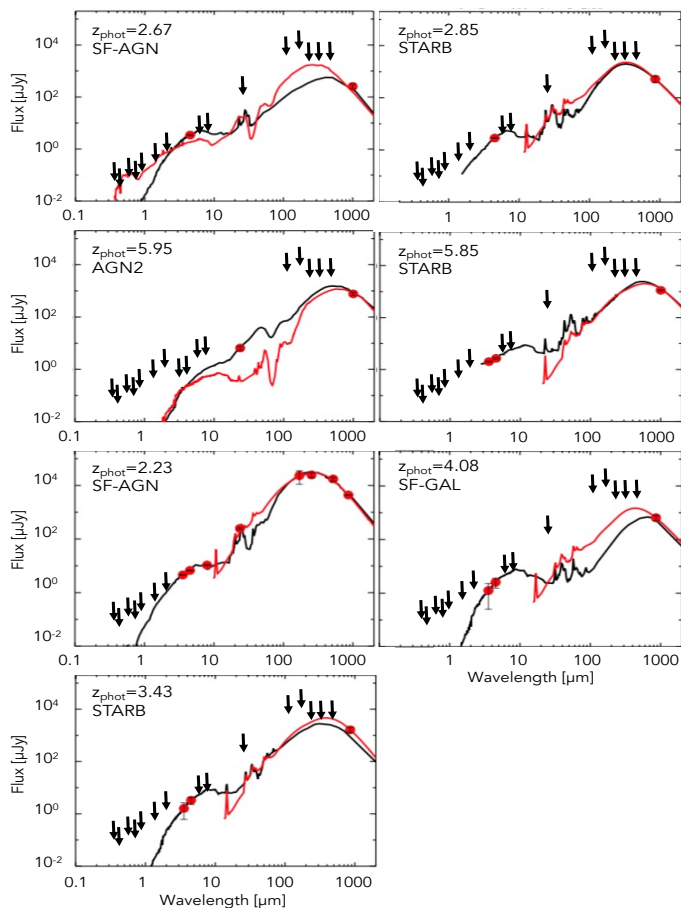


Fig. 5. Observed SEDs for the HST+near-IR-dark galaxies, with their tentative best-fitting templates (black for the broad-band SED, red for the far-IR SED, as in Figure 2) and photometric redshifts found with LE PHARE. The fits are based only on the IRAC (or MIPS) and ALMA data points, combined with the 3σ UV, optical, near- and far-IR 3σ upper limits.

a mid-IR counterpart + 2 [C II] emitters). The observed SEDs of the 7 dark galaxies with an IRAC or MIPS counterpart, and their best-fit template found by LE PHARE, are shown in Figure 5. Their photometric redshifts are in the range 2.2–6, with an average value $\bar{z}_{\text{dark}} \approx 3.7 \pm 0.6$. We stress again that the estimated redshifts for 6 of these sources are extremely uncertain (while for 1 are available IRAC, MIPS and *Herschel* data to constrain the photo- z): the width of the probability distribution function (PDF) can be as large as ~ 1 –1.5. Moreover, with few photometric data, the best-fitting solutions can degenerate in the photo- z/A_V space (i.e., Caputi et al. 2012). However, in our case the ALMA detection and the absence of optical and near-IR counterparts come to our aid, by ruling out the low- z solutions and better constraining the photo- z .

In order to check whether we can detect and eventually measure an average flux in the optical and near-IR bands for these dark sources, we have performed stacking at their positions in the HST-ACS band and in all the four Subaru, Ultra-VISTA and IRAC bands. Note that in the Subaru, Ultra-VISTA and IRAC bands, we have co-added images at different wavelengths: we have thus applied average corrections to the fluxes when required (i.e., multiplied by a factor 1.22 the 2'' aperture photometry value of the IRAC stacked flux). In fact, the aim of our stacking analysis was not to measure accurate values, but just to validate our conclusions by detecting and estimating an average flux den-

sity for the ALPINE galaxies undetected in optical and near-IR. In Figure 6 we show the results of our stacking analysis for the 7 HST+near-IR dark galaxies (*top* row) in the ACS-I, Subaru ($g + i + z + y$), Ultra-VISTA ($Y + J + H + K_s$) and IRAC ($ch1 + ch2 + ch3 + ch4$) bands (from left to right respectively), compared to the results obtained for the 2 [C II] emitters without any counterparts (*middle* row) and for the 3 unidentified sources (*bottom* row). A positive signal comes up clearly in the Ultra-VISTA and IRAC bands for the 7 HST+near-IR dark galaxies, providing an average flux of (1.25 ± 0.08) and (2.58 ± 0.18) μJy respectively. A barely visible signal (at $\sim 2\sigma$) appears at the centre of the Subaru stacked image, while in the ACS image we detect only the background. The images co-added at the positions of the two [C II] emitters without counterpart show a faint signal only in the Ultra-VISTA bands, and maybe in the IRAC ones, nothing in the ACS and Subaru bands. The 3 unidentified galaxies do not show any signal in the stacked images, at any wavelengths. In a future paper (Gruppioni et al. in preparation) we will investigate and discuss in more detail the nature and average properties of the ALPINE optical and near-IR dark sources (detected both in continuum and [C II]).

Previous studies have found ALMA galaxies completely missed at optical and near-IR wavelengths (Franco et al. 2018; Wang et al. 2019; Yamaguchi et al. 2019), even in the deepest surveys in GOODS. The fraction of HST-dark sources discovered in the GOODS-ALMA survey by Franco et al. (2018) is 20% of their sample, similar to the fraction found for the ASAGAO survey by Yamaguchi et al. (2019), while in our case the sources not detected in both the HST and near-IR bands constitute 16% of the sample (excluding the three likely spurious sources without any counterparts). If we exclude also the 2 [C II] emitters, likely associated to the ALPINE targets, we find 12.5% of serendipitous HST+near-IR dark galaxies. However, for a fair comparison, we must note that the HST-dark galaxies found by Franco et al. (2018) are undetected in GOODS-S, whose photometry is deeper than in COSMOS. Therefore, some of our HST-galaxies could have been detected in optical or near-IR images as deep as the ones covering the GOODS-S field. Indeed, this would further reduce our fraction of HST-dark sources, increasing the difference with the previous results. While the depth and size of the GOODS-ALMA survey are different from ours (it is about $2.5\times$ in size and 2 – $3\times$ shallower), the ASAGAO survey is similar to ALPINE, both in size and sensitivity. However, our detections are either at 860 or 1000 μm , while the two mentioned surveys in GOODS-S are at 1100–1200 μm . A similar depth but in two different selection bands, in a range where the galaxy SEDs are steep, makes our survey about 2 – $3\times$ deeper than the ASAGAO survey. Given all these factors (ALPINE deeper in ALMA, but shallower in the counterpart identification), we would have expected to find a larger fraction of galaxies undetected in the HST and/or UltraVISTA bands in ALPINE (COSMOS) than in GOODS-ALMA or ASAGAO. However, we must note that, considering the shot noise, the uncertainties in equivalence of detection and matching methodology, the data quality and depth in various bands, we cannot take this as a really significant difference.

The stellar masses estimated for the HST+near-IR dark galaxies in our sample (shown in Figure 4 in a different colour with respect to the total distribution) span about an order of magnitude in stellar mass, from 2×10^{10} to $3 \times 10^{11} M_{\odot}$ (approximately the entire range covered by the whole sample, although on the high-mass side). The dark galaxies found at higher redshifts (i.e., $z > 4$) show higher stellar masses (i.e., $M^* \gtrsim 10^{11} M_{\odot}$), similar to those of the (photometrically identified) [C II] emit-

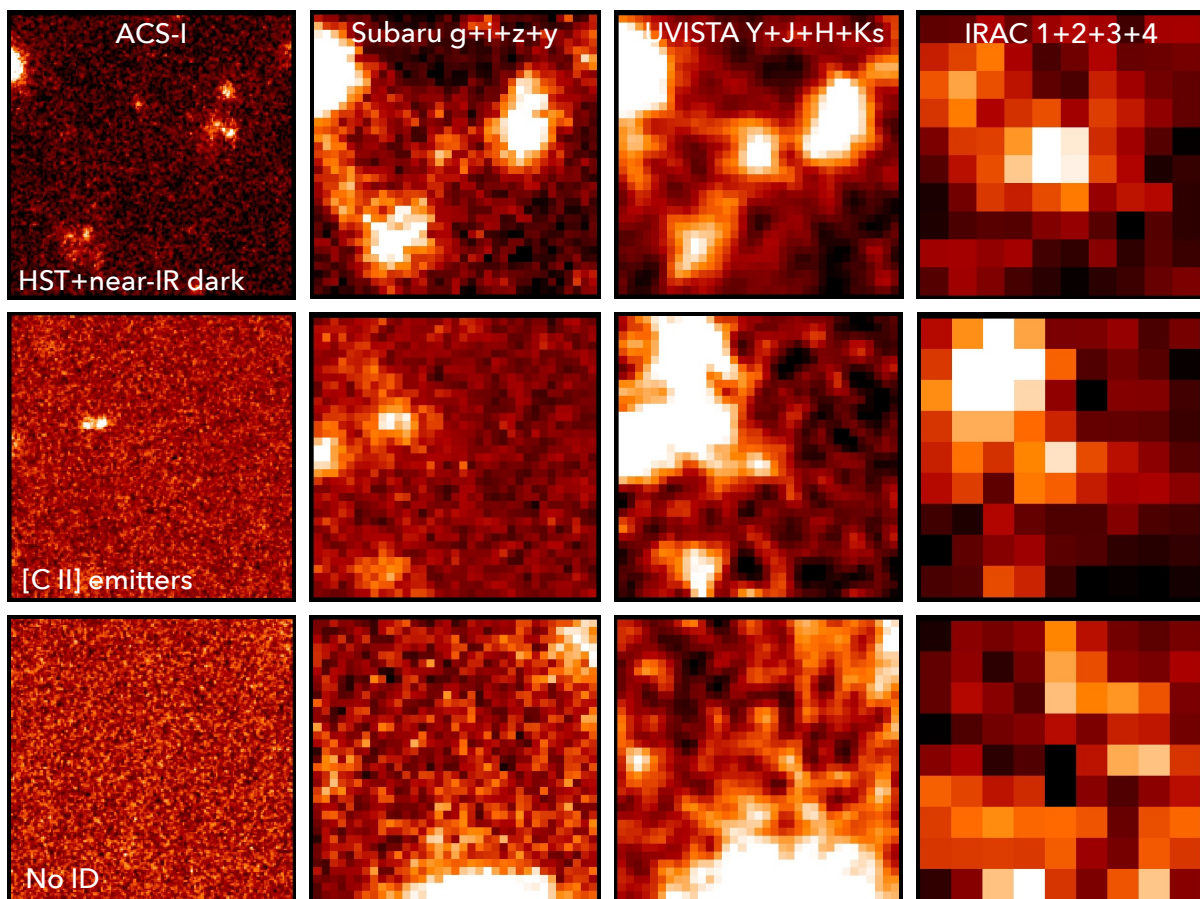


Fig. 6. Stacked images resulting of co-addition of the ACS-I, Subaru $g + i + z + y$, Ultra-VISTA $Y + J + H + K_s$ and IRAC $ch1 + ch2 + ch3 + ch4$ bands (from *left to right* respectively) at the positions of the 7 HST+near-IR dark galaxies (*top*), of the 2 [C II] emitters without photometric counterparts (*middle*) and of the 3 unidentified sources (*bottom*).

ters at the same redshift of the ALPINE targets. In general, the HST+near-IR dark galaxies in our sample show similar properties to those of the other $z > 2$ ALPINE sources.

