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# Understanding galaxy formation and evolution through an all-sky submillimetre spectroscopic survey

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## Abstract

We illustrate the extraordinary discovery potential for extragalactic astrophysics of a far-infrared/submillimetre (far-IR/submm) all-sky spectroscopic survey with a 3-m-class space telescope. Spectroscopy provides both a 3-dimensional view of the Universe and allows us to take full advantage of the sensitivity of present-day instrumentation, close to fundamental limits, overcoming the spatial confusion that affects broadband far-IR/submm surveys. A space telescope of the 3-m class (which has already been described in recent papers) will detect emission lines powered by star formation in galaxies out to  $z \simeq 8$ . It will specifically provide measurements of spectroscopic redshifts, star-formation rates, dust masses, and metal content for millions of galaxies at the peak epoch of cosmic star formation and of hundreds of them at the epoch of reionization. Many of these star-forming galaxies will be strongly lensed; the brightness amplification and stretching of their sizes will make it possible to investigate (by means of follow-up observations with high-resolution instruments like ALMA, *JWST*, and SKA) their internal structure and dynamics on the scales of giant molecular clouds (40–100 pc). This will provide direct information on the physics driving the evolution of star-forming galaxies. Furthermore, the arc-minute resolution of the telescope at submm wavelengths is ideal for detecting the cores of galaxy proto-clusters, out to the epoch of reionization. Due to the integrated emission of member galaxies, such objects (as well as strongly lensed sources) will dominate at the highest apparent far-IR luminosities. Tens of millions of these galaxy-clusters-in-formation will be detected at  $z \simeq 2$ –3, with a tail extending out to  $z \simeq 7$ , and thousands of detections at  $6 < z < 7$ . Their study will allow us to track the growth of the most massive halos well beyond what is possible with classical cluster surveys (mostly limited to  $z \lesssim 1.5$ –2), tracing the history of star formation in dense environments and teaching us how star formation and galaxy-cluster formation are related across all epochs. The obscured cosmic star-formation-rate density of the Universe will thereby be constrained. Such a survey will overcome the current lack of spectroscopic redshifts of dusty star-forming galaxies and galaxy proto-clusters, representing a quantum leap in far-IR/submm extragalactic astrophysics.

**Keywords:** galaxies: luminosity function – galaxies: evolution – galaxies: clusters: general – galaxies: high-redshift – submillimeter: galaxies

## 1 INTRODUCTION

The L-class space mission proposed by [Delabrouille et al. \(2019\)](#) will have a tremendous impact on our understanding of the Universe and on many branches

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of astrophysics. The project features two instruments at the focus of a 3-m-class, cold (8K) telescope: (i) a broad-band, multi-frequency, polarimetric imager operating over the 20–800 GHz frequency range that would map the cosmic microwave background (CMB) at high sensitivity, as well as the thermal and kinetic Sunyaev-Zeldovich (SZ) effects and the Galactic and extragalactic continuum emissions; and (ii) a moderate spectral resolution ( $R \simeq 300$ ) filter-bank spectrometer covering the 100–1000 GHz band. These two instruments would comprise tens of thousands of millimetre (mm) and submillimetre (submm) detectors cooled to sub-kelvin temperatures for sky-background-limited performance.

A set of Fourier-transform spectrometers (FTSs), covering the full 10–2000 GHz band with spectral resolution ranging from 2.5 to 60 GHz, could also be hosted on the same platform. This instrument would carry out absolute measurements of the CMB spectrum with a sensitivity 4 to 5 orders of magnitude better than *COBE-FIRAS*.

An overview of the scientific goals of the project has been presented by [Delabrouille et al. \(2019\)](#), while other white papers related to the ESA “Voyage 2050”<sup>1</sup> call have elaborated on specific science cases. [Basu et al. \(2019\)](#) dealt with the use of the CMB as a “back-light”, illuminating the entire observable Universe, thus allowing us to obtain a complete census of the total mass, gas, and stellar contents of the Cosmos across time. [Silva et al. \(2019\)](#) looked into the promise of mapping the intensity of the many mm/submm/far-IR lines detectable by the proposed instrument to address several open questions relating to the reionization process, galaxy evolution, the cosmic infrared background, and fundamental cosmology. Additionally, the unique information on the thermal history of the Universe provided by absolute spectral measurements has been highlighted by [Chluba et al. \(2019\)](#).

Here we argue that the high-sensitivity spectroscopic and imaging surveys carried out by this space mission would revolutionize our understanding of galaxy formation and evolution and of the growth of large-scale structure back to the epoch of reionization.

For more than 20 year, surveys at far-infrared (FIR) to submm wavelengths have played a key role in our understanding of early galaxy and active galactic nuclei (AGN) evolution (for reviews see [Lutz, 2014](#); [Casey et al., 2014](#)). The SCUBA discovery of a copious population of submm-bright galaxies ([Smail et al., 1997](#); [Barger et al., 1998](#); [Hughes et al., 1998](#)), shown to be at high redshifts ([Ivison et al., 1998](#); [Barger et al., 1999](#); [Swinbank et al., 2004](#); [Chapman et al., 2005](#); [Pope et al., 2006](#)), strongly challenged the widely accepted pictures of galaxy formation and evolution. In fact, simple merger-driven models dramatically underpredicted the abundance of bright submm galaxies and the cosmic infrared back-

ground (CIB) intensity, using standard assumptions for the stellar initial mass function (IMF) and for the dust temperature distribution (see, e.g., [Kaviani et al., 2003](#); [Baugh et al., 2005](#); [Somerville et al., 2012](#); [Niemi et al., 2012](#); [Gruppioni et al., 2015](#)).

The submm spectral region is exceptionally well suited to provide access to the dust-enshrouded most active star-formation phases of young galaxies in the high- $z$  Universe. This is because, for a large redshift range, submm wavelengths (in the observer’s frame) are in the Rayleigh-Jeans region of the dust emission spectrum, where the flux density scales as  $S_\nu \propto \nu^{2+\beta}$ , the dust emissivity index,  $\beta$ , generally being in the range 1.5–2. The corresponding, so-called “negative  $K$ -correction” largely compensates, and may even slightly exceed, the effect on the flux density of the increase of the luminosity distance ([Franceschini et al., 1991](#); [Blain & Longair, 1993](#)), providing roughly luminosity-limited samples. Thus, dusty star-forming galaxies (DSFGs) can be detected out to  $z \simeq 8$ –10 without the need for extreme sensitivities.

Ground-based observations at submm wavelengths are severely limited by water vapour in the atmosphere, leaving only a few windows even in the driest sites; hence the need for space missions. The *Herschel* observatory surveyed about 1300 deg<sup>2</sup> of the extragalactic sky, primarily thanks to the *Herschel* Astrophysical Terahertz Large Area Survey (H-ATLAS; [Eales et al., 2010](#)), to the *Herschel* Multi-tiered Extragalactic Survey (HerMES; [Oliver et al., 2012](#)) and to the *Herschel* Stripe 82 Survey (HerS; [Viero et al., 2014](#)), which covered 660 deg<sup>2</sup>, 380 deg<sup>2</sup> and 79 deg<sup>2</sup>, respectively.

The *Herschel* surveys with the Spectral and Photometric Imaging Receiver (SPIRE), operating at 250, 350 and 500  $\mu\text{m}$ , were confusion limited at rms values of 5.8, 6.3, and 6.8 mJy beam<sup>-1</sup>, respectively ([Nguyen et al., 2010](#)). Source confusion does not allow us to take full advantage of the sensitivity (which is close to fundamental limits) of present-day detectors. The problem can be overcome using larger telescopes, thereby providing better angular resolution, but this implies higher costs and limits on the total area that can be surveyed.

An interesting alternative is offered by spectroscopy. Adding the third dimension essentially removes the confusion problem. The reason for this is clear – moderate resolution spectroscopy with, say,  $R \equiv \nu/\Delta\nu = 300$ , apportions sources detected with broadband photometry with, e.g.,  $\Delta\nu/\nu = 0.3$  to 100 almost equally populated narrow redshift bins, each with much lower, generally negligible, confusion noise. Precisely how to most efficiently disentangle the spectra of sources from spatially-confused (but spectrally unconfused) data cubes remains an open research question (see discussion in appendix E.1 of [Meixner et al., 2019](#)), but it is clear that in principle the information is there to extract.

The relatively large beam sizes of submm telescopes have another serious drawback: the difficulty in identify-

<sup>1</sup>Call by ESA in order to prepare the long-term plan of the ESA science program.

ing multi-frequency counterparts to measure their spectroscopic redshifts. High- $z$  dusty star-forming galaxies (DSFGs) are generally very faint at other wavelengths, such as in the optical or near-IR that do not benefit from the negative  $K$ -correction (e.g., Dannerbauer et al., 2002, 2004; Pope et al., 2005; Dannerbauer et al., 2008; Dunlop et al., 2004; Younger et al., 2007; Walter et al., 2012). The surface densities of faint optical/near-IR sources are very high, making the identification of the correct counterpart difficult. Deep radio observations help a lot in this respect (e.g., Ivison et al., 2002; Dannerbauer et al., 2004; Biggs et al., 2010). Acquiring spectroscopic redshifts through follow-up studies with mm/submm telescopes is a time-consuming process, impractical for very large galaxy samples. Although FIR/submm surveys have discovered tens of thousands of distant DSFGs, the number of measured spectroscopic redshifts is still not more than a few hundreds (e.g., Casey et al., 2012a,b; Bothwell et al., 2013; Weiß et al., 2013; Danielson et al., 2017; Fudamoto et al., 2017; Zhang et al., 2018a; Neri et al., 2020). Thus, only coarse FIR-photometric redshift estimates are generally possible for samples of several hundred to thousands of high- $z$  IR-luminous objects.

A moderate spectral resolution ( $R \simeq 300$ ) filter-bank spectrometer at the focus of a 3-m-class telescope will yield exciting results in several areas. For definiteness we consider a cold (8 K) telescope with a 3.5-m aperture primary (the same size as *Herschel*) with a secondary mirror and cold stop at 4 K and 20 dB edge taper, as proposed by Delabrouille et al. (2019).

This instrument would deliver unique results in many branches of astrophysics. Here we will specifically discuss its potential for:

- investigating the physical processes driving the assembly of galaxies and exploring the evolution of their metal and dust content out to  $z \simeq 8$ ;
- measuring the early growth (to  $z \simeq 7$ ) of large-scale structures (i.e., galaxy proto-clusters), when their member galaxies were actively star forming, and when the hot gas, making them detectable in X-rays or via the SZ effect, was not necessarily in place yet.

The plan of the paper is the following. In Sect. 2 we give the  $5\sigma$  line-detection limits of the proposed instrument and the corresponding minimum star-formation rate (SFR), as a function of redshift, detectable in lines for the average relationship between line luminosity and SFR. In Sect. 3 we briefly describe our reference model and present predictions of the redshift distributions of galaxies detected in lines and of the cumulative SFR functions at various redshifts, out to  $z \simeq 8$ . In Sects. 4 and 5 we highlight examples of the new science enabled by these data on strongly gravitationally lensed and unlensed galaxies. In Sect. 6 we compare the proposed survey with those of other forthcoming or planned instru-

ments. Section 7 discusses the potential of this project for reconstructing the full history of the most massive virialized structures in the Universe, namely galaxy clusters. Section 8 presents a comparison with cluster surveys in other wavebands. Finally, Sect. 9 summarizes our main conclusions.

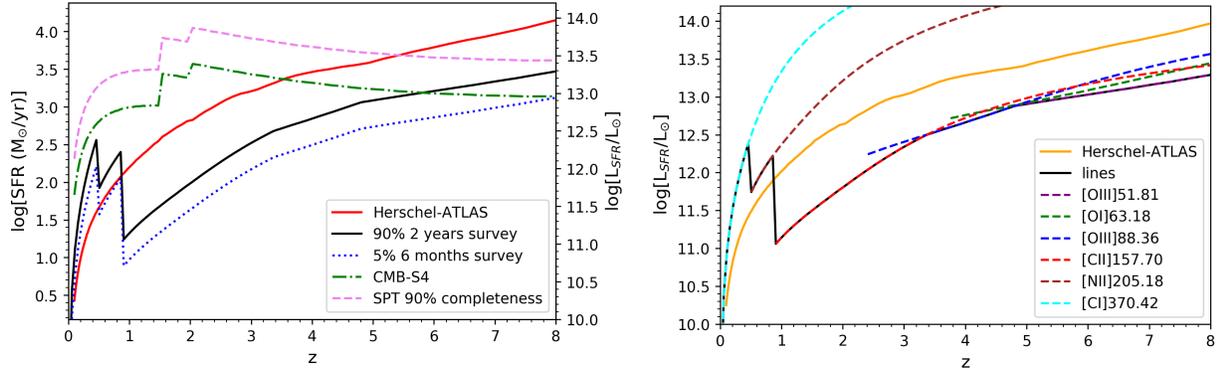
We adopt a flat  $\Lambda$ CDM cosmology with the latest values of the parameters derived from Planck CMB power spectra:  $H_0 = 67.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ; and  $\Omega_m = 0.315$  (Planck Collaboration VI, 2018).

## 2 LINE-DETECTION LIMITS

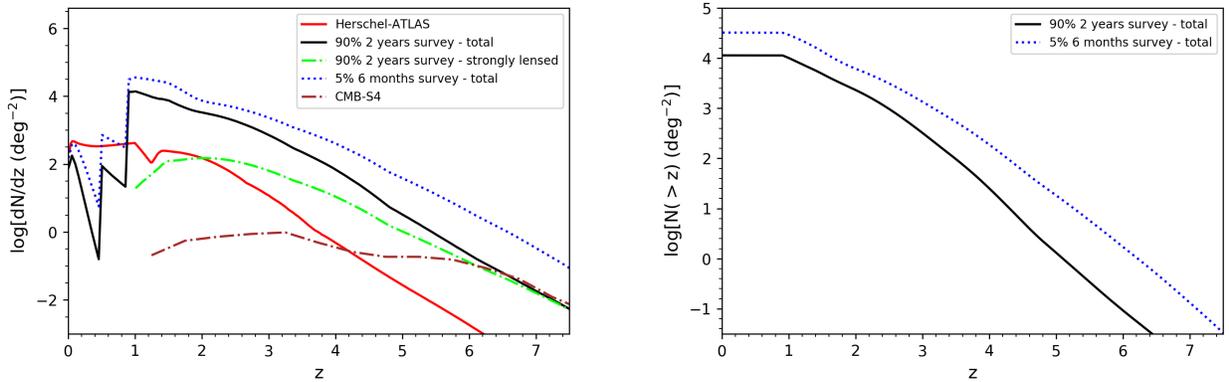
Table 1 shows the estimated sensitivity and the  $5\sigma$  point source and line-detection limits at a set of frequencies for a 2-year survey of 90% of the sky with 64 polarized channelizers, covering the frequency range 100–1000 GHz with  $R = 300$ , using close to background limited MKID detectors (we assume a conservative 30% optical efficiency, and instrumental noise matching the sky background noise). A 6-month duration survey of 5% sky is also being considered; it goes deeper by a factor of approximately  $\sqrt{5}$ .

Exploiting observations, mostly from *Spitzer* and *Herschel*, Bonato et al. (2019) reported tight correlations between the main mid-IR-to-submm lines from neutral or ionized atomic gas and from molecular gas and the total IR luminosity,  $L_{\text{IR}}$  (conventionally defined over 8–1000  $\mu\text{m}$ ), of dust heated by newly formed stars. The brightest lines detectable in the frequency range considered here are [NII] 205.18  $\mu\text{m}$ , [C I] 170.42  $\mu\text{m}$ , [C II] 157.7  $\mu\text{m}$ , [O III] 88.36  $\mu\text{m}$ , [O I] 63.18  $\mu\text{m}$  and [O III] 51.81  $\mu\text{m}$ .

The line- $L_{\text{IR}}$  relations obtained by Bonato et al. (2019) are based on observations of dusty galaxies, for which the unabsorbed fraction of the emission from young stars is small, so that  $L_{\text{IR}}$  is a measure of the total SFR. One might wonder whether the line luminosities are primarily related to  $L_{\text{IR}}$  or to the SFR and an answer was provided by De Looze et al. (2014). For their sample of low-metallicity galaxies with moderate dust emission they found that [O III] 88.36  $\mu\text{m}$  and [O I] 63.18  $\mu\text{m}$  are good probes of the SFR measured through a composite tracer (*GALEX* FUV + *Spitzer*-MIPS 24  $\mu\text{m}$  luminosity). The case is less clear for [C II] 157.7  $\mu\text{m}$ ; however, the [C II] emission in star-forming galaxies primarily arises from photo-dissociation regions (PDRs; Stacey et al., 2010), although it can also come from the partly ionized interstellar medium (e.g., Sutter, 2019). Since PDRs are heated by the UV radiation emitted by young stars, [C II] has also been used as a measure of the SFR (e.g., Carniani et al., 2018). The [C II] luminosities of the  $z \simeq 6.8$  galaxies without detected FIR emission, observed by Smit et al. (2018) were found to be good SFR estimators. Schaerer et al. (2020) reported no or weak evolution of the [C II]–SFR relation over the last 13 Gyr,



**Figure 1.** *Left:* Minimum SFR as a function of redshift, for galaxies detected in lines in the 100–1000 GHz range in an “all-sky” survey (2 years, 90% of the sky, solid black line) and for a deep survey 6-months duration over 5% of the sky (dotted blue line); see text for details. The scale on the right refers to the bolometric luminosity due to star formation,  $L_{\text{SFR}}$ , based on the calibration by Kennicutt & Evans (2012). The solid red line, the green dot-dashed line, and the magenta dashed line show, for comparison, the IR (8–1000  $\mu\text{m}$ ) luminosity,  $L_{\text{IR}}$ , corresponding to the  $4\sigma$  detection limits (approximately 90% completeness) of the H-ATLAS survey covering 660  $\text{deg}^2$ , to confusion limit of the CMB-S4 survey at 220 GHz expected to cover 43% of the sky (5 mJy; Abazajian et al., 2019), and to the 90% completeness limit (15 mJy) of the South Pole Telescope (SPT; Mocanu et al., 2013) survey covering 2,500  $\text{deg}^2$ , respectively. Here  $L_{\text{IR}}$  is a measure of the dust-obscured SFR. *Right:* Minimum  $L_{\text{SFR}}$  (or SFR) corresponding to the  $5\sigma$  detection limits of the brightest IR/submm lines over the 100–1000 GHz range, for the “all-sky” survey.



**Figure 2.** *Left:* Predicted differential redshift distributions of galaxies detected in at least one line by the “all-sky” survey (2 yr, 90% of the sky, with the solid black line being the total and the dot-dashed green line being for strongly lensed galaxies) and by the “deep” survey (6 months, 5% of the sky, with the dotted blue line showing the total distribution). For comparison the solid red line shows the estimated redshift distribution of galaxies detected by the H-ATLAS survey over 660  $\text{deg}^2$  above the  $4\sigma$  limit in at least one SPIRE channel, based on the Cai et al. (2013) model. The dot-dashed brown line shows the predicted redshift distribution at the confusion limit of the CMB-S4 survey (with an expected sky coverage of 43%), derived from the cumulative distribution in figure 26 of the CMB-S4 Science Case paper (Abazajian et al., 2019). *Right:* Total cumulative redshift distributions for the “all-sky” and for the “deep” survey (solid black line and dotted blue lines, respectively).