To the purpose of the luminosity function calculation, the HST-dark galaxies have been considered, although with large uncertainties in their redshifts and 8–1000 μm integrated luminosities (accounted for in our simulations).

4. Luminosity function

The size and depth of our sample allow us to derive the far-IR LF in more than one redshift bins, spanning from $z \approx 0.5$ up to $z \sim 6$. Because of the redshift range covered by our continuum sample, we would need to make significant extrapolations in wavelength when computing the rest-frame LFs at any chosen wavelengths. In order to apply the smallest extrapolations for the majority of our sources, we choose to derive the far-IR LF at the rest-frame wavelength corresponding to the median redshift of the sample (~ 3): we therefore derive the rest-frame luminosity function at 250 μm . Given the excellent multi-wavelength coverage of our fields, the SEDs of most of our sources are very well determined from the UV to the sub-mm. The extrapolations are therefore well constrained by accurately defined SEDs, even at redshifts lower and higher than the median value. However, there are few sources for which the photometric redshift is based only on the ALMA and one or two mid-IR fluxes, therefore the redshift itself is very uncertain and the SED not well sampled. The extrapolation for these sources is thus not very accurate and the luminos-

ity is derived with large indeterminateness (i.e., it may vary by a factor of 2–3). We have taken into account these uncertainties in the error bars associated to the LF values (as discussed in detail in Section 4.3).

4.1. Method

The LFs are derived using the $1/V_{\text{max}}$ method (Schmidt 1968). This method is non-parametric and does not require any assumptions on the LF shape, but derives the LF directly from the data. In order to derive the monochromatic and total IR LFs, we have used all the sources with a spectroscopic or photometric redshift, with the exception of two sources (SC_1_DEIMOS_COSMOS_787780, SC_1_vuds_cosmos_5101210235) that were excluded also from the continuum number counts by Bethermin et al. (2020) because their flux density was found to be boosted by an emission line (CO(7-6) at $z=1.28$ and [C II] at $z=4.51$ respectively). At $z \approx 5$ we have computed (and compared) two different LFs by either excluding or including the 5 [C II] emitters likely associated to the ALPINE targets: in the former case we have used 46 sources, in the latter 51, spread over all the redshifts. We have divided the sample into five different redshift bins (over the range $0.5 \lesssim z \lesssim 6$), selected to be similarly populated. In each redshift bin we have computed the co-moving volume available to each

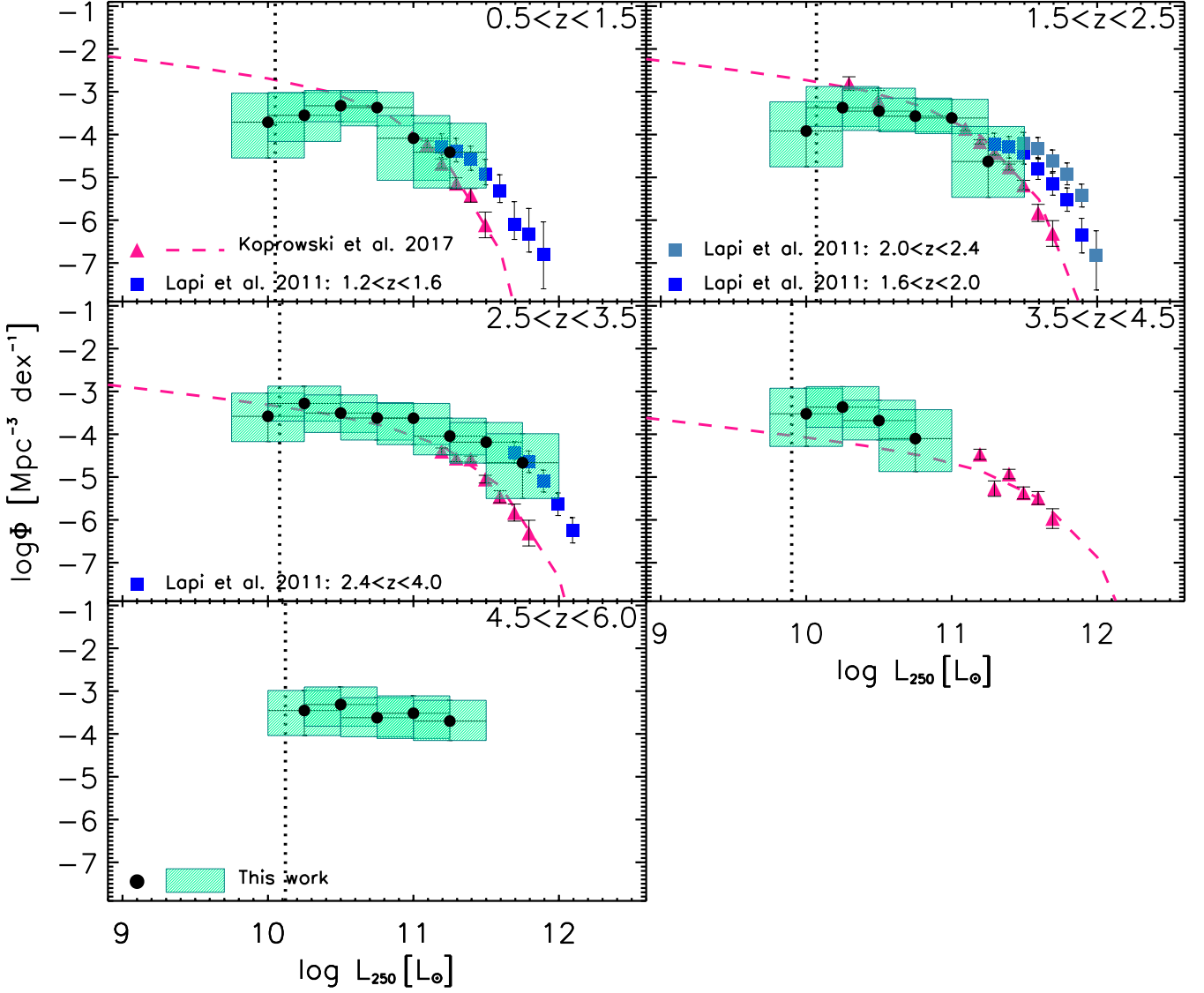


Fig. 7. Rest-frame $250\ \mu\text{m}$ Luminosity Function estimated with the $1/V_{\text{max}}$ method from the ALPINE continuum sample (green boxes and black filled circles). The luminosity bins have a width of $0.5\ \text{dex}$ in $L_{250\ \mu\text{m}}$, and step through the luminosity range in steps of $0.25\ \text{dex}$. For this reason, the individual bins are not statistically independent. The error-bars in the data points represent the uncertainties obtained from the simulations (as described in Section 4.3). The deep-pink triangles and dashed curves are the SCUBA-2 $250\text{-}\mu\text{m}$ LFs by Koprowski et al. (2017), while the blue filled squares are the *Herschel* ATLAS $250\text{-}\mu\text{m}$ LFs by Lapi et al. (2011), the latter in slightly different redshift intervals. The vertical dotted line shows the completeness limit estimated for our continuum survey.

source belonging to that bin, defined as

$$V_{\text{max},i} = \int_{z_{\text{min}}}^{z_{\text{max}}} \Omega_{\text{eff},i} \frac{dV}{d\Omega dz} dz = V(z_{\text{max},i}) - V(z_{\text{min},i}) \quad (1)$$

where z_{max} is the minimum between the maximum redshift at which a source would still be included in the sample – given the limiting flux of the survey – and the upper boundary of the considered redshift bin; analogously, z_{min} is the maximum between the minimum redshift above which the source will be detected in the survey and the lower boundary of the redshift bin. The quantity $dV/(d\Omega dz)$ is the comoving volume element per unit solid angle and unit redshift, while $\Omega_{\text{eff},i}$ is the effective area of the i -th galaxy and depends on both the flux density (i.e., becoming the total area covered by the survey, $24.92\ \text{arcmin}^2$, at bright fluxes, since only the brightest sources can be detected distant from the centre of the pointing) and the size of each source (e.g., compact sources have a better completeness than extended ones

at a given flux density). Note that to calculate the areal coverage of the serendipitous detections, we have excluded the $1\ \text{arcsec}$ central area where the target source was extracted. The effective area is derived from the completeness $\text{Compl}(S_{850}, \theta_i, x_i, y_i)$ at the position (x_i, y_i) of the i -th source:

$$\Omega_{\text{eff},i}(S_{850}, \theta_i) = \sum_{\text{pointings}} \iint \text{Compl}(S_{850}, \theta_i, x_i, y_i) d\Omega \quad (2)$$

where the sum is over the 118 pointings. The completeness have been derived through accurate simulations by Bethermin et al. (2020), where in their Figure 8 is shown the effective area as a function of the $850\text{-}\mu\text{m}$ flux for different source sizes.

For each luminosity and redshift bin, the LF is given by:

$$\phi(L, z) = \frac{1}{\Delta \log L} \sum_i \frac{1}{V_{\text{max},i}} \times \text{incompl}(z) \quad (3)$$

where $\Delta \log L$ is the size of the logarithmic luminosity bin, $incompl(z)$ is the correction for redshift incompleteness (i.e., sources without redshift) and $V_{\max,i}$ is the maximum comoving volume over which the i -th galaxy could be observed given its luminosity and redshift (Equation 1). We have adopted $incompl(z)=1$ for $z \leq 6$, under the assumption that the unidentified sources are all at $z > 6$ or spurious. In any case, considering or not the redshift incompleteness (e.g., assuming that the 3 unidentified sources are at $z > 3$) will not affect our conclusions.

Uncertainties in the infrared LF values depend on the number of sources in the luminosity bin (i.e., Poissonian error) and on the photometric redshift uncertainties. In particular, significant errors on the redshift estimate can shift a low redshift galaxy to higher redshifts and vice versa, thus modifying the number density of sources in a given redshift bin. To study the impact of these uncertainties on the inferred IR LF, we have performed Monte Carlo simulations, as described in section 4.3.

4.2. The Rest-Frame 250- μm Luminosity Function

By following the method described above, we have derived the 250- μm LF of the ALMA ALPINE sources. We have divided the samples into five redshift bins: $0.5 < z \leq 1.5$; $1.5 < z \leq 2.5$; $2.5 < z \leq 3.5$; $3.5 < z \leq 4.5$; $4.5 < z \leq 6$. We have considered luminosity bins of 0.5 dex, covering the whole luminosity range by overlapping by 0.25 dex. In this way the luminosity bins are not statistically independent (they are “alternately” independent), but we can better observe the “shape” of the LF and the position of the sources within the bin (e.g., if the bin is uniformly populated, or the sources are grouped at the edge of a bin). To study the possible bias introduced by the 5 sources with spectroscopic redshifts (from [C II] 158 μm line emission) very close to that of the ALPINE targets, we have derived two LFs at $4.5 < z < 6$: one by excluding and another by including these sources from/in the calculation. The comparison between the two LFs (excluding and including the 5 sources) will be presented and discussed only in Section 4.3, to avoid repetitions.