**Table 1** Sensitivity in temperature,  $\Delta T$  (in units of temperature times square root of solid angle), point source detection limits,  $S_{\text{lim}}$ , and line-detection limits,  $\log(F_{\text{lim}})$ , at selected frequencies,  $\nu$ , (or wavelengths  $\lambda$ ) for a 2-yr survey of 90% of the sky with the instrument described in the text. Both  $S_{\text{lim}}$  and  $F_{\text{lim}}$  are at the  $5\sigma$  significance level. The angular resolution of the instrument, measured by the FWHM (full-width at half maximum of the beam) at each frequency, is at the diffraction limit.

$\nu$ [GHz]	$\lambda$ [mm]	FWHM [arcmin]	$\Delta T$ [ $\mu\text{K}\cdot\text{arcmin}$ ]	$S_{\text{lim}}$ [mJy]	$\log(F_{\text{lim}})$ [ $\text{W m}^{-2}$ ]
100	2.998	3.80	58.70	30.87	-18.988
120	2.498	3.17	51.86	32.73	-18.883
140	2.141	2.72	45.76	33.69	-18.803
160	1.874	2.38	40.38	33.98	-18.742
180	1.666	2.11	35.51	33.61	-18.695
200	1.499	1.90	31.18	32.80	-18.660
220	1.363	1.73	27.33	31.62	-18.635
240	1.249	1.58	23.91	30.18	-18.617
260	1.153	1.46	20.88	28.55	-18.607
280	1.071	1.36	18.23	26.84	-18.601
300	0.999	1.27	15.89	25.07	-18.601
320	0.937	1.19	13.81	23.24	-18.606
340	0.882	1.12	12.02	21.49	-18.613
360	0.833	1.06	10.47	19.82	-18.624
380	0.789	1.00	9.10	18.18	-18.638
400	0.749	0.95	7.94	16.71	-18.652
420	0.714	0.91	6.91	15.27	-18.670
440	0.681	0.86	6.05	14.01	-18.687
460	0.652	0.83	5.30	12.81	-18.707
480	0.625	0.79	4.67	11.78	-18.725
500	0.600	0.76	4.11	10.82	-18.744
520	0.577	0.73	3.66	10.00	-18.761
540	0.555	0.70	3.26	9.27	-18.778
560	0.535	0.68	2.93	8.63	-18.793
580	0.517	0.66	2.65	8.09	-18.806
600	0.500	0.63	2.42	7.64	-18.816
620	0.484	0.61	2.22	7.24	-18.825
640	0.468	0.59	2.06	6.92	-18.831
660	0.454	0.58	1.92	6.67	-18.833
680	0.441	0.56	1.80	6.43	-18.836
700	0.428	0.54	1.70	6.25	-18.836
720	0.416	0.53	1.62	6.12	-18.833
740	0.405	0.51	1.54	6.00	-18.830
760	0.394	0.50	1.47	5.88	-18.827
780	0.384	0.49	1.42	5.83	-18.819
800	0.375	0.48	1.37	5.77	-18.813
820	0.366	0.46	1.33	5.72	-18.806
840	0.357	0.45	1.29	5.68	-18.798
860	0.349	0.44	1.25	5.66	-18.790
880	0.341	0.43	1.22	5.65	-18.781
900	0.333	0.42	1.19	5.63	-18.772
920	0.326	0.41	1.16	5.63	-18.763
940	0.319	0.40	1.14	5.62	-18.754
960	0.312	0.40	1.11	5.63	-18.744
980	0.306	0.39	1.09	5.63	-18.735
1000	0.300	0.38	1.07	5.64	-18.726

i.e. up to  $z \sim 8$ .

Based on these results, following [Bonato et al. \(2019\)](#) we assume that the luminosity of FIR fine-structure lines primarily correlates with the SFR. Thus, the relations derived by [Bonato et al. \(2019\)](#) allow us to estimate the values of SFR as a function of  $z$  corresponding to the  $5\sigma$  line-detection limits listed in [Table 1](#). The results are shown in [Fig. 1](#), where the solid black line refers to the survey of 90% of the sky (the ‘‘all-sky’’ survey), while the dotted blue line refers to the deep survey of 5% of the sky. At each redshift we have computed the minimum SFR detectable in the various lines and taken the smallest one.

Our calculations assume that the lines are unresolved at  $R = 300$ , corresponding to line widths of  $1,000 \text{ km s}^{-1}$ . This is almost always the case for individual galaxies. The spectroscopy of 15 H-ATLAS galaxies at  $2.08 < z < 4.05$  obtained by [Neri et al. \(2020\)](#) with the IRAM NOrthern Extended Millimeter Array (NOEMA) yielded line widths (FWHM) between 150 and  $1100 \text{ km s}^{-1}$  (mean  $700 \pm 300 \text{ km s}^{-1}$ , median  $800 \text{ km s}^{-1}$ ). The [CII]  $157.7 \mu\text{m}$  observations by [Gullberg et al. \(2015\)](#) of 16 spectrally resolved strongly lensed star-forming galaxies at  $3.0 < z < 5.7$  yielded line FWHMs ranging from  $198 \pm 34$  to  $800 \pm 200 \text{ km s}^{-1}$  with a median of  $\simeq 541 \pm 110 \text{ km s}^{-1}$ . [Nesvadba et al. \(2019\)](#) measured the FWHMs of the [OI]  $370.42 \mu\text{m}$  and  $609.14 \mu\text{m}$  lines in the range from  $220 \pm 21$  to  $639 \pm 100 \text{ km s}^{-1}$  (median  $475 \text{ km s}^{-1}$ ) for 11 strongly lensed submm galaxies detected by *Planck*. Similar values (from  $220 \pm 50$  to  $770 \pm 80 \text{ km s}^{-1}$ , median  $370 \text{ km s}^{-1}$ ) were measured by [Cooke et al. \(2018\)](#) for 10 serendipitous [CII]  $157.7 \mu\text{m}$  emitters at  $z \sim 4.5$ .

A somewhat lower median FWHM ( $252 \text{ km s}^{-1}$ ) was reported by [Bethérmin et al. \(2020\)](#) for 75 ALPINE-ALMA large program targets at  $4.4 < z < 5.9$ , detected in the [CII]  $157.7 \mu\text{m}$  line. These targets have substantially lower SFRs than the strongly lensed galaxies observed by [Gullberg et al. \(2015\)](#) and [Nesvadba et al. \(2019\)](#). A result close to that by [Bethérmin et al. \(2020\)](#) was found by [Fujimoto et al. \(2019\)](#) for a sample of 18 galaxies at a higher mean redshift ( $5.153 \leq z \leq 7.142$ ): the weighted average FWHM of the [CII]  $157.7 \mu\text{m}$  line for their sample is  $270 \text{ km s}^{-1}$ .

At still higher redshifts, [Tamura et al. \(2019\)](#) and [Hashimoto et al. \(2018\)](#) reported lower FWHMs of the [OIII]  $88.36 \mu\text{m}$  line for galaxies at  $z = 8.31$  ( $141 \pm 21 \text{ km s}^{-1}$ ) and at  $z = 9.11$  ( $154 \pm 39 \text{ km s}^{-1}$ ), respectively. An even lower line width ( $\simeq 43 \text{ km s}^{-1}$ ) was derived by [Laporte et al. \(2017\)](#) for a galaxy at  $z = 8.38$ .

Thus, for ultraluminous submm galaxies the signal dilution due to the modest spectral resolution of the instrument is moderate, up to  $z \simeq 5\text{--}6$ , while it is stronger at higher  $z$  and at lower luminosities.

The information on the velocity dispersion of galaxies

in high- $z$  proto-cluster *cores* of submm galaxies is still very limited. Hill et al. (2020) estimated a line-of-sight velocity dispersion  $\sigma_r = 376 \pm 68 \text{ km s}^{-1}$  for the  $z = 4.3$  proto-cluster core discovered by Miller et al. (2018). Oteo et al. (2018) found a substantially higher  $\sigma_r$  ( $794 \pm 68 \text{ km s}^{-1}$ ) for their  $z = 4.0$  proto-cluster core. However, they argued that the detected galaxies actually belong to two groups, each with a much lower  $\sigma_r$ . Venemans et al. (2007) measured velocity dispersions of forming clusters of galaxies near powerful radio galaxies at  $2.0 < z < 5.2$ . They found that  $\sigma_r$  increases from  $\sim 300 \text{ km s}^{-1}$  at  $z > 4$  to  $500\text{--}700 \text{ km s}^{-1}$  at  $z \sim 3$ . In the two lowest redshift fields ( $z = 2.86$  and  $z = 2.16$ ) the velocity distribution is bimodal, indicating the presence of subgroups with  $\sigma_r = 200\text{--}500 \text{ km s}^{-1}$ . This shows that, on one side, the lines from the spatially unresolved cluster cores are spectrally unresolved except at the lowest redshifts and, on the other hand, that the signal dilution is expected to be from moderate to low.

The results for the brightest lines are shown in the right-hand panel of Fig. 1. The best lines are [C I]  $170.42 \mu\text{m}$  for  $z \lesssim 0.5$ , [N II]  $205.18 \mu\text{m}$  for  $0.5 \lesssim z \lesssim 0.9$ , [C II]  $157.7 \mu\text{m}$  for  $0.9 \lesssim z \lesssim 3.4$ , [O III]  $88.36 \mu\text{m}$  for  $3.4 \lesssim z \lesssim 4.8$  and [O III]  $51.81 \mu\text{m}$  for  $z \gtrsim 4.8$ .