The results of the computation of our rest-frame 250- μm LFs are reported in Table 2; the errors have been computed through Monte Carlo simulations to study the impact of redshift uncertainties on the LFs. We refer to next Section for a detailed description of the simulation. Given the area covered by our survey and the number of independent pointings, the contribution due to cosmic variance (from Driver & Robotham 2010) is always negligible with respect to the uncertainties due to photo- z and luminosity. Our 250- μm LFs are shown in Figs. 7. For comparison, we overplot to our data previous results from the literature at 250 μm , i.e. the LFs derived by Koprowski et al. (2017) from the SCUBA-2 S2CLS survey and by Lapi et al. (2011) from the *Herschel*-ATLAS survey.

In the common redshift intervals, our data are almost complementary to the literature data, mostly covering the faint-end of the LFs, i.e., below the knee, while both Koprowski et al. (2017) and Lapi et al. (2011) LF data cover the bright-end (i.e., above the knee). In 3 of the 4 redshift intervals in common with Koprowski et al. (2017) (i.e., $0.5-1.5$, $1.5-2.5$ and $3.5-4.5$), in the very limited common range of luminosity, our 250- μm LFs are consistent with the SCUBA-2 one around the knee (at $z=2.5-3.5$ our knee is at brighter luminosities). Our LFs at the faint-end are flatter than the extrapolation of the Koprowski et al. (2017) fit at low z , consistent at $z \sim 3$ and higher at $z \sim 4$. In fact, in the higher redshift bin in common, i.e., $3.5 < z < 4.5$, our data, that reach an order of magnitude fainter luminosities, are slightly higher than the faint-L extrapolation of their Schechter fit. Note

that Koprowski et al. (2017) can constrain the Schechter curve with data (from Dunlop et al. 2017) at $L_{250\mu\text{m}} < 10^{11} L_{\odot}$ only in the $1.5 < z < 2.5$ redshift interval.

Given the error-bars of our LFs, in the overlapping redshift range (i.e., at $z < 3.5$) we are fully consistent with the *Herschel* LFs by Lapi et al. (2011), although only our highest luminosity bin is in common with their faintest one. However, in the redshift bin where our redshift distribution peaks and our data cover a wider luminosity range (i.e., $2.5 < z < 3.5$), our LF is higher at bright luminosities (e.g., at $L_{250} > 10^{11} L_{\odot}$) than the S2CLS one, while it shows good agreement with the Lapi et al. (2011) H-ATLAS derivation (although almost complementary and calculated in somewhat different redshift bins). Both our LFs and the *Herschel* ones indicate a more prominent bright-end (i.e., more luminous sources) than derived from SCUBA-2. The consistency between our 250- μm LFs and the Lapi et al. (2011) ones (derived from a different sample and instrument, using a different template SED to fit the data and a far-IR based method to derive photometric redshifts) gives us confidence that, at least in the common redshift intervals, the photo- z uncertainties do not significantly affect our computation.

On the other hand, the underestimated bright-end by the Koprowski et al. (2017) S2CLS LF had previously been noted by Gruppioni & Pozzi (2019) regarding the total IR LF (obtained with the same SCUBA-2 data used for the 250- μm derivation) at $z=2-3$, and likely ascribed to the use of different template SEDs (i.e., they considered a low temperature SED, $T \approx 35$ K) to compute the 8–1000 μm luminosity and to incompleteness issues. A similar difference is now observed also with our monochromatic derivation at similar redshifts, although these are the redshifts at which our data are less affected by SED extrapolations. Therefore, it is likely that incompleteness issue in S2CLS data are the principal cause of the observed discrepancy.

At $z > 4.5$ no comparison data from the literature are available, with our derivation providing the first ever determination of the luminosity and density distribution of dusty galaxies at such high redshifts. What is really surprising is that, even excluding the 5 sources at the same redshifts of the ALPINE targets, and despite the large uncertainties, at $4.5 < z < 6$ there are no hints of significant decrease in the volume density of dusty galaxies (i.e., in the LF normalisation) with respect to the epoch commonly considered of major galaxy activity (i.e., cosmic noon, $z \sim 1-3$). A comparison between the LFs obtained with and without the 5 sources is shown in the next section for the total IR LF.

4.3. The Total Infrared Luminosity Function

In order to derive the total IR luminosities (and LFs), we integrate the best-fit SED of each source over the range $8 \leq \lambda_{\text{rest}} \leq 1000 \mu\text{m}$ ($L_{\text{IR}} = L[8-1000 \mu\text{m}]$). This integration for most of our sources has been performed on well constrained SEDs covered by data in several bands (see Figure 2), while for few sources an extrapolation of the SED with no data constraining the far-IR peak was required (thus reflecting in large uncertainties in L_{IR}). We have computed the total IR LFs in the same redshift bins considered for the monochromatic LFs at 250 μm (i.e., $0.5 < z < 1.5$, $1.5 < z < 2.5$, $2.5 < z < 3.5$, $3.5 < z < 4.5$, $4.5 < z < 6$) and with the same method ($1/V_{\max}$) described in the previous section.

As already mentioned, we have studied the impact of redshift uncertainties on the total IR LFs by performing a set of Monte Carlo simulations. We have iterated 100 times the computation of the monochromatic and total IR LFs, each time varying the photometric redshift of each source (i.e., assigning a ran-

Table 2. ALPINE rest-frame 250- μ m LF

$\log(L_{250}/L_{\odot})$	$\log(\phi/\text{Mpc}^{-3} \text{ dex}^{-1}) [N_{\text{obj}}]$					
	$0.5 < z < 1.5$	$1.5 < z < 2.5$	$2.5 < z < 3.5$	$3.5 < z < 4.5$	Excl. [C II] emitters	All
<i>9.75 – 10.25</i>	<i>(-3.71^{+0.68}_{-0.83} [1])^a</i>	<i>(-3.92^{+0.68}_{-0.83} [1])</i>	<i>(-3.58^{+0.54}_{-0.59} [2])</i>	<i>-3.52^{+0.59}_{-0.76} [1]</i>		
10.00 – 10.50^b	-3.51^{+0.54}_{-0.61} [2]	-3.37^{+0.49}_{-0.43} [4]	-3.28^{+0.40}_{-0.41} [5]	-3.36^{+0.48}_{-0.47} [2]	-3.45^{+0.47}_{-0.58} [2]	-3.49^{+0.45}_{-0.65} [2]
<i>10.25 – 10.75</i>	<i>-3.33^{+0.36}_{-0.37} [6]</i>	<i>-3.45^{+0.53}_{-0.45} [4]</i>	<i>-3.51^{+0.42}_{-0.45} [4]</i>	<i>-3.68^{+0.48}_{-0.45} [2]</i>	<i>-3.31^{+0.41}_{-0.51} [3]</i>	<i>-3.21^{+0.30}_{-0.37} [4]</i>
10.50 – 11.00	-3.37^{+0.36}_{-0.43} [6]	-3.57^{+0.42}_{-0.36} [7]	-3.62^{+0.35}_{-0.51} [7]	-4.10^{+0.68}_{-0.76} [1]	-3.62^{+0.47}_{-0.44} [2]	-3.61^{+0.47}_{-0.44} [3]
<i>10.75 – 11.25</i>	<i>-4.08^{+0.52}_{-0.98} [2]</i>	<i>-3.61^{+0.43}_{-0.36} [7]</i>	<i>-3.62^{+0.35}_{-0.62} [8]</i>		<i>-3.51^{+0.41}_{-0.59} [3]</i>	<i>-3.52^{+0.41}_{-0.58} [4]</i>
11.00 – 11.50	-4.41^{+0.68}_{-0.83} [1]	-4.63^{+0.81}_{-0.83} [1]	-4.04^{+0.42}_{-0.44} [4]		-3.70^{+0.48}_{-0.45} [2]	-3.61^{+0.34}_{-0.47} [3]
<i>11.25 – 11.75</i>			<i>-4.19^{+0.46}_{-0.49} [3]</i>			<i>-3.91^{+0.46}_{-0.62} [2]</i>
11.50 – 12.00			-4.66^{+0.68}_{-0.83} [1]			-3.91^{+0.46}_{-0.62} [2]

Notes. ^(a) Values between parentheses correspond to luminosity bins that might be affected by incompleteness due to survey limits.

^(b) The bold (or alternatively italic) fonts denote independent luminosity bins.

domly selected value, according to the probability density function, PDF, distribution associated to each redshift). Each time, we have then recomputed the monochromatic and total IR luminosities, as well as the V_{max} , but keeping the previously found best-fitting template for each object (i.e., we have not performed the SED-fitting again, since the effect of the k-correction is not significant in the sub-mm wavelength range). For the total uncertainty in each luminosity bin, we have assumed the larger dispersion between that provided by the Monte Carlo simulations and the Poissonian one (following Gehrels 1986), although the effect of the photometric redshift uncertainty on the error bars is larger than the simple Poissonian value in the majority of cases.

The values of our ALPINE total IR LFs in each redshift and luminosity bin, with uncertainties derived by the Monte Carlo simulations, are reported in Table 3, with the alternately independent luminosity bins shown in italic and bold face, as in Table 2.

4.3.1. Comparison with previous results from the literature

In Fig. 8 the total IR LFs obtained from the ALPINE sample is shown and compared with other derivations available in the literature at similar redshifts. The *Herschel* (e.g., Gruppioni et al. 2013), SCUBA-2 (e.g., Koprowski et al. 2017) and ALMA (e.g., Hatsukade et al. 2018) LFs are reported in the common or similar redshift ranges.

We stress that this is the first total IR LF derivation reaching such faint luminosities and high redshifts: thanks to ALMA and the depth reached by the ALPINE survey, we are finally able to sample IR luminosities typical of “normal” (i.e., main-sequence) star-forming galaxies, rather than only those of extreme starbursts. We are therefore able to shape the LFs over a large luminosity range, by joining the ALMA data to the somewhat complementary *Herschel* and SCUBA-2 ones, at least up to $z \approx 4$. Globally, data from different surveys and wavelengths agree relatively well over the common z -range (up to $z \lesssim 4-4.5$): despite the large redshift and SED extrapolation uncertainties, the total IR LF derived from the ALPINE data is in broad agreement with

those obtained from previous works. No continuum survey data are available for comparison at $z > 4.5$, since our IR LF is the first at such high redshifts. We can only compare our data with line LFs at those redshifts.

We observe a difference with previous data in the lower redshift bin, 0.5–1.5, where both the *Herschel* and SCUBA-2 LFs are higher at the faint-end and lower at the bright-end, with their knee occurring at slightly fainter L_{IR} . Indeed, the low- L_{IR} discrepancy (i.e., at $< 10^{11.5} L_{\odot}$) with *Herschel* is mostly determined by a single *Herschel* data point below the completeness limit of the ALPINE survey. The *Herschel* data beyond that limit are consistent within the errors with the ALPINE derivation. The SCUBA-2 curve is a low-luminosity extrapolation, if we consider Figure 3 of Koprowski et al. (2017).

The faint-end extrapolation of the *Herschel* and SCUBA-2 LFs are still slightly steeper (and higher) than ours at $1.5 < z < 2.5$, though also at those redshifts the inconsistency is observed mostly below the ALPINE completeness limit, in a range where no *Herschel* (and probably also SCUBA-2, if we judge from the 250- μ m data points in their Figure 3) data are available to constrain the slope.

In the luminosity range $11.5 < \log(L_{\text{IR}}/L_{\odot}) < 12.5$ the agreement between *Herschel* and ALPINE is reasonably good, while at larger luminosities the ALPINE LF seems to remain higher (at least in the two brighter bins). The ALMA LFs from the ASAGAO survey (Hatsukade et al. 2018) agrees within the errors with our derivation (in the common luminosity range, around the knee L^*), at all redshifts (from $z=0.5$ to $z=3.5$).

At $\log(L_{\text{IR}}/L_{\odot}) > 12.5$ the S2CLS LF (Koprowski et al. 2017) shows an even steeper and lower bright-end than the *Herschel* one, although we can compare only to the best-fit curve, with no data values available to check whether the agreement could have been better if we had limited to the luminosity range sampled by the SCUBA-2 data. The discrepancy with the S2CLS LF at the bright-end is observed in all the common redshift bins, up to the $3.5 < z < 4.5$ interval.

On the contrary, the agreement between ALPINE and the *Herschel* LF derivation increases with increasing redshifts, with

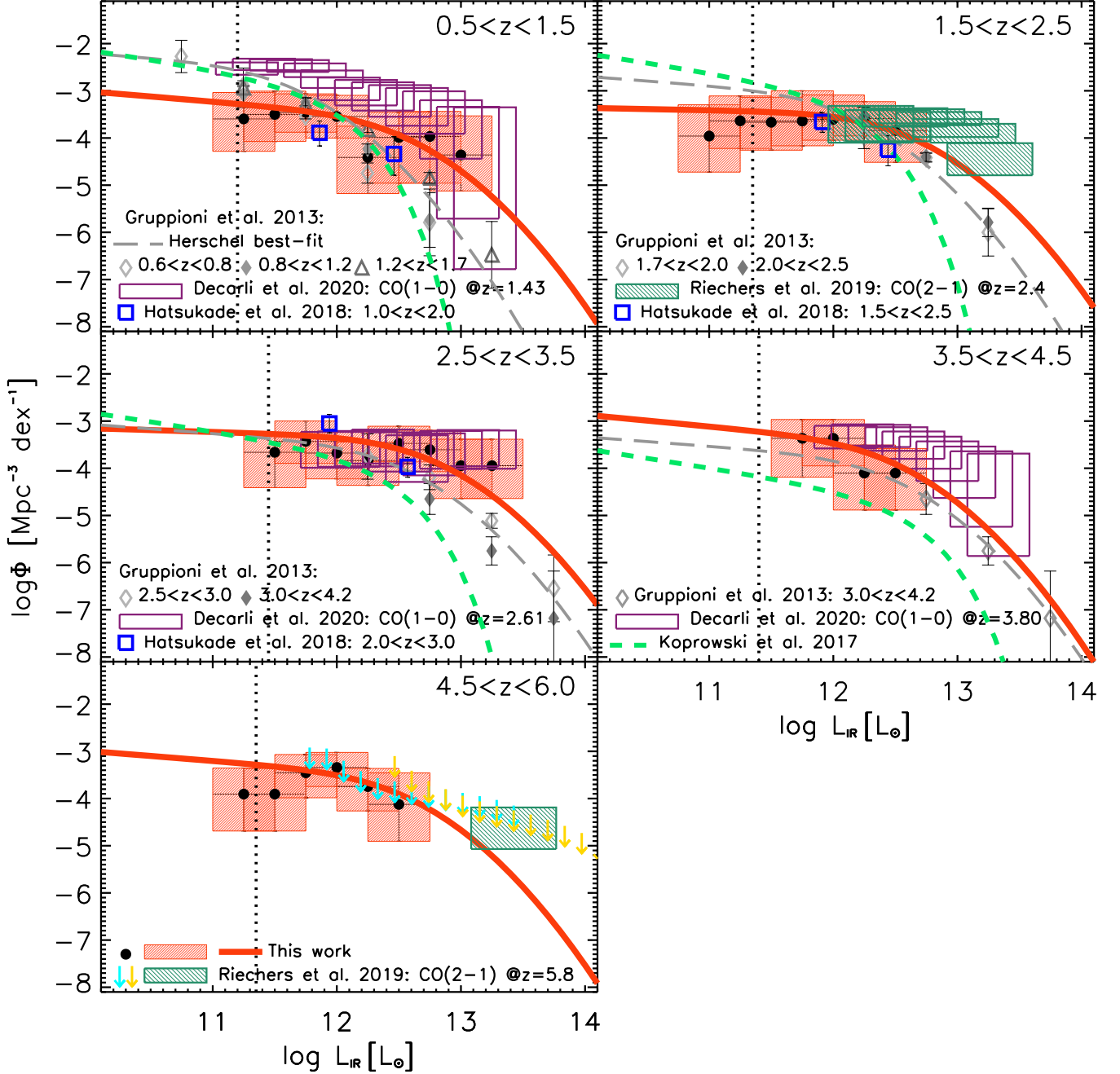


Fig. 8. Total IR Luminosity Function of the ALPINE non-target continuum detections (red boxes and black filled circles). The luminosity bins have a width of 0.5 dex in L_{IR} , and step through the luminosity range in steps of 0.25 dex. For this reason, the individual bins are not statistically independent. The red filled boxes and error-bars indicate the 1σ errors derived through simulations (taking into account the photometric redshifts uncertainties). The red solid curve is the best-fit modified Schechter function derived through the MCMC analysis, while, the grey long-dashed curve represents the best-fit (modified Schechter function) to the *Herschel* PEP+HerMES total IR LF by Gruppioni et al. (2013), interpolated to the redshift bins considered in this work. The *Herschel* PEP+HerMES $1/V_{\text{max}}$ data and error-bars (in slightly different redshift intervals) are plotted as grey symbols. The green short-dashed curves represent the SCUBA-2 S2CLS derivation by Koprowski et al. (2017). The blue open squares show the ALMA ASAGAO LFs by Hatsukade et al. (2018). The dark-green dashed boxes and downward arrows are the COLDz CO(1-0) and CO(2-1) LFs and limits by Riechers et al. (2019) at $z=2.4$ and 5.8 respectively, converted to L_{IR} as described in the text. The vertical dotted line shows the ALPINE continuum survey completeness limit in L_{IR} .

the *Herschel* data being almost complementary in luminosity, but consistent with our data within the errors in most of the common L_{IR} bins. We note that at $2.5 < z < 3.5$ – the redshift range corresponding to the peak of our z -distribution – the ALPINE LF seems to remain slightly higher at the bright-end than the *Herschel* one, while the faint-end is in good agreement with the *Herschel* best-fit extrapolation.

At $3.5 < z < 4.5$ the ALPINE data are totally complementary to the *Herschel* ones, the former covering the faint-end and the latter the bright-end of the LF, in a sort of continuity and agreement between the two derivations. The S2CLS LF, instead, is lower than the ALPINE and *Herschel* ones not only at the bright-end, but also in normalisation, over the whole luminosity range. The underestimation of the bright-end and normalisation of the total

Table 3. ALPINE total IR LF

$\log(L_{\text{IR}}/L_{\odot})$	$\log(\phi/\text{Mpc}^{-3} \text{ dex}^{-1}) [N_{\text{obj}}]$					
	$0.5 < z < 1.5$	$1.5 < z < 2.5$	$2.5 < z < 3.5$	$3.5 < z < 4.5$	$4.5 < z < 6.0$ Excl. [C II] emitters	All
10.75 – 11.25^a		(−3.96^{+0.66}_{−0.76} [1])^b				
<i>11.00 – 11.50</i>	<i>(−3.60^{+0.56}_{−0.68} [2])</i>	<i>(−3.64^{+0.53}_{−0.59} [2])</i>			<i>(−3.91^{+0.55}_{−0.78} [1])</i>	<i>(−3.94^{+0.55}_{−0.78} [1])</i>
11.25 – 11.75	−3.50^{+0.49}_{−0.57} [3]	−3.67^{+0.53}_{−0.59} [2]	(−3.66^{+0.37}_{−0.75} [2])		−3.91^{+0.54}_{−0.78} [1]	−3.91^{+0.54}_{−0.78} [3]
<i>11.50 – 12.00</i>	<i>−3.46^{+0.40}_{−0.42} [4]</i>	<i>−3.64^{+0.64}_{−0.52} [3]</i>	<i>−3.43^{+0.43}_{−0.47} [4]</i>	<i>−3.37^{+0.40}_{−0.82} [2]</i>	<i>−3.45^{+0.39}_{−0.53} [2]</i>	<i>−3.45^{+0.38}_{−0.53} [4]</i>
11.75 – 12.25	−3.54^{+0.45}_{−0.46} [3]	−3.60^{+0.52}_{−0.44} [5]	−3.68^{+0.45}_{−0.55} [4]	−3.37^{+0.40}_{−0.58} [2]	−3.34^{+0.32}_{−0.40} [3]	−3.38^{+0.34}_{−0.48} [3]
<i>12.00 – 12.50</i>	<i>−4.41^{+0.66}_{−0.76} [1]</i>	<i>−3.59^{+0.36}_{−0.37} [7]</i>	<i>−3.84^{+0.39}_{−0.52} [5]</i>	<i>−4.10^{+0.59}_{−0.78} [1]</i>	<i>−3.75^{+0.38}_{−0.52} [2]</i>	<i>−3.79^{+0.41}_{−0.63} [2]</i>
12.25 – 12.75	−3.99^{+0.53}_{−0.97} [2]	−3.84^{+0.42}_{−0.67} [4]	−3.47^{+0.36}_{−0.39} [9]	−4.10^{+0.52}_{−0.78} [1]	−4.12^{+0.67}_{−0.78} [1]	−4.16^{+0.59}_{−0.78} [1]
<i>12.50 – 13.00</i>	<i>−3.97^{+0.53}_{−0.99} [2]</i>		<i>−3.61^{+0.41}_{−0.46} [6]</i>			<i>−3.76^{+0.55}_{−0.78} [1]</i>
12.75 – 13.25	−4.36^{+0.83}_{−0.76} [1]		−3.95^{+0.56}_{−0.69} [2]			−3.63^{+0.43}_{−0.79} [2]
<i>13.00 – 13.50</i>			<i>−3.95^{+0.56}_{−0.69} [2]</i>			<i>−4.21^{+0.55}_{−0.78} [1]</i>

Notes. ^(a) The bold (or alternatively italic) fonts denote independent luminosity bins.

^(b) Values between parentheses correspond to luminosity bins that might be affected by incompleteness due to survey limits.

IR LF by the S2CLS data could be attributed to the method of deriving L_{IR} by Koprowski et al. (2017) and to an incompleteness issue due to the SCUBA-2 data sensitivity, as discussed by Gruppioni & Pozzi (2019).