The right-hand panel of Fig. 1 shows that the detection limits for [C II]  $157.7 \mu\text{m}$ , [O III]  $88.36 \mu\text{m}$ , [O I]  $63.18 \mu\text{m}$ , and [O III]  $51.81 \mu\text{m}$  correspond to values of SFR that are quite close to each other. Hence a substantial fraction of galaxies will be detected both in the [C II]  $157.7 \mu\text{m}$  and [O III]  $88.36 \mu\text{m}$  lines for  $z \gtrsim 2.4$  (when the second line shows up at  $\nu < 1000 \text{ GHz}$ ). The [O I]  $63.18 \mu\text{m}$  and [O III]  $51.81 \mu\text{m}$  lines come in at  $z \geq 3.7$  and  $z \geq 4.8$ , respectively.

For comparison, the solid red line in the left-hand panel of Fig. 1 also shows the minimum  $L_{\text{IR}}$ , or the minimum dust-enshrouded SFR, among those corresponding to the  $4\sigma$  detection limits of the H-ATLAS survey (the largest extragalactic survey with *Herschel*, having sensitivities of 29.4, 37.4, and 40.6 mJy at 250, 350, and 500  $\mu\text{m}$ , respectively; Valiante et al., 2016). The monochromatic luminosities corresponding to these detection limits have been converted to  $L_{\text{IR}}$  using the spectral energy distributions (SEDs) adopted by Cai et al. (2013). More precisely, for  $z < 1.5$  we have used the “warm” (starburst) SED and at  $z > 2$  the “proto-spheroidal” SED; at intermediate redshifts we considered both SEDs and chose the more favourable one, i.e., the one yielding the lower  $L_{\text{IR}}$ . Since the submm continuum measures only the light re-emitted by dust, while the fine-structure lines measure the total SFR, the comparison of the two measurements, both made by the proposed instrument, provides information on the effective optical depths of galaxies.

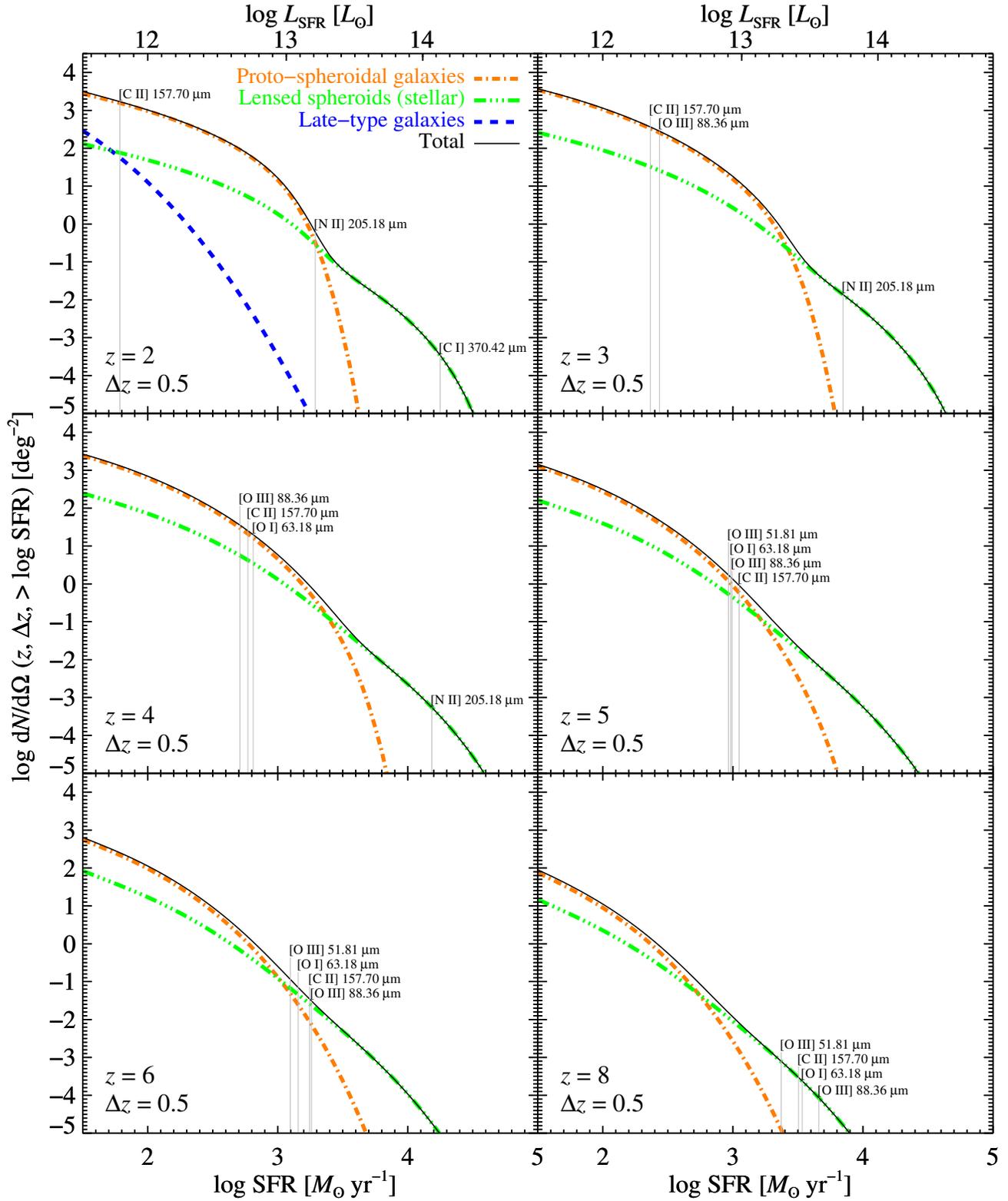
### 3 SFR FUNCTIONS AND REDSHIFT DISTRIBUTIONS

To investigate quantitatively the discovery potential of the proposed spectroscopic survey, the relationships between line luminosity and SFR need to be coupled with a model for the redshift-dependent SFR function. We adopted the physically grounded model by Cai et al. (2013). This model is built on the consideration that, in the local Universe, spheroids (i.e., ellipticals and bulges of disk galaxies) are mostly inhabited by old stellar populations (formation redshifts  $z \gtrsim 1\text{--}1.5$ ), while the populations of disk galaxies are generally younger, with luminosity-weighted ages mostly  $\lesssim 7 \text{ Gyr}$  (cf., e.g., Bernardi et al., 2010), corresponding to formation redshifts  $z \lesssim 1$ . Thus, spheroid progenitors (referred to as proto-spheroids or proto-spheroidal galaxies) are the dominant star-forming population at  $z \gtrsim 1.5$ , whereas most of the star formation at  $z \lesssim 1.5$  occurs in disks.

These different evolutionary histories are dealt with adopting a “hybrid” approach. The model provides a physically grounded description of the redshift-dependent co-evolution of the SFR of proto-spheroidal galaxies and of the active nuclei at their centers, while the description of the evolution of late-type galaxies and of AGN associated with them is phenomenological and parametric.

The calculation of the evolving SFR function of proto-spheroids hinges upon the halo formation rate as a function of redshift,  $z$ , and of halo mass,  $M_{\text{H}}$ , provided by large-scale  $N$ -body simulations. The analytical approximation of the halo mass function,  $N(M_{\text{H}}, z)$ , derived by Sheth & Tormen (1999) was used. The positive term of its time derivative was adopted as a good approximation of the halo formation rate. High resolution  $N$ -body simulations (e.g., Wang et al., 2011) showed that, after a fast collapse phase, including major mergers, the halo growth (mostly by minor mergers and diffuse accretion) mainly affects the halo outskirts and has little impact on the inner potential well where the visible galaxy resides. Based on these results, the model assumes that the main drivers of star formation and AGN growth are in-situ processes. The star-formation history of proto-spheroids is computed by solving a set of equations describing the evolution of gas phases and of the active nucleus, including cooling, condensation into stars, radiation drag, accretion, and feedback from supernovae and from the AGN.

Solving these equations, we obtain the SFR of each galaxy and the bolometric luminosity of the AGN as a function of halo mass, formation redshift, and galactic age. Coupling the SFR( $M_{\text{H}}, z$ ) with the halo formation rate we get the SFR function of proto-spheroids at any redshift. As for late-type galaxies, Cai et al. (2013) adopted a phenomenological evolutionary model, with different parameters for starburst and “normal”



**Figure 3.** Cumulative SFR functions of galaxies within  $\delta z = 0.5$  derived from the Cai et al. (2013) model at redshifts from 2 to 8. The vertical lines show the SFRs corresponding to the  $5\sigma$  line-detection limits of the brightest lines.

disk galaxies. The global (proto-spheroids plus late-type galaxies) SFR functions yielded by the model are in excellent agreement with observational determinations obtained combining information from far-IR/submm, UV and Ly  $\alpha$  surveys (Cai et al., 2014; Mancuso et al., 2015). Therefore, the results based on them are essentially model independent.

Figures 2 and 3 show that the spectroscopic survey will allow us to extend the study of the global star-formation history and the build-up of metals and dust all the way through the epoch of reionization. The survey will detect thousands of star-forming galaxies at  $z \simeq 6$  and several tens at  $z \simeq 8$ . Note that the predicted abundances of high- $z$  galaxies reported in these figures may be underestimated if the stellar initial mass function (IMF) becomes more top-heavy (i.e., has a larger fraction of massive stars compared to standard IMFs) at high- $z$ , as suggested by theoretical arguments (e.g., Papadopoulos et al., 2011) and indicated by some observational evidence (Zhang et al., 2018b). A more top-heavy IMF would yield higher surface densities of ultra-luminous high- $z$  galaxies. An excess of  $z \gtrsim 4$  dusty galaxies over model expectations has been reported, but the issue is controversial (see Cai et al., 2020, for a recent discussion and references).