A bright-end remaining significantly high, even to brighter luminosities than those sampled by our data, is observed also in the CO LFs by Riechers et al. (2019) and Decarli et al. (2019), shown in Figure 8 as dark-green dashed boxes and down-pointing arrows (upper limits), and as empty purple boxes respectively. These CO LFs have been obtained from the blind CO surveys "CO Luminosity Density at High Redshift" (COLDz; Riechers et al. 2019) and Wide "ALMA Spectroscopic Survey in the Hubble Ultra Deep Field" (ASPECS; Decarli et al. 2019) at $z \approx 2.4$, 5.8 and $z = 1.43$, 2.61, 3.80 respectively. In order to allow a direct comparison with our data, the CO luminosities (L'_{CO} , in $\text{K km s}^{-1} \text{ pc}^2$) have been converted to IR luminosities (in L_{\odot}) by following Carilli & Walter (2013) to pass from $L'_{\text{CO}(1-0)}$ to L_{IR} (i.e., $\log L_{\text{IR}} = 1.37 \log L'_{\text{CO}(1-0)} - 1.74$) and Decarli et al. (2016) to convert $L'_{\text{CO}(2-1)}$ to $L'_{\text{CO}(1-0)}$ (i.e., $\log L'_{\text{CO}(1-0)} = \log L'_{\text{CO}(2-1)} - \log(0.76)$). We note that in the common luminosity bins, the COLDz derivation is in very good agreement with our estimate, with the CO LFs extending the high bright-end to even higher luminosities. The ASPECS LF is also in agreement with our estimate, especially at $2.5 < z < 3.5$, while at $3.5 < z < 4.5$ it extends the bright-end to higher luminosities than sampled by our data. At low redshift (i.e., $0.5 < z < 1.5$) it is well consistent with our LF at the bright-end, while it is higher at fainter luminosities (i.e. $< 10^{12} L_{\odot}$). Overall, the good consistency with these completely independent derivations validate the existence of a prominent bright-end in the dusty galaxies LF, so far highly debated in the literature and often attributed to source blending due to low resolution in far-IR/sub-mm data.

4.3.2. Luminosity Function at $z \approx 5$

In the highest redshift bin covered by our survey ($4.5 < z < 6$), we find no comparison data in the IR from the literature, but only constraints from the CO emission (Riechers et al. 2019). The hints provided by our LF in the $z = 4.5 - 6$ redshift range, in good agreement with those by Riechers et al. (2019), are that the volume density of dusty sources continues to remain high (almost as much as at $z \approx 2 - 3$), with no evident drop in normalisation at $z > 2.5 - 3$. The global shape of the LF does not change significantly from low to high redshift. The faint-end of the LF does not show any evident steepening, and the LF knee, though barely constrained by data, seems to fall at bright luminosities, similar to those found at lower redshifts.

In Figure 9 we compare the total IR LF at $4.5 < z < 6$ obtained by excluding the 5 sources found at the same redshift of the ALPINE targets (the same shown in Figure 8: red boxes and black filled circles) to that obtained by including also these galaxies (yellow-dashed boxes and brown open squares). We note that the inclusion of the 5 [C II] emitters does not alter the shape of the LF in the common luminosity range, indeed what happens is that 4 of the 5 sources populate higher luminosity bins, extending the bright-end of the LF to higher L_{IR} . The reason why these sources – associated to the ALPINE central targets? – have luminosities higher than the other sources at similar redshifts is not clear: however, this investigation is beyond the scope of this work and will be treated in a future paper. We have also performed a further check to test the robustness of our result in this redshift bin by recomputing the LF after excluding the sources with more uncertain photo- z , i.e. the two at $z = 5.95$ and 5.98. The result is shown in Figure 9 as cyan-dashed boxes. The luminosity range covered by the LF is smaller, but the normalisation remains the same and also the best-fit curve passes well through the data. We therefore find that even if those two sources

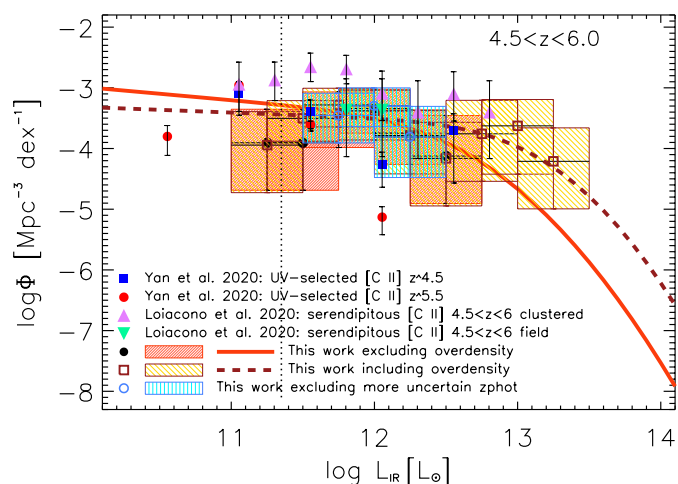


Fig. 9. Total IR Luminosity Function of the ALPINE non-target continuum detections in the redshift interval $4.5 < z < 6$: the results shown in Figure 8 (red boxes and black filled circles, red solid curve) – obtained by excluding the five sources with spectroscopic redshift equal to that of the ALPINE target at the centre of the pointing – are compared to those obtained by including also these objects (yellow boxes and brown open squares). The brown dashed line is the MCMC modified Schechter fit to the latter LF derivation. The cyan dashed boxes show the LF recomputed after excluding the sources with more uncertain photo- z , i.e. the two at $z=5.95$ and 5.98 . This test was performed to check the robustness of our result at these critical redshifts. The error-bars in all the LFs show the 1σ errors obtained by combining the Poissonian errors with those derived with simulations, the latter considering the photometric redshifts uncertainties. The vertical dotted line shows the ALPINE continuum survey completeness limit in this redshift interval. For comparison, we report the ALPINE [C II] $158\ \mu\text{m}$ LFs (converted to total IR LFs as described in the text) at similar redshifts, obtained by Yan et al. (in preparation) for the UV-selected ALPINE targets detected in [C II] ($z \approx 4.5$: blue filled squares, $z \approx 5.5$: red filled circles), and by Loiacono et al. (in preparation) for the serendipitous [C II] detections at $4.5 < z < 6.0$ (lines falling in the same spectral window of the targets, i.e., “clustered”: violet filled triangles; lines separated by that of the targets by $>2000\ \text{km s}^{-1}$, i.e., “field”: green upside-down triangles).

were at a redshift smaller than estimated, our high- z derivation and conclusions would not be affected.

For comparison, in the figure we plot also the [C II] LFs obtained at similar redshifts by Yan et al. (in preparation) for the UV-selected ALPINE targets detected in [C II] ($z \approx 4.5$: blue filled squares, $z \approx 5.5$: red filled circles), and by Loiacono et al. (in preparation) for the serendipitous [C II] detections in the ALPINE pointings (at $4.5 < z < 6.0$). The latter LF is divided in two derivations: one considers the lines in the same ALMA spectral window of the targets (i.e., “clustered”: violet filled triangles), the other the lines spectrally distant from the targets by $>2000\ \text{km s}^{-1}$ (i.e., “field”: green upside-down triangles). To allow the comparison with our continuum data, we have converted the [C II] luminosities ($L_{[\text{C II}]}$) to L_{IR} by following the recipe of Hemmati et al. (2017), i.e., adopting $\log_{10}(L_{\text{FIR}}/L_{[\text{C II}]})=2.69$ (value from Zanella et al. 2018), then a ratio $L_{\text{IR}}/L_{\text{FIR}}(=L_{[8-1000\ \mu\text{m}]} / L_{[42-122\ \mu\text{m}]})=1.3$. The results do not change if we convert $L_{[\text{C II}]}$ to SFR using the De Looze et al. (2014) relation, then the SFR to L_{IR} through the Kennicutt (1998) calibration.

The [C II] LFs of the ALPINE targets (UV-selected; Yan et al. in preparation) at both $z \approx 4.5$ and 5.5 are lower and steeper than our best-fit curve, although the high- L data point at $z \approx 4.5$, at $\log_{10}(L_{\text{IR}}/L_{\odot})=12.5$, rises again, reaching our values. The fact

that the ALPINE targets have been selected in UV-rest frame can explain the steeper bright-end, because the UV selection can miss the dustier sources.

On the other hand, the [C II] LF of the “field” serendipitous detections (Loiacono et al. in preparation) is in perfect agreement with our data. The [C II] LF of the “clustered” serendipitous detections instead is slightly higher than our derivation (though consistent within the uncertainties), especially below our completeness limit. Similarly to our LF obtained by including the 5 sources at the redshift of the ALPINE targets, also the [C II] “clustered” LF extends to higher luminosities than the “field” one. This seems to imply that sources belonging to an overdensity are more luminous than the “field” ones.

4.3.3. Evolution

In order to facilitate the comparison between the LFs at different redshifts, in the *bottom* panel of Figure 10 we plot the total IR LFs at all redshifts with their $\pm 1\sigma$ uncertainty regions (different colours for different z -intervals). The errors are large, therefore it is difficult to detect any significant evolution of the LF with z ; it is however surprising to note that there does not seem to be any appreciable evolution from $z \sim 0.5$ to $z \sim 6$, both in shape and normalisation.

However, we must stress that with ALPINE we are mostly covering the faint-end of the total IR LF over the whole redshift range, with the exception of the $2.5 < z < 3.5$ interval, where we span a slightly larger range of luminosities and we are able to reach also luminosities above the knee. Therefore, the apparent non-evolution of the LF found in this work, is not inconsistent with previous results (i.e., based on *Herschel* data) claiming a strong luminosity evolution up to $z \approx 2-3$ (e.g., Gruppioni et al. 2013), because the evolution in the *Herschel* LFs is observed principally at its bright-end, where ALPINE has limited constraining power.

In the *top* panel of Figure 10 we show only the median value of the LFs in each luminosity bin in all the redshift intervals, each scaled by a factor of 0.5 relatively to the previous one, from the lowest to the highest redshift, in order to facilitate the shape comparison. From the figure we note that in general the LFs at all redshifts seem to present two “bumps”, one at lower and the other at higher luminosities, though at very low significance (i.e., 1.5σ). The two bumps are noticeable in particular where our sample covers the wider range of luminosities, i.e., at $z=0.5-1.5$ and $2.5-3.5$ (dark green and red curves – *top* – and dashed areas – *bottom*). In the lowest redshift bin the bump at brighter luminosities has a lower normalisation than the one peaking at fainter L_{IR} . At $1.5-2.5$ and $3.5-4.5$ our LFs sample only the fainter luminosities (and the fainter bump?), while at $4.5-6$ a sort of double-peaked distribution is observed when we consider all the serendipitous detections (i.e., without excluding the sources at the same redshift of the ALPINE targets; bright green). By comparing the results from the lowest to the highest redshift, the peaks of the two bumps seem to shift towards higher luminosities with increasing z , the higher- L one increasing in normalisation, at least from $z \approx 0.5$ to 3.5 . If the two bumps are real and are due to two different populations, the one responsible for the higher L_{IR} bump will become more dominant with increasing z . We would need more data to confirm these hints: with the current data we can only make speculations.