The excellent sensitivity of the instrument, the high luminosity of the [C II]  $157.7 \mu\text{m}$ , [O III]  $88.36 \mu\text{m}$ , [O I]  $63.18 \mu\text{m}$ , and [O III]  $51.81 \mu\text{m}$  lines and the immunity to the confusion limit make the spectroscopic survey far more efficient than broadband surveys at detecting high- $z$  star-forming galaxies. This is illustrated by the comparison with the estimated redshift distribution of H-ATLAS galaxies.

The redshift distribution of the spectroscopic survey (Fig. 2) peaks at  $z \simeq 1\text{--}1.5$ . The brightest line within the frequency range covered by the instrument varies with redshift (see the right-hand panel of Fig. 1). These variations produce the indentations at low  $z$  and the secondary peak at  $z \simeq 0.6$ . The solid red line shows, for comparison, the estimated redshift distribution of galaxies detected by the H-ATLAS survey above the  $4\sigma$  limit in at least one SPIRE channel (based on the Cai et al. 2013 model). The dip at  $z \simeq 1.5$  corresponds to the change of the dominant star-forming population: late-type plus starburst galaxies and proto-spheroidal galaxies at lower and higher redshifts, respectively.

#### 4 STRONGLY LENSED GALAXIES

Figures 2 and 3 also show that most spectroscopically detected  $z \gtrsim 4$  galaxies and the brightest galaxies at lower redshifts are strongly lensed (see discussions in Perrotta et al., 2002; Negrello et al., 2007; Paciga et al., 2009; Lima et al., 2010). The availability of large samples of strongly lensed galaxies out to high redshifts will drive a real breakthrough in the study of the early

evolutionary phases of galaxies. The *Herschel* surveys H-ATLAS and HerMES, the *Planck* all-sky survey and the SPT survey have already provides several hundreds of lensed galaxy candidates, with painstaking follow-up campaigns world-wide and at all wavelengths (e.g., Negrello et al., 2010, 2014, 2017a; Lupu et al., 2012; Vieira et al., 2013; Wardlow et al., 2013; Hezaveh et al., 2013; Cañameras et al., 2015; Harrington et al., 2016; Nayyeri et al., 2016; Harrington et al., 2018; Yang et al., 2017; Díaz-Sánchez et al., 2017; Massardi et al., 2018; Bakx et al., 2018; Dannerbauer et al., 2019b).

Strong lensing not only boosts the observed global flux by a factor  $\mu$  but also increases the angular sizes of galaxies by an average factor of  $\mu^{1/2}$ . Since the magnification  $\mu$  can be several tens, the expansion of the image can be quite substantial. The study in great detail of the internal structure and kinematics of galaxies will then become accessible to high resolution instruments like ALMA or the *James Webb Space Telescope (JWST)*.

A spectacular demonstration of the power of strong gravitational lensing in this respect was provided by ALMA 0.1 arcsec resolution observations of the *Planck* source PLCK G244.8+54.9 at  $z \simeq 3.0$ , with  $\mu \simeq 30$  (Cañameras et al., 2017). These observations reached the astounding spatial resolution of 60 pc, comparable to the size of GMCs (around 40–100 pc). Very recently, ALMA high resolution observations of a strongly lensed, normal star-forming galaxy at  $z = 1.06$  (the “Cosmic Snake”) even reached a spatial resolution of 30 pc in the source plane (Dessauges-Zavadsky et al., 2019). Intriguingly, the 17 identified GMCs in this source have different physical properties on average than those of nearby galaxies.

AGN-driven outflows are a key ingredient of current galaxy evolution models (see e.g., Heckman & Best, 2014), since they provide the most plausible explanation for the deviation of the galaxy stellar mass function from the halo mass function at large masses, i.e., for the low star-formation efficiency in massive halos, only less than 10% of baryons initially present in such halos are used to form stars. However, information on the effect of feedback on the direct fuel for star formation (namely, molecular gas) during the epoch of the most active cosmic star formation is largely missing, due to the weakness of spectral signatures of molecular outflows.

Gravitational lensing allows us to overcome these difficulties. Cañameras et al. (2017) obtained CO spectroscopy with a velocity resolution of  $40\text{--}50 \text{ km s}^{-1}$ . This spectral resolution makes possible a direct investigation of massive outflows driven by AGN feedback at high  $z$ , with predicted velocities of order  $1000 \text{ km s}^{-1}$  (King & Pounds, 2015). Spilker et al. (2018) and Jones et al. (2019) detected, by means of ALMA spectroscopy, massive molecular outflows in two strongly lensed galaxies at  $z = 5.3$  and  $z = 5.7$ , respectively, discovered by SPT survey. Cañameras et al. (2018) detected

a molecular wind signature in the strongly lensed galaxy PLCK G165.7+49.0, discovered by *Planck*, at  $z = 2.2$ , with magnification factors between 20 and 50 over most of the source of emission.

## 5 UNLENSED GALAXY POPULATIONS

The evolution of the dust-obscured star formation is still poorly known. Gruppioni et al. (2013), Magnelli et al. (2013) and Wang et al. (2019b) estimated the IR luminosity functions of galaxies based on the *Herschel* PACS and SPIRE survey data. Above  $z \simeq 2.5$  the overwhelming majority of redshifts are photometric (at  $z > 3$  there are only about 4–6% spectroscopic redshifts, depending on the survey field). Substantially increasing the fraction of spectroscopic redshifts is hard because of the faintness of these galaxies in the optical/near-IR.

All these studies required the use of optical/near-IR data for photometric redshift estimates. This means that heavily dust-obscured galaxies are missed. Recent investigations (Wang et al., 2019a; Dudzevičiūtė et al., 2020; Williams et al., 2019) have shown that a substantial fraction of massive galaxies at  $z > 3$  are optically dark.

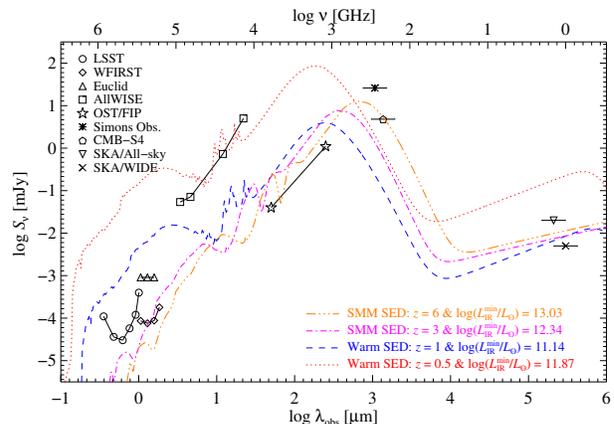
The proposed spectroscopic survey will provide an unbiased determination of the redshift-dependent IR luminosity function up to  $z \simeq 6$ . For the first time we will have spectroscopic redshifts for a huge number of lensed and non-lensed DSFGs, obtained in an unbiased way, independent of the identification/pre-selection method. Out to  $z \simeq 4$  the luminosity functions will be determined down to below the characteristic  $L_{\star, \text{IR}}$ . At  $z \gtrsim 2.4$  we expect detections in both the [C II] 157.7  $\mu\text{m}$  and the [O III] 88.36  $\mu\text{m}$  line.

Such an all sky survey offers the opportunity to search for non-lensed, hyper-luminous infrared galaxies (HyLIRGs;  $L_{\text{IR}} > 10^{13} L_{\odot}$ ). Currently, only a few examples are known in the distant Universe (Fu et al., 2012; Ivison et al., 2013; Riechers et al., 2013), whilst models predict a factor of 2 higher numbers of HyLIRGs (Cai et al., 2013). Furthermore, the fraction of HyLIRGs within the brightest *Herschel* galaxies is still unknown.

We note that, in particular, far-IR fine-structure lines seem to be the best way to obtain spectroscopic redshifts of rest-frame UV-selected galaxies beyond  $z = 7$  (e.g., Inoue et al., 2016; Carniani et al., 2017; Hashimoto et al., 2018; Laporte et al., 2017; Smit et al., 2018; Tamura et al., 2019).

## 6 COMPARISON AND SYNERGIES WITH OTHER LARGE-AREA SURVEYS

Large samples of strongly lensed and unlensed dusty galaxies are expected to also be obtained by next generation CMB experiments, like the “CMB-S4” (ground-based; Abazajian et al., 2019, CMB-S4;) and the spaceborne Probe of Inflation and Cosmic Origins (*PICO*;



**Figure 4.** Detection limits ( $5\sigma$ ) of large area surveys at optical (LSST Science Collaboration, 2009), near-IR (*Euclid* and *WFIRST*, Laureijs et al., 2011; Spergel et al., 2015), mid-IR (AllWISE, Cutri et al., 2013, and [http://wise2.ipac.caltech.edu/docs/release/allwise/expsup/sec2\\_3a.html](http://wise2.ipac.caltech.edu/docs/release/allwise/expsup/sec2_3a.html)), far-IR/submm (OST/FIP, CMB-S4 and Simons Observatory, Meixner et al., 2019; Abazajian et al., 2019; Ade et al., 2019), and radio (SKA, Prandoni & Seymour, 2015) wavelengths compared with model SEDs of galaxies having the minimum  $L_{\text{IR}}$  detectable in lines at  $z = 0.5, 1, 3$ , and 6. At the two lower redshifts we have adopted the “warm” (starburst) SED, while at the two higher redshifts, we use the proto-spheroidal SED (Cai et al., 2013).

Hanany et al., 2019). However, the depth of *PICO* surveys is limited by confusion, due to the modest telescope size (1.4 m).