In general, the ALPINE total IR LFs seem to confirm the “flat” shape already found by *Herschel*, at both its faint- and bright-end. In particular, the bright-end remains significantly high even in the higher redshift interval, where the volume den-

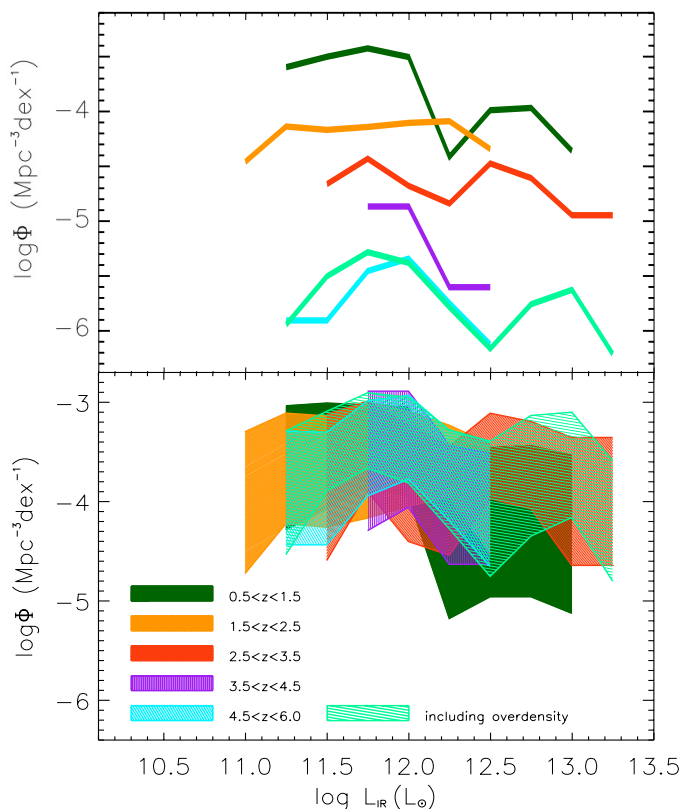


Fig. 10. Total IR Luminosity Function shown in the different panels of Figure 8 plotted in all the different redshift intervals considered in this study, from $z \sim 0.5$ to $z \sim 6$. *Top*: median value of the LFs in each luminosity bin in all the redshift intervals, each scaled by a factor of 0.5 relatively to the previous, from the lowest to the highest redshift. The different colours show the different redshift intervals (same as in the legend in the *bottom* panel). *Bottom*: The different colour-filled areas represent the $\pm 1\sigma$ uncertainty regions at different redshifts obtained from the Monte Carlo simulations. Note that for the highest redshift interval, i.e., $4.5 < z < 6.0$, in both panels the LF is shown for both derivations, obtained by excluding (cyan) and including (green) the sources at the same redshifts of the ALPINE targets.

sity of ultra-/hyper-luminous IR galaxies equals that of more “normal” galaxies. The presence of such (and so many) bright IR galaxies at high- z is a real challenge for galaxy formation models (already at $z \sim 2$ –3, even worse at higher z), with no current model being able to explain the existence of massive, dusty and actively star forming galaxies at such early epochs.

On the other hand, the “flat” faint-end implies a minor contribution from low-luminosity/low-mass galaxies to the dust emission, while a main contribution from high-luminosity/high-mass systems, up to the highest redshifts is required by the bright-end. The increasing number of low-mass systems with increasing redshift predicted by the hierarchical structure formation scenario is not observed in our data. It might however be that low-mass and/or low dust-mass systems become more important/numerous at higher redshifts, but do not produce/heat enough far-IR emission/dust to be detected in far-IR/mm surveys.

In order to study the evolution of the total IR LF and of the SFRD with z , we obtain a parametric estimate of the luminosity function at different redshifts. Although the ALPINE LFs may have a more complex shape (i.e., a double-peaked distribution), for simplicity and to better compare the values of the parameters with previous results, we have assumed a modified-Schechter

Table 4. MCMC best-fitting parameters

z	α	$\log(L^*/L_\odot)$	$\log(\phi^*/\text{Mpc}^{-3}\text{dex}^{-1})$
0.5–1.5	$1.22^{+0.15}_{-0.17}$	$11.95^{+0.41}_{-0.36}$	$-3.44^{+0.24}_{-0.23}$
1.5–2.5	$1.15^{+0.17}_{-0.12}$	$12.01^{+0.36}_{-0.43}$	$-3.45^{+0.18}_{-0.19}$
2.5–3.5	$1.08^{+0.17}_{-0.11}$	$12.12^{+0.20}_{-0.24}$	$-3.32^{+0.14}_{-0.15}$
3.5–4.5	$1.25^{+0.43}_{-0.55}$	$11.90^{+0.65}_{-0.43}$	$-3.43^{+0.49}_{-0.40}$
4.5–6.0	$1.21^{+0.17}_{-0.16}$	$11.94^{+0.66}_{-0.47}$	$-3.40^{+0.43}_{-0.32}$

function (i.e. Saunders et al. 1990), with $\phi(L)$ given by

$$\phi(L) d\log L = \phi^* \left(\frac{L}{L^*}\right)^{1-\alpha} \exp\left[-\frac{1}{2\sigma^2} \log^2\left(1 + \frac{L}{L^*}\right)\right] d\log L, \quad (4)$$

behaving as a power law for $L \ll L^*$ and as a Gaussian in $\log L$ for $L \gg L^*$. The adopted LF parametric shape depends on 4 parameters (α , σ , L^* and ϕ^*), whose best fitting values and uncertainties have been derived using a Monte Carlo Markov Chain (MCMC) procedure. Since the ALPINE data do not sample the bright luminosities, the slope of the bright-end is almost unconstrained: we have therefore fixed the value of σ (the parameter shaping the bright-end slope) to that found for the *Herschel* LFs ($\sigma=0.5$). We have considered flat priors to the other three parameters (α , L^* and ϕ^*), limiting the MCMC exploration to a reasonably wide range of values (i.e., $\log(L^*/L_\odot)$: [10,13], $\log(\phi^*/\text{Mpc}^{-3}\text{dex}^{-1})$: [-2,-5], α : [-1,2]). The result of the MCMC analysis is shown in Figures 8 (red solid curve) and 9 (red solid and brown dashed curves), and presented in Table 4.

5. Contribution to the cosmic SFRD

We derive the evolution of the comoving luminosity density (ρ_{IR}) of the ALPINE continuum non-target sources by integrating the total IR LF in the different redshift bins, from $z \approx 0.5$ –1.5 to $z \approx 4.5$ –6 (i.e., $\rho_{\text{IR}}(z) = \int \phi(\log L_{\text{IR}}, z) L_{\text{IR}} d\log L_{\text{IR}}$). In order to do this, we extrapolate the modified Schechter functions that best reproduce our data down to $\log(L_{\text{IR}}/L_\odot)=8$. If the overall contribution to the IR luminosity density from the AGN components of galaxies is small, ρ_{IR} can be considered as a proxy of the comoving SFRD ($\rho_{\text{SFR}}(z)$), assuming the Kennicutt (1998) relation that connects the SFR and L_{IR} . We cannot reliably decompose our SEDs, since there are not enough data in the mid-/far-IR to separate the AGN from the star formation contribution, however although we cannot exclude the presence of an AGN inside our galaxies, the large majority of the SEDs are best-fitted by star-forming/composite templates. The best-fit templates that reproduce the ALPINE SEDs are similar to those found to reproduce the majority of the *Herschel* PEP+HerMES galaxies at $z \approx 2$ –3 (Gruppioni et al. 2013), whose decomposition and separation into AGN and SF contributions showed a negligible contribution to L_{IR} (<10 per cent) from the AGN, and a SF component dominating the far-IR even in the SEDs reproduced by more powerful AGN templates (see also Lemaux et al. 2014). Since in ALPINE we found very few AGN-dominated templates, we do not expect that contamination related to accretion activity can significantly affect the results in terms of ρ_{SFR} . We therefore use the relation

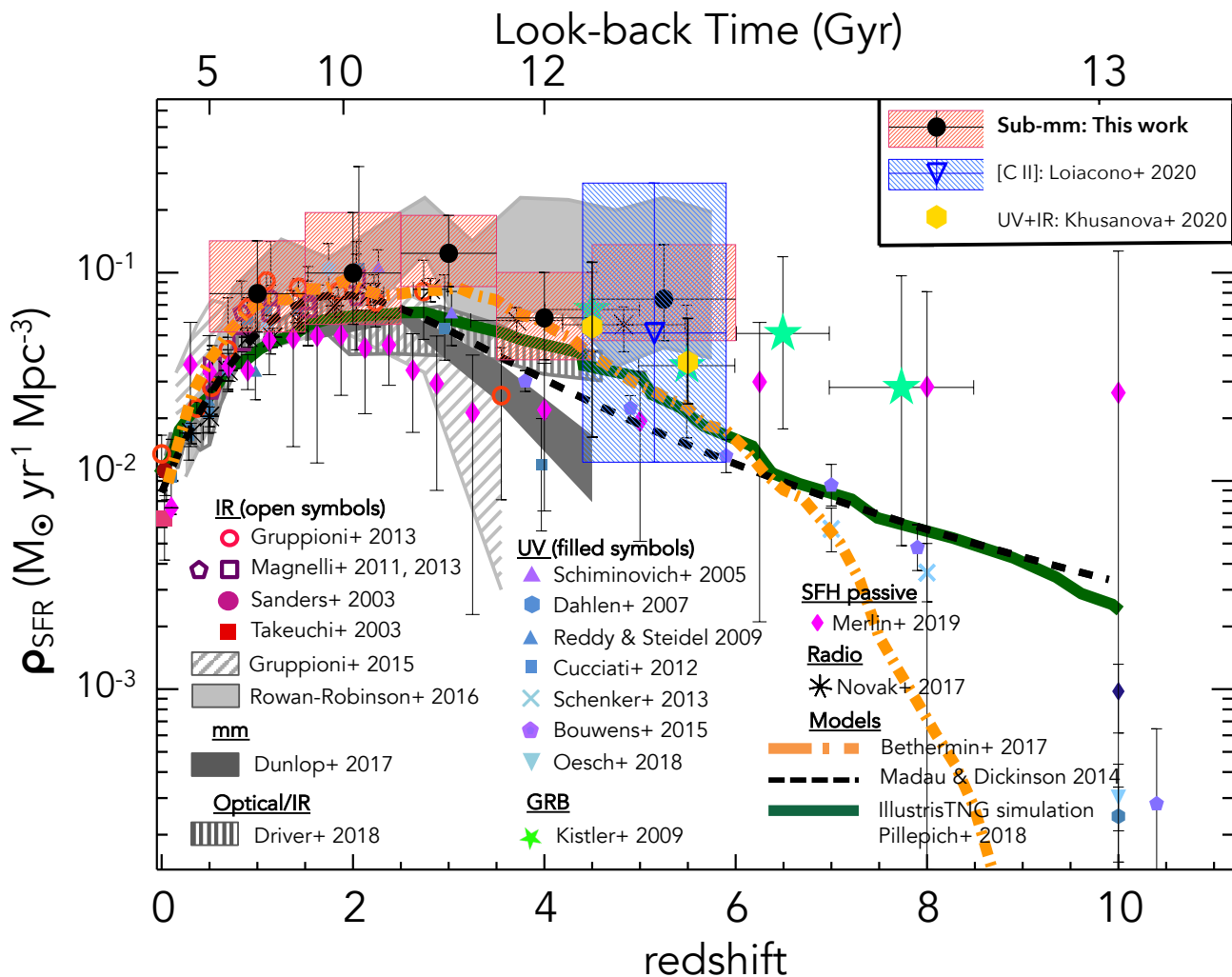


Fig. 11. Redshift evolution of the comoving star formation rate density (ρ_{SFR}), obtained by integrating the modified Schechter function that best reproduces the ALPINE total IR LF of the continuum non-target detections excluding the 5 [C II] emitters (black circles). The error-bars and the red boxes around our data points show the 1σ uncertainty range derived through the MCMC analysis of the LF. The SFRD estimates from ALPINE (legend in the top right corner of the plot) are also shown for comparison: the blue box with blue open square represent the result obtained from the [C II] LF of the serendipitous line emitters by Loiacono et al. (in preparation), while the yellow filled hexagons with error-bars are the values obtained by Khusanova et al. (in preparation) from the UV+IR emission of the ALPINE targets. For comparison, estimates from other surveys (UV: Schiminovich et al. 2005; Dahlen et al. 2007; Reddy & Steidel 2009; Cucciati et al. 2012; Schenker et al. 2013; Bouwens et al. 2015; Oesch et al. 2018; optical/near-IR: Driver et al. 2018; Merlin et al. 2019; far-IR: Sanders et al. 2003; Takeuchi et al. 2003; Magnelli et al. 2011, 2013; Gruppioni et al. 2013, 2015; Rowan-Robinson et al. 2016; mm: Dunlop et al. 2017; radio: Novak et al. 2017; gamma-ray bursts: Kistler et al. 2009) are also shown, as grey shaded areas and open or filled symbols, as described in the legend at the bottom of the plot. The models by Madau & Dickinson (2014) and Béthermin et al. (2017) are shown as black dashed and orange dot-dashed curves respectively, while the prediction of the IllustrisTNG simulation (Pillepich et al. 2018) is shown as dark-green solid curve.