Confusion is a limiting factor also in the case of the 6-m telescopes used as part of CMB-S4, since they operate at mm wavelengths. Another practical limit is set by atmospheric noise. If the effective depths of the CMB-S4 surveys are similar to those of the SPT (a 10-m telescope), the detection of only a few hundred strongly lensed galaxies at  $z \geq 6$  is expected. However the CMB-S4 survey will provide deeper photometry at mm wavelengths, which is important to quantify the cold dust emission.

A great advantage of a spectroscopic survey is the direct measurement of redshifts, while surveys of the continuum require a lengthy follow-up programme that may be impractical for hundreds of thousands of optically very faint or almost invisible (e.g., Dannerbauer et al., 2002; Younger et al., 2007; Dannerbauer et al., 2008; Wang et al., 2019a) galaxies. In addition, the target lines allow us to single out the star-formation luminosity. It may be difficult to disentangle this from the AGN contribution using broadband photometry alone (Symeonidis et al., 2016; Symeonidis, 2017).

As illustrated in Fig. 4, there are important synergies with large-area surveys at other wavelengths. For example, the Large Synoptic Survey Telescope (LSST; LSST Science Collaboration, 2009) will survey 20,000  $\text{deg}^2$  of the sky in six photometric bands. The final coadded depths (point sources;  $5\sigma$ ) are  $u = 26.3$ ,  $g = 27.5$ ,

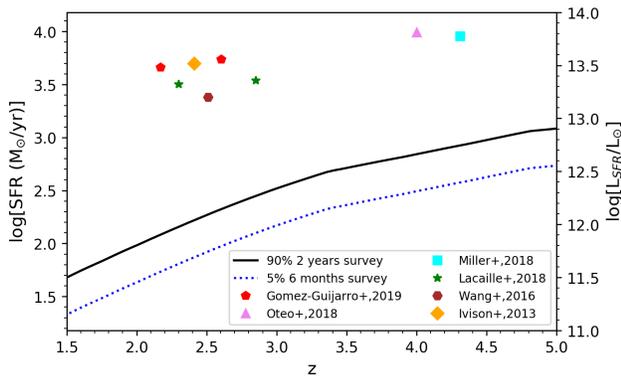
$r = 27.7$ ,  $i = 27.0$ ,  $z = 26.2$ , and  $y = 24.9$  AB magnitudes.

*Euclid* (Laureijs et al., 2011) will cover  $15,000 \text{ deg}^2$  of the sky to  $Y$ ,  $J$ , and  $H = 24$  mag. The *Wide Field Infrared Survey Telescope* (*WFIRST*; Spergel et al., 2015) will carry out large area, deep multi-filter imaging surveys at high Galactic latitudes. As an example, we show in Fig. 4 the expected depths for a nominal 2.5-year survey of  $2,500 \text{ deg}^2$  down to  $J \sim 27$  AB mag. The All-WISE survey (Wright et al., 2010) has already provided shallower all-sky surveys at  $3.4$ ,  $4.6$ ,  $12$ , and  $22 \mu\text{m}$ .

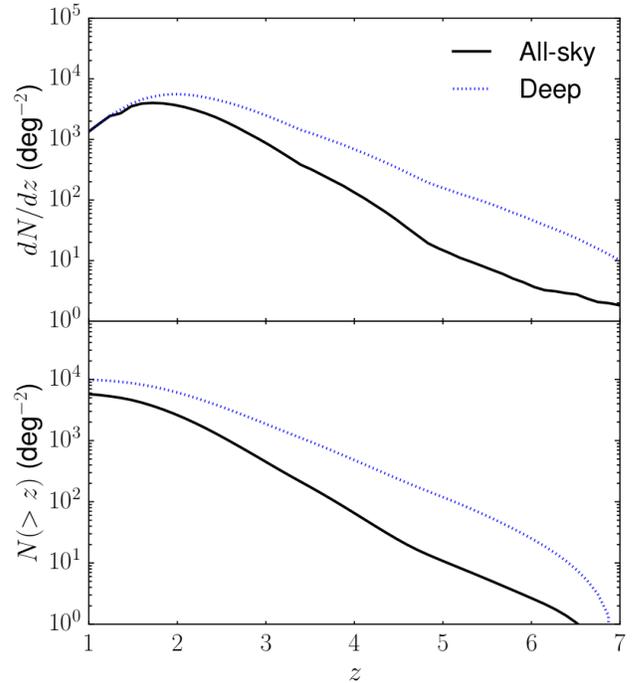
The Far-infrared Imager and Polarimeter (FIP) on the *Origins Space Telescope* (OST; Meixner et al., 2019) will deliver an ultra-wide-field survey ( $10,000 \text{ deg}^2$ ) at  $250 \mu\text{m}$  down to the confusion limit ( $1.1 \text{ mJy}$ ) and a Wide survey ( $500 \text{ deg}^2$ ) at  $50 \mu\text{m}$  down to  $40 \mu\text{Jy}$ . The Simons Observatory (Ade et al., 2019) Large Aperture Telescope will survey 40% of the sky with arc-minute resolution down to  $26 \text{ mJy}$  at  $280 \text{ GHz}$ . CMB-S4 (Abazajian et al., 2019) will reach the confusion limit ( $4.8 \text{ mJy}$  at  $220 \text{ GHz}$ ) over a large fraction of the sky, and will cover several frequency bands.

The Square Kilometer Array (SKA) “all-sky” survey will cover  $31,000 \text{ deg}^2$  at  $1.4 \text{ GHz}$  down to  $20 \mu\text{Jy beam}^{-1}$  ( $5\sigma$ ), while the SKA/Wide survey at around  $1 \text{ GHz}$  will reach  $5 \mu\text{Jy beam}^{-1}$  ( $5\sigma$ ) over  $1,000 \text{ deg}^2$  (Prandoni & Seymour, 2015).

As illustrated in Fig. 4, the *WFIRST*, the *Origins*/FIP and the SKA/Wide surveys are expected to detect practically all the dusty galaxies seen in lines in our proposed spectroscopic survey, although over limited sky areas. On the other hand, the other surveys mentioned above will also detect a substantial fraction of them, thus providing complementary information on stellar and dust components.



**Figure 5.** SFRs of the spectroscopically confirmed, submm-bright proto-cluster cores discovered so far, compared with the minimum SFRs detectable at  $5\sigma$  by the “all-sky” (solid black line; 2 years, 90% of the sky) and by the “deep” (dotted blue line; 5% of the sky, six months) spectroscopic surveys. The data points are: Ivison et al. (2013) at  $z = 2.41$ ; Gómez-Guijarro et al. (2019) at  $z = 2.171$  and  $z = 2.602$ ; Wang et al. (2016) at  $z = 2.51$ ; Miller et al. (2018) at  $z = 4.31$ ; Oteo et al. (2018) at  $z = 4.0$ ; and Lacaille et al. (2019) at  $z \simeq 2.85$  and  $\simeq 2.30$ .



**Figure 6.** Predicted differential and cumulative redshift distributions (upper and lower panels, respectively) of proto-clusters detected in at least one line by the “all-sky” survey (2 yr, 90% of the sky; solid black line) and by the deep survey (6 months, 5% of the sky; dotted blue line). We expect the detection of tens of millions of proto-clusters at  $z \simeq 2$  and of tens of thousands of them at  $z \simeq 6$ .

## 7 REVEALING GALAXY PROTO-CLUSTERS VIA DUSTY STARBURSTS

N-body simulations in the framework of the currently standard  $\Lambda\text{CDM}$  cosmology have elucidated how primordial perturbations have grown into collapsed halos distributed within a filamentary structure (the cosmic web; e.g. Springel et al., 2005; Boylan-Kolchin et al., 2009). However an observational validation of how these objects are assembled is still missing. Understanding the full evolutionary history of present-day galaxy clusters is of fundamental importance for the observational validation of the formation history of the most massive dark-matter halos, a crucial test of models for structure formation, as well as for investigating the impact of environment on the formation and evolution of galaxies (Kravtsov & Borgani, 2012; Overzier & Kashikawa, 2019; Dannerbauer et al., 2019a).

To address the many still open questions on cluster formation and evolution we need to follow all their evolutionary stages through cosmic time, starting from their progenitors, galaxy clusters in formation, so-called “proto-clusters” (for a review see Overzier, 2016). This needs a coordinated multi-frequency effort. Cluster identification via classical methods (optical/IR imaging and

detection of X-ray or SZ signals from the hot ICM) has been very effective at relatively low redshifts. Samples of SZ-selected clusters have been recently extended to a few thousand objects, primarily thanks to surveys with the *Planck* satellite (Planck Collaboration XXVII, 2016), the South Pole Telescope (SPT; Bleem et al., 2020) and the Atacama Cosmology Telescope (ACT; Hilton et al., 2018). A few thousand clusters have also been detected in X-rays (Klein et al., 2019). Both ICM-based techniques have yielded just a handful of clusters above  $z \simeq 1.5$ . The *e-ROSITA* all-sky survey is expected to boost the number of X-ray-detected clusters to around  $10^5$ , but again few detections are expected at  $z \gtrsim 1.5$  (Grandis et al., 2019). There is also a limit to detecting X-rays and the SZ effect at very high redshifts because of the lack of virialised gas.

Galaxy cluster searches looking for overdensities of galaxies in large-area optical/IR surveys (e.g., Oguri et al., 2018; Wen & Han, 2018; Gonzalez et al., 2019) are generally limited to  $z \lesssim 1.5$  due to the subtle density contrasts of the object. Observations indicate that  $z \simeq 1.5$  corresponds to a critical epoch in galaxy cluster evolution. At lower redshifts the global SFR of galaxies is anti-correlated with local density (Dressler, 1980; Kauffmann et al., 2004; Lemaux et al., 2019). However, the specific SFR (i.e., the SFR per unit stellar mass) increases faster in clusters than in the field, catching up with that in the field at  $z \simeq 1.5$  (Alberts et al., 2014, 2016; Wagner et al., 2017). Thus galaxy clusters selected through optical/IR observations are rare at  $z \gtrsim 1.5$  (Gobat et al., 2011).

Above  $z \simeq 1.5$ , when a large fraction of member galaxies are in the dust-obscured star-formation phase (e.g., Dannerbauer et al., 2014; Clements et al., 2016; Kato et al., 2016; Wagner et al., 2017; Nantais et al., 2017), proto-cluster searches are most conveniently carried out at submm wavelengths. Negrello et al. (2005) predicted the detection by *Planck* and *Herschel* submm surveys of unresolved intensity peaks made by the summed emission of dusty star-forming high- $z$  proto-cluster members within the beam. Motivated by this work, Planck Collaboration Int. XXXIX (2016) have reported the detection of 2151 proto-cluster candidates over the cleanest 26% of the sky – these are unresolved sources with “red” submm colours, consistent with redshifts  $z > 2$ .

Follow-up observations of a subset of these sources with *Herschel* (Planck Collaboration Int. XXVII, 2015) have shown that, apart from a tiny fraction of strongly lensed galaxies (the GEMS sample, see Cañameras et al., 2015), they are associated with overdensities of dusty star-forming galaxies. However, Negrello et al. (2017b) argued that most of them are probably not individual proto-clusters, but could be made of physically unrelated high- $z$  structures falling by chance within the relatively large *Planck* beam (FWHM  $\simeq 5'$ ). This has been confirmed by spectroscopic measurements and/or photomet-

ric redshift estimates for two objects, showing that each consists of two independent overdensities along the line of sight (Flores-Cacho et al., 2016; Kneissl et al., 2019).

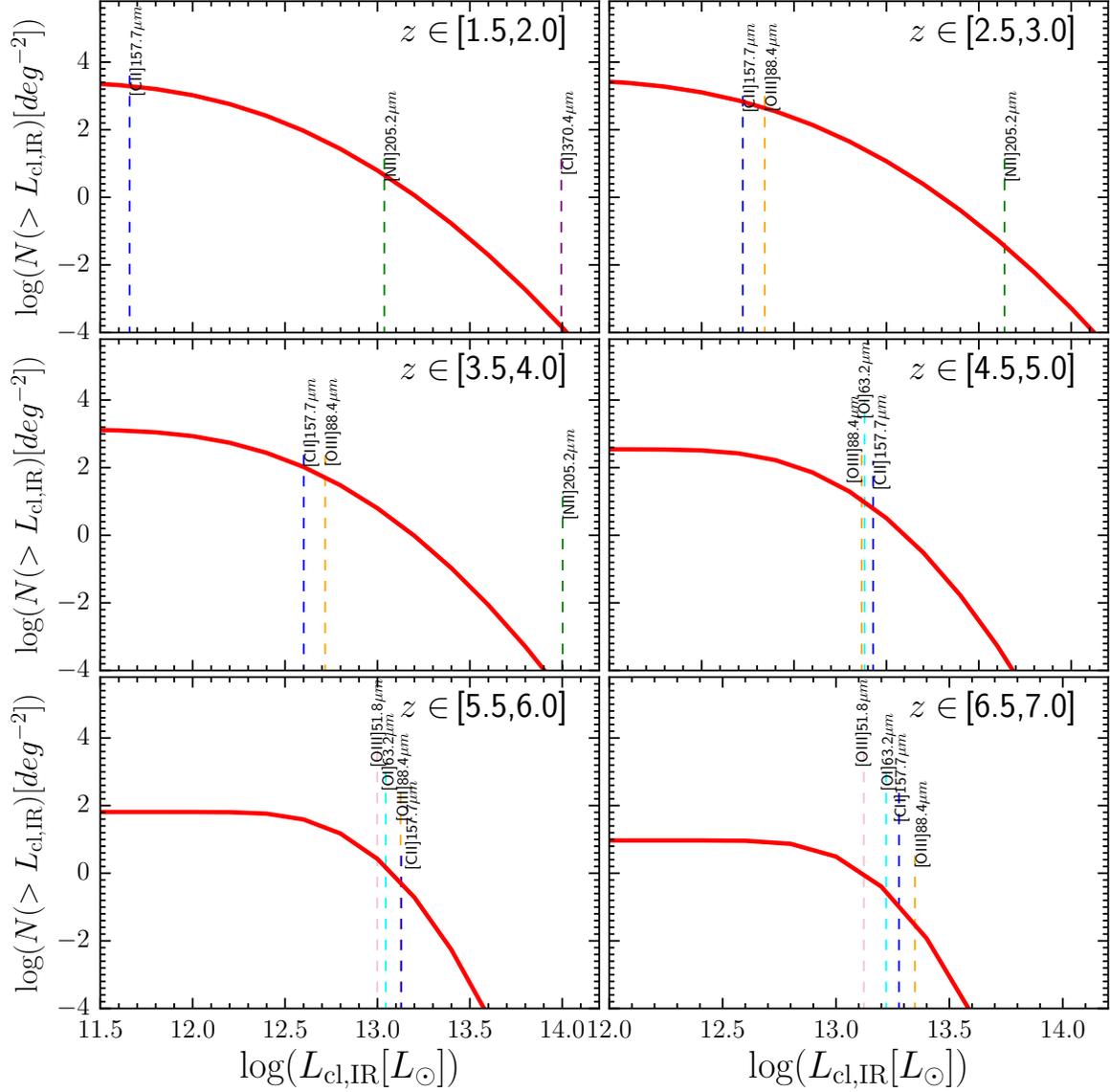
The confusion problem (blending of independent proto-clusters along the line of sight) affecting *Planck* surveys is due to its poor angular resolution. The instrument considered here has angular resolution  $\leq 1'$  at  $\nu \geq 380$  GHz (cf. Table 1). This is the ideal angular resolution for searches of submm-bright proto-clusters. The angular correlation function of faint submm galaxies measured by Chen et al. (2016) in photometric redshift bins up to  $z \simeq 5$  showed that the 1-halo component, corresponding to the source distribution within the proto-cluster halo, dominates at  $\theta \lesssim 1'$ . This is in keeping with the results of Alberts et al. (2014) on 274 clusters with  $0.3 \leq z \leq 1.5$ . They found that the density of IR-emitting cluster members clearly exceeds that of the background field level only within 0.5 Mpc of the cluster centre. Such a linear scale corresponds to an angular scale of about  $1'$  at redshifts in the range 1.5–2.5.

The clustering measurements by Chen et al. (2016) also gave clear indications of a steepening of the correlation function on arcsec angular scales. Negrello et al. (2017b) modelled this in terms of an additional component with a spatial correlation function  $\xi(r) \propto r^{-3.3}$ . This component, which dominates for  $r \lesssim 50$  kpc, may represent the cluster core. Submm-bright proto-cluster cores, with linear diameters of order 100 kpc, have been discovered by Ivison et al. (2013, 2019) at  $z = 2.41$ , Gómez-Guijarro et al. (2019) at  $z = 2.2$  and  $z = 2.6$ , Wang et al. (2016) at  $z = 2.5$ , and Miller et al. (2018) at  $z = 4.3$ . Oteo et al. (2018) reported the identification of a dusty proto-cluster core at  $z = 4.0$ , whose member galaxies are distributed over a  $260 \text{ kpc} \times 310 \text{ kpc}$  region. Additionally Lacaille et al. (2019) spectroscopically confirmed the detection of two submm proto-clusters at  $z \simeq 2.8$  and  $\simeq 2.3$ , with  $1'$  angular radius.

The spectroscopically confirmed proto-cluster cores listed above are unresolved at the resolution of the instrument, except perhaps at the highest frequencies, where the maps can be degraded to arcmin resolution. The summed IR-luminosities of detected members of the spectroscopically confirmed high- $z$  proto-clusters (lower limits to the proto-cluster total IR luminosities) range from a few to several  $\times 10^{13} L_{\odot}$  and are all well above the line-detection limits (see Fig. 5) of our proposed surveys.

High- $z$  proto-clusters with enhanced star formation on larger (few to several Mpc) scales have also been reported by Dannerbauer et al. (2014), Casey et al. (2015), Kato et al. (2016), Hung et al. (2016), and Umehata et al. (2019). All proto-clusters with similar properties will be detected by our spectroscopic survey.

As illustrated in Figs. 6 and 7, the instrument considered here will detect millions of proto-clusters at the peak of cosmic star-formation activity ( $z = 2-3$ ). For a



**Figure 7.** Cumulative IR (8–1000  $\mu\text{m}$ ) luminosity functions of proto-clusters within  $\delta z = 0.5$  at six redshifts. The predictions are based on the model of Negrello et al. (2017b). The line luminosities corresponding to  $L_{\text{IR}}$  were computed as described in the text. The vertical lines show the detection limits for the brightest lines, assuming the instrument performances described in the text. Such an instrument will detect strongly lensed galaxies (cf. Fig. 3) and proto-clusters of dusty galaxies all the way out to the reionization redshift.

large fraction of proto-clusters, especially at  $z \geq 2.4$ , at least two lines will be detected, allowing a solid redshift determination without requiring follow-up observations.

## 8 COMPARISON WITH OTHER LARGE-AREA CLUSTER SURVEYS

No other foreseen survey can do anything similar to the future spectroscopic satellite. *Euclid*'s "Wide" survey over  $15,000 \text{ deg}^2$  is expected to detect galaxy clusters and proto-clusters only out to  $z \simeq 2$ . The estimated surface density of clusters detected at  $5\sigma$  in the redshift range  $1.5 \leq z \leq 2$  is  $\simeq 0.19 \text{ deg}^{-2}$  (Sartoris et al., 2016, see their figure 3).