found by Kennicutt (1998) to convert L_{IR} to SFR, then $\rho_{\text{IR}}(z)$ to $\rho_{\text{SFR}}(z)$, for a Chabrier (2003) IMF:

$$\text{SFR}(M_{\odot}\text{yr}^{-1}) \simeq 1.09 \times 10^{-10} L_{\text{IR}}(L_{\odot}) \quad (5)$$

In Figure 11 we show $\rho_{\text{SFR}}(z)$ estimated from our total IR LF (values presented in Table 5) and compare it with results obtained from previous surveys in different bands, from the optical/UV to the radio (see references in the figure legend and caption). Since our lower redshift bin is centred at $z=1$, our comoving SFRD does not show the rapid rise from $z \sim 0$ to $z \sim 1$ observed in other surveys. It shows however a very flat distribution from $z=0.5$ to $z=6$, with no significant decrease beyond the cosmic noon ($z \approx 1-3$), as instead observed from optical/UV surveys. Other SFRD derivation from the ALPINE collaboration are shown for comparison: from the serendipitous [C II] LF (blue box; Loiacono et al. in preparation) and from the UV+IR

SFR of the ALPINE targets (yellow filled hexagons; Khusanova et al., in preparation), highlighted in the top right corner of the plot. The [C II] result agrees well with our $z \approx 5$ value, and also the UV+IR target data are consistent with ours within the uncertainties, though the higher redshift one is slightly lower (possibly due to the UV selection missing highly obscured galaxies).

Our data are in very good agreement also with the far-IR results (from *Spitzer* and *Herschel*) over the common redshift range (e.g., 1–3: Rodighiero et al. 2010; Magnelli et al. 2011, 2013; Gruppioni et al. 2013), and in particular with the sub-mm results of Rowan-Robinson et al. (2016) – highly debated because based on exceptional *Herschel* SPIRE 500- μm galaxies – over the whole redshift range. In addition, we find a good agreement with the results of Kistler et al. (2009) from gamma-ray bursts at $z > 4$, and with the $\rho_{\text{SFR}}(z)$ derived by Novak et al. (2017) from radio surveys at $z \approx 1-5$.

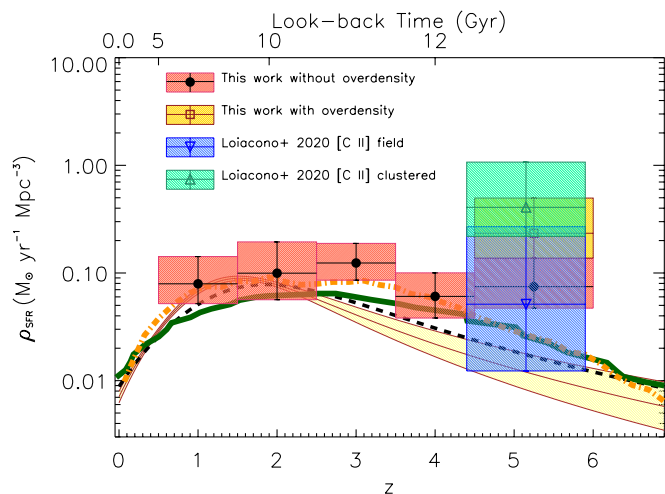


Fig. 12. Comparison between the SFRD obtained by excluding the 5 [C II] emitters (red boxes and black circles, same as in Figure 11) and that estimated by integrating the best-fit curve to the $4.5 < z < 6$ LF obtained from all the continuum detections, including the 5 [C II] emitters (yellow boxes and brown open square). For comparison we report also the results obtained by Loiacono et al. (in preparation) by integrating the [C II] LF of the serendipitous line emitters “field” (i.e., lines separated by that of the ALPINE targets by $>2000 \text{ km s}^{-1}$: blue box and open up-side down triangle) and “clustered” sources (i.e., lines falling in the same spectral window of the ALPINE targets: green box and open triangle). The models by Madau & Dickinson (2014), Béthermin et al. (2017) and Pillepich et al. (2018) are also reported as black dashed, orange dot-dashed and dark-green solid curves respectively. In addition, we plot also the prediction by Maniyar et al. (2018) obtained by modelling the CIB, as light-yellow dashed area.

Table 5. SFRD

z	SFRD	SFRD_min [$M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$]	SFRD_max
0.5–1.5	7.93×10^{-2}	5.19×10^{-2}	1.42×10^{-1}
1.5–2.5	9.96×10^{-2}	5.64×10^{-2}	1.94×10^{-1}
2.5–3.5	1.23×10^{-1}	8.57×10^{-2}	1.88×10^{-1}
3.5–4.5	6.06×10^{-2}	3.82×10^{-2}	1.00×10^{-1}
4.5–6.0	7.46×10^{-2}	4.71×10^{-2}	1.36×10^{-1}

On the other hand, the SFRD derived from optical/UV surveys, although extending to higher redshifts (i.e., $z \approx 10$), are always significantly lower than our estimates at $z > 3$. The difference increases with redshift, becoming about a factor of 10 at $z \sim 6$. When performing this comparison, we must note that, while we integrate the IR LF down to $10^8 L_{\odot}$ (i.e., a SFR of $\approx 10^{-2} M_{\odot} \text{ yr}^{-1}$) to derive the SFRD, the SFRD estimates for UV-selected galaxies are always integrated down to the detection limits of the highest redshift LF (e.g., to a SFR limit of $0.3 M_{\odot} \text{ yr}^{-1}$ at $z=10$; Oesch et al. 2018). This is done because the faint-end slope of the UV LF at high redshift is found to be very steep, leading the UV LF integration to diverge. However, given the very flat faint-end of our IR LF, integrating it to SFR limits similar to those of the UV works would not significantly modify our results.

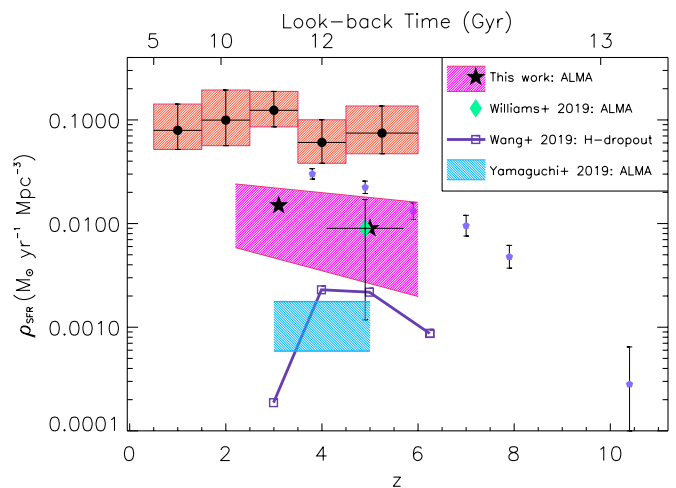


Fig. 13. Contribution of the HST+near-IR dark galaxies to $\rho_{\text{SFR}}(z)$: the derivation from this work (ALMA selection) in two redshift intervals, i.e., 2.2–4.0 and 4.0–6.0, is shown as magenta filled area and black stars, and compared to the derivation by Wang et al. (2019) from H-dropout selection (blue open squares and line), by Yamaguchi et al. (2019) from ASAGAO (turquoise filled area) and by Williams et al. (2019) from ALMA selection (green diamond). The red boxes with black circles and the filled pentagons (the same as in figure 11) represent the obscured and unobscured SFRD, from this work and from Bouwens et al. (2015) respectively.

The models by Madau & Dickinson (2014), Béthermin et al. (2017) and Pillepich et al. (2018) are also reported as black dashed, orange dot-dashed and dark-green solid curves respectively. We can notice that the more recent galaxy formation simulations (e.g., IllustrisTNG, Pillepich et al. 2018) and the model by Béthermin et al. (2017) are consistent with the ALPINE 1σ lower error up to $z \sim 4$ (excluding the $z=3$ bin, where our data are always higher), but significantly lower than the ALPINE $\rho_{\text{SFR}}(z)$ at $z \geq 4$, with the difference becoming a factor of $\geq 5-6$ at $z \sim 6$. In Figure 12, less crowded by data, we report again the three models for a better comparison with our results, and we also add the prediction by Maniyar et al. (2018) obtained by modelling the CIB (light-yellow dashed area). This latter prediction, similarly to the Madau & Dickinson (2014) model, is lower than our data at $z \geq 2.5$.

From the comparison of all the data shown in Figure 11, we can conclude that a significant amount of SF activity at high- z is still missed by surveys sampling the UV rest-frame of galaxy emission. Indeed, all the far-IR/sub-mm and radio estimates agree within the uncertainties in showing an almost constant SFRD distribution from $z \sim 1$ to 6, implying a significant and increasing contribution of dust-obscured activity, which, starting from $z > 3-4$, cannot be recovered by the dust-extinction corrected UV data. A similar discrepancy is observed with the predictions of galaxy formation simulations, that are not able to predict such a high amount of SFR in galaxies as we observe from $z \sim 3-4$ to higher redshifts. As discussed also by Rowan-Robinson et al. (2016), this result implies a significantly earlier start of the epoch of high SFRD than assumed by galaxy formation models and by UV-based works. Therefore, the epoch of major activity in galaxies, corresponding to the rapid heavy element formation, extended at least from redshift 6 to redshift 1, at odds with the predictions of the semi-analytic models for galaxy formation (e.g., Henriques et al. 2015), which set the epoch of intense star-formation at $z \approx 1-2$. Our result strengthens the debated result of Rowan-Robinson et al. (2016), but also the previous conclusion

of Gruppioni et al. (2015), that the semi-analytic models underpredict the high SFRs observed in the *Herschel* galaxies already at $z \gtrsim 1.5$ –2.

5.1. Comparison with the SFRD derived from the ALPINE [C II] LFs

In Figure 12 we compare the SFRD obtained by excluding the 5 [C II] emitters (red boxes and black circles, same as in Figure 11) and that estimated by integrating the best-fit curve to the $4.5 < z < 6$ LF obtained from all the continuum detections, including the 5 [C II] emitters (yellow-dashed boxes and brown open square). The inclusion of the 5 [C II] emitters enhances significantly our SFRD in the highest redshift bin, causing a discontinuity with respect to the SFRD at lower redshifts, due to the overdensity associated to the ALPINE targets to which these sources likely belong. A similar – and even more pronounced effect – is observed with the [C II] SFRD by Loiacono et al. (in preparation, also shown in the Figure for comparison), where the SFRD derived for the detected [C II] lines in the same side-band of the ALPINE targets (i.e., "clustered": green square and open triangle) is about an order of magnitude higher than the SFRD of the [C II] emitters not associated to the targets (i.e., "field": blue square and upside-down triangle). Therefore, we can conclude that by including also the sources detected because associated to the primary targets of the ALMA observation, we would have likely introduced a bias (overestimate) in our SFRD derivations.

5.2. Contribution of the optically and near-IR dark galaxies to the SFRD

In Figure 13 we show the estimated contribution to the SFRD at $z \approx 3$ and 5 from the ALPINE optically+near-IR dark galaxies. Our result, obtained by summing the SFR contribution of the HST+near-IR sources in the two redshift intervals 2.2–4.0 and 4.0–6.0 (i.e., 4 and 3 sources respectively if we exclude the [C II] emitters in the latter bin) is compared to previous estimates from the literature, obtained either through ALMA selection (e.g., Yamaguchi et al. 2019; Williams et al. 2019) or with different techniques (e.g., H-dropouts; Wang et al. 2019). Despite the large uncertainties, our estimates are significantly higher than the SFRD contribution of the HST-dark galaxies selected by Wang et al. (2019) as H-dropouts, and of those selected by Yamaguchi et al. (2019) from the ASAGAO ALMA survey. However, our result is consistent with the estimate based on a single sub-mm galaxy published by Williams et al. (2019): they have $\rho_{\text{IR}}^{\text{HSTdark}}(z \approx 5) \approx 0.9_{-0.7}^{+2.0} \times 10^{-2} \text{ M}_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$, while we find $(1.5 \pm 0.9) \times 10^{-2}$ and $(0.9 \pm 0.7) \times 10^{-2} \text{ M}_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$ at $z \approx 3$ and 5 respectively. From Figure 13 we note that the contribution to the comoving SFRD of the HST+near-IR dark galaxies in ALPINE at $z \approx 5$ is almost equal to the extinction-corrected contribution from all the known ultraviolet-selected galaxies at similar redshifts. This means that the dust-obscured star-formation continues to contribute a significant fraction of the total SFRD also beyond $z > 3$, and at least up to $z \approx 6$, where the available IR and mm estimates are still scanty.

We note however that the contribution at $z \approx 5$ from HST+near-IR dark is only 1/6 of the total (i.e., from all the sources), therefore the bulk of the difference between the corrected-UV and the total SFRD is not due to the dark galaxies, but likely to the dust-correction of the UV samples which is too difficult to estimate from optical data.

The fact that we identified 7 dark galaxies in a survey of 24.9 arcmin^2 implies a source density of about 0.3 arcmin^{-2} , of the same order of that derived by Williams et al. (2019), i.e., 0.13 arcmin^{-2} , about a factor of 4 higher than the density of near-IR dark galaxies in ASAGAO (e.g., 2 sources in 26 arcmin^2 : $\sim 8 \times 10^{-2} \text{ arcmin}^{-2}$; Yamaguchi et al. 2019). At $z > 3$ our dark galaxies have a density of $\sim 0.12 \text{ arcmin}^{-2}$, $\sim 10 \times$ higher than that of $z > 4$ SMGs (1 – $2 \times 10^{-2} \text{ arcmin}^{-2}$; e.g., Danielson et al. 2017; Marrone et al. 2018). Similar densities, i.e., $(0.042 \pm 0.028) \text{ arcmin}^{-2}$, are reported by Riechers et al. (2020) for optically-dark CO emitters at $z > 5$ detected down to an equivalent $870 \mu\text{m}$ flux density of $\sim 5 \text{ mJy}$.

By considering the volumes corresponding to each source in our survey, we derive a space density of HST+near-IR dark galaxies in ALPINE of $\sim (1.3 \pm 0.7) \times 10^{-4}$ and $(6.0 \pm 4.3) \times 10^{-5} \text{ Mpc}^{-3}$ at $z \approx 3$ and 5 respectively. The value found in the highest redshift interval is higher, though consistent within the uncertainties, than the source density of dark galaxies estimated by Williams et al. (2019) at $z \approx 4.1$ –5.7, i.e., $2.9 \times 10^{-5} \text{ Mpc}^{-3}$, and by Riechers et al. (2020) at $z > 5$, i.e., $(1.0 \pm 0.7) \times 10^{-5} \text{ Mpc}^{-3}$.

5.3. Contribution of the optically and near-IR dark galaxies to the stellar mass density

Although the mass estimates for the ALPINE-detected, HST+near-IR dark galaxies are very uncertain (given the paucity of photometric points available), these sources are likely to contribute significantly to the cosmic stellar mass density (SMD or ρ_*) at high redshifts. Indeed, by summing up the volume weighted masses of our dark galaxies, we find that they might represent a fraction of the total SMD (as derived by Davidzon et al. 2017 for the COSMOS15 galaxies) as high as $\sim 20\%$ and $> 50\%$ at $z \approx 3$ and 5 respectively. They could even dominate the high-mass end of the stellar mass function at $z > 3$ (see also Rodighiero et al. 2007). In fact, we find that the number density of the ALPINE dark galaxies with $M^* > 10^{10.8} \text{ M}_{\odot}$ is $\sim (4.2 \pm 3.2) \times 10^{-5} \text{ Mpc}^{-3}$, comparable to that of the more massive quiescent galaxies at $z \gtrsim 3$ –4 (e.g., $\sim 2 \times 10^{-5} \text{ Mpc}^{-3}$; Gobat et al. 2012; Straatman et al. 2014; Song et al. 2016; Glazebrook et al. 2017). The early formation of such a large number of massive, dusty galaxies is not predicted by the current semi-analytical models (e.g., Henriques et al. 2015) and hydrodynamic simulations (e.g., Pillepich et al. 2018), which largely underestimate the density of massive galaxies at high redshifts (see, e.g., Alcalde Pampliega et al. 2019; Wang et al. 2019). Similarly, the galaxy formation models and simulations are also not able to explain the observed large density of IR luminous galaxies at $z > 2$ (e.g., Gruppioni et al. 2015; Rowan-Robinson et al. 2016). The direct implication of these large abundances of massive and IR luminous (dusty) galaxies in the early Universe unexpected by the up-to-date state-of-the-art models is that our current knowledge of the formation and evolution of massive/luminous galaxies is still far from being complete and the relative theories might need important revisions.

In the near future, further investigations of the nature and physical parameters of the HST+near-IR dark galaxies will be necessary to consolidate our results and conclusions. In particular, follow-up studies in the mid-IR (photometry and/or spectroscopy) with the James Webb Space Telescope, and in the sub-mm/mm (continuum and/or spectral-scanning) with ALMA or NOEMA will be the foreseen key.

6. Conclusions

We have used the 56 sources blindly detected in continuum (ALMA Band 7, i.e., at 860 or 1000 μm) within the ALPINE survey, to investigate the nature and evolution of the dusty galaxy population across the redshift range $0.5 \lesssim z \lesssim 6$. In particular, our work can be summarized as follows:

1. we have performed a detailed identification analysis, either by matching the positions of the ALPINE continuum sources with the available multi-wavelength and photo- z catalogues, or by looking for counterparts in the deep photometric images, then performing ad-hoc photometry and deriving photometric redshifts. Seven of the continuum sources showed a faint counterpart only in the mid-IR, with no HST or near-IR matches. Five (2 with no counterparts at all) have been identified with [C II] emitters at $z \sim 5$ (same z of the ALPINE targets at the centre of the pointings).
2. we have completely characterised the multi-wavelength SEDs of the ALPINE non-target sources by performing a detailed SED-fitting analysis and comparison with known template library of IR populations. The SED-fitting analysis provided the main physical parameters of the sources, i.e., L_{IR} , SFR, M^* , galaxy class, k-correction and, if needed, a photo- z estimate. The median redshift of the whole ALPINE non-target, continuum-detected sub-mm galaxy population is $\bar{z} \approx 2.84 \pm 0.16$ (2.66 ± 0.18 if we exclude the 5 sources at the same z of the ALPINE targets), while for the HST and near-IR dark galaxies is $\bar{z}_{\text{dark}} \approx 3.7 \pm 0.6$ (although their z -distribution shows two peaks around $z \sim 3$ and 5). The ALPINE continuum sources on average resulted to be massive galaxies, with stellar masses in the range $10^{10} - 10^{11.5} M_{\odot}$ ($\bar{M}^* \approx 10^{10.5} M_{\odot}$ for the HST+near-IR dark galaxies at $z \sim 3$, $\approx 10^{11.2} M_{\odot}$ at $z \sim 5$).
3. we have computed the rest-frame LFs at 250 μm in different redshift bins, from $0.5 < z < 1.5$ up to $4.5 < z < 6$ and compared it with the *Herschel* and SCUBA-2 LFs at the same wavelength available in the literature. The ALPINE LF is almost complementary to the previous ones, the former mostly sampling the faint-end, the latter the bright-end. In the common redshift and luminosity range, our results are more consistent with the *Herschel* ones.
4. we have integrated the SEDs over $\lambda_{\text{rest}} = 8 - 1000 \mu\text{m}$, computed the total IR LFs in different redshift intervals (from $z \approx 0.5$ up to $z \sim 6$) and studied its evolution with z . Although ALPINE mostly covers the faint-end of the LFs, the global shape appears flat, with a low faint-end slope and a high bright-end, not dropping at bright L_{IR} . There are no signs of a significant decrease in the normalisation nor of a change in shape from $z = 0.5$ to $z = 6$. Our results are in very good agreement with those from CO LFs by Riechers et al. (2019) and Decarli et al. (2016, 2019).
5. we have derived the comoving SFRD over the redshift range $z \approx 0.5 - 6$ and the contribution of HST and near-IR dark galaxies at $z \approx 3$ and 5. The SFRD shows a flat distribution over the whole z -range, with no significant decrease beyond the cosmic noon ($z \approx 1 - 3$). Our result is in agreement with those from previous far-IR and radio surveys, but higher than that found by optical/UV surveys at $z > 3$. The difference with UV results increases with redshift, becoming about a factor of 10 at $z \sim 6$. The HST+near-IR dark galaxies contribute a significant fraction i.e., about (10%) of the total SFRD at high- z . We can conclude that a considerable amount of SF activity at high- z is still missed by surveys sampling the UV rest-frame (most of it not due to dark galaxies), with a significant and

increasing contribution of dust-obscured activity that cannot be recovered even correcting the UV data for dust-extinction. Similarly, the current galaxy formation models and simulations are not able to predict such a high amount of SFR in dusty galaxies as is observed beyond cosmic noon.

6. we have derived the contribution of the ALPINE HST+near-IR dark galaxies to the cosmic mass density, finding in particular that the number density of $M^* > 10^{10.8} M_{\odot}$ dark galaxies is comparable to that of the more massive quiescent galaxies at $z \gtrsim 3$. Given that neither the current semi-analytical models or the more recent hydrodynamic simulations can explain the early formation of such a large number of massive, dusty galaxies, we will need to revise our current understanding of the formation of massive/luminous galaxies.

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