A survey of  $8,300 \text{ deg}^2$  by *WFIRST* (Spergel et al., 2015) is expected to detect 20,000 clusters with masses  $M_{\text{cl}} \geq 7.4 \times 10^{13} M_{\odot}$  at  $z = 1.5\text{--}2$  and 2,800 clusters at  $z = 2\text{--}2.5$  for the same masses. The corresponding surface densities are of 2.4 and  $0.34 \text{ deg}^{-2}$ , respectively.

For comparison, we expect around  $2000 \text{ deg}^{-2}$  ( $1300 \text{ deg}^{-2}$ ) detections in the [CII]  $157.7 \mu\text{m}$  line only and  $\simeq 5 \text{ deg}^{-2}$  ( $\simeq 0.4 \text{ deg}^{-2}$ ) detections in two lines ([CII]  $157.7 \mu\text{m}$  and [NII]  $205.18 \mu\text{m}$ ) at  $1.5 \leq z \leq 2$  ( $2.0 \leq z \leq 2.5$ ), as shown in Fig. 7.

Cluster searches with ground-based, large-area optical surveys like LSST (LSST Science Collaboration, 2009) and the Javalambre Physics of the Accelerating Universe Astrophysical Survey (J-PAS; Benitez et al., 2014) are limited to  $z < 1.5$ . As mentioned above, the X-ray cluster survey of *e-ROSITA* is also limited to  $z \lesssim 1.5$  (Grandis et al., 2019).

The most extensive optical search for high- $z$  proto-clusters is being conducted using a wide-field survey with the Hyper Suprime-Cam (HSC) instrument mounted at the prime focus of the Subaru telescope. The wide HSC survey will cover  $1,400 \text{ deg}^2$ . Toshikawa et al. (2018) carried out a blind search for proto-clusters at  $z \simeq 3.8$  over an area of  $121 \text{ deg}^2$  using colour criteria to select galaxies at  $z \simeq 3.3\text{--}4.2$ . They found 216 overdensities that were significant at the  $> 4\sigma$  level. The estimated comoving density of these objects is  $1.4 \times 10^{-7} \text{ Mpc}^{-3}$  for the cosmology adopted here. At higher redshifts Higuchi et al. (2019) reported 14 and 26 proto-cluster candidates at  $z = 5.7$  and  $z = 6.6$ , covering an area of 14 and  $16 \text{ deg}^2$ , respectively.

Kubo et al. (2019) reported statistical evidence of submm emission from HSC candidate proto-clusters in *Planck* high-frequency maps, confirming the ubiquity of intense star formation in high- $z$  proto-clusters. The estimated average IR luminosity and SFR are well above the detection limits of the proposed spectroscopic survey.

At  $z = 3.75$ , i.e., close to the redshift of the optical search by Toshikawa et al. (2018), the spectroscopic survey will detect  $100 \text{ deg}^{-2}$  proto-clusters in the [CII]  $157.7 \mu\text{m}$  line and  $50 \text{ deg}^{-2}$  also in the [OIII]  $88.36 \mu\text{m}$  line. The corresponding comoving vol-

ume densities are  $1\text{--}2 \times 10^{-5} \text{ Mpc}^{-3}$ , i.e., about two orders of magnitude higher than that achieved by Toshikawa et al. (2018). As pointed out by the latter authors, overdensity searches via optical imaging surveys are expected to be highly incomplete (completeness around 6%) because most overdensities are swamped by projection effects. On the contrary, the statistical detection on *Planck* maps of large SFRs in optically-selected proto-clusters suggests a high completeness level for the planned spectroscopic survey.

It is important to stress that the proposed instrument can measure both the SFR and the SZ effect in clusters. It will thus simultaneously probe the evolution of star formation in dense environment and of the hot IGM, allowing us to investigate the relationship between the two aspects of cluster evolution. It will thereby provide key data on the still unexplored, crucial transition period at  $z \simeq 1.5\text{--}2$  when cluster galaxies were vigorously forming stars and at the same time the hot IGM was taking root.

Figure 7 shows that the spectroscopic survey will detect enough proto-clusters within relatively narrow redshift bins to accurately measure their two-point spatial correlation,  $\xi(r)$ , as a function of redshift out to  $z \simeq 6$  and, at fixed  $z$ , as a function of  $L_{\text{IR}}$  (or equivalently of SFR). From the function  $\xi(r)$  we can infer the effective halo mass (Sheth et al., 2001), so that the observed proto-cluster abundance provides constraints on the evolution of the high-mass tail of the halo mass function and on the relationship between halo mass and  $L_{\text{IR}}$  or SFR.

Note that the abundance and clustering of galaxy clusters are both probes of large-scale structure growth. Their determination as a function of mass and redshift enables us to constrain cosmological parameters primarily through the linear growth rate of perturbations. This has been proven to be competitive with and complementary to other probes (e.g., Planck Collaboration XXIV, 2016; de Haan et al., 2016; Sridhar et al., 2017).

At lower redshifts, the comparison of cluster samples detected via star formation and via the SZ effect will quantify the history of star-formation quenching in galaxy clusters, a still open issue (Boselli et al., 2016; Rodríguez-Muñoz et al., 2019). In particular, we will learn about the quenching timescale at different redshifts and for different cluster halo masses, inferred from the amplitude of the SZ effect, and of the ICM density inferred from X-ray observations, e.g., from *e-ROSITA*. This is key information for identifying the mechanism(s) responsible for the environmental quenching.

## 9 CONCLUSIONS

The high-sensitivity spectroscopic and imaging surveys carried out by the space mission proposed by Delabrouille et al. (2019) will revolutionize our view of

galaxy evolution and of the growth of galaxy clusters.

Spectroscopy enables full exploitation of the sensitivity of present-day instrumentation, bypassing the confusion limits that severely constrain the depth of submm surveys with telescopes of the 3-m class, like that of the *Herschel* Observatory.

The high luminosity of far-IR lines such as [CII]  $157.7\ \mu\text{m}$ , [OIII]  $88.36\ \mu\text{m}$ , [OI]  $63.18\ \mu\text{m}$  and [OIII]  $51.81\ \mu\text{m}$ , makes it possible to detect, at  $z > 1$ , star-forming galaxies with SFRs about one order of magnitude lower than those reached by the *Herschel*-ATLAS survey. Moreover, we have argued that these fine-structure lines track the full SFR, not only the dust-obscured fraction measured by the far-IR/submm continuum.

Most importantly, the spectroscopic survey directly provides the 3D distribution of star-forming galaxies all the way through the reionization epoch. Many tens of millions of galaxies will be detected over the redshift range  $1 < z < 3$  (Fig. 2) where the cosmic SFR peaks. SFRs well below those of typical galaxies at these redshifts will be reached (Figs. 1 and 3). For example, at  $z = 2$  the [CII]  $157.7\ \mu\text{m}$  line will allow the detection of SFRs down to about  $60\ \text{M}_\odot\ \text{yr}^{-1}$  by the “all-sky” survey and down to  $30\ \text{M}_\odot\ \text{yr}^{-1}$  for the “deep” survey. Our conservative estimates, that do not allow for the possibility of a top-heavier IMF at high  $z$  indicated by theoretical arguments and by some observational results (see Cai et al., 2020, for a discussion), yield the detection of thousands of galaxies at  $z \simeq 6$  and of several tens at  $z \simeq 8$ .

This outcome is far better than can be achieved by existing and forthcoming continuum surveys, which, moreover, require time-consuming redshift follow-up programmes that are impractical for millions of optically very faint sources.

The spectroscopic survey will detect millions of strongly lensed galaxies, which dominate the bright tails of the high- $z$  SFR functions, above uncorrected SFRs of a few thousand  $\text{M}_\odot\ \text{yr}^{-1}$ . Additionally, strong lensing will allow us to probe SFR functions below the nominal detection limit.

The brightest strongly lensed galaxies are obvious targets for follow-up observations with high-resolution instruments like ALMA or *JWST*. The combination of their extreme luminosity and of the stretching of their images offers a unique possibility of peering into the internal structure of high- $z$  galaxies down to scales of tens of parsecs, comparable to or smaller than the size of giant molecular clouds in the Milky Way. Data at this resolution are the only way to directly investigate the complex physical processes driving the early evolution of galaxies.

The arcmin (or better) angular resolution at submm wavelengths of the proposed survey is ideal to detect proto-cluster cores out to  $z \simeq 7$ . The summed line emis-

sion of star-forming member galaxies within the beam of the instrument makes these objects produce the brightest intensity peaks at each redshift. Proto-clusters can thus be detected independently of whether they contain the hot IGM that would make them detectable in X-rays or via the SZ effect.

We predict the spectroscopic detection of millions of proto-clusters at  $z > 1.5$ , i.e., in the redshift range hardly accessible to classical cluster-detection methods. This will provide a complete view of the star-formation history in dense environments. The statistical detection of intense star formation in optically-selected high- $z$  proto-clusters (Kubo et al., 2019) suggests that the planned spectroscopic survey will have a high completeness level.

Enough proto-clusters will be detected within relatively narrow redshift bins to accurately measure their clustering  $\xi(r, z)$  out to  $z \simeq 6$  and, at fixed  $z$ , as a function of their SFR. Since  $\xi(r)$  allows us to estimate the halo mass, we can derive the first observational constraints on the evolution of the high-mass tail of the halo mass function and on the relationship between halo mass and SFR.

At lower redshifts ( $z \lesssim 1.5-2$ ), the mission will simultaneously measure the SFR and the SZ effect for early structures. In combination with X-ray data from *e-Rosita* and with data from optical surveys measuring stellar masses, this will elucidate several key issues, e.g., the transition from the active star-forming to passive evolution phases of cluster members, the origin of the hot IGM, and the mechanisms responsible for the environmental quenching of star formation.

In all these areas, the proposed spectroscopic survey transcends any other foreseen project.

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