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PROPERTIES OF THE INTERSTELLAR MEDIUM IN DISTANT STAR-FORMING GALAXIES

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Contents

Abstract	v
1 Introduction	1
1.1 Observational tools	2
1.1.1 Weighting a galaxy: measurements of the (stellar) mass	2
1.1.2 The Star Formation Rate	5
1.1.3 Dust attenuation	6
1.1.4 Dust emission	12
1.1.5 Gas-phase metallicity	13
1.2 The Main Sequence of star-forming galaxies	13
1.2.1 Galaxies along the MS: observational properties and some outstanding questions	14
1.2.2 Starburst galaxies: known facts and open issues	17
1.2.3 A galaxy life on the $M_{\star}$ -SFR plane	18
1.3 Active Galactic Nuclei and their role in galaxy formation	19
1.3.1 AGN in a nutshell	19
1.3.2 Evidences of an AGN/Galaxy co-evolution and causal connection	20
1.4 From MS to QSO via major mergers	23
1.4.1 Probing the Starburst-QSO evolutionary sequence though outflows	25
1.5 This work: overview	28
2 Dust attenuation in $z \sim 1$ galaxies from Herschel and 3D-HST $H\alpha$ measurements	31
2.1 Introduction	31
2.2 Sample and data-set	33
2.2.1 The <i>Herschel</i> /PEP survey	33
2.2.2 Multi-wavelength photometry	34
2.2.3 The 3D-HST survey	35
2.2.4 Cross correlation and cleaning of the sample	35
2.2.5 The final sample	36
2.3 Spectral analysis	37
2.3.1 $H\alpha$ fluxes and redshift measurements	38
2.3.2 Flux correction by SED scaling	39
2.4 Derivation of the main physical quantities of the sample galaxies	40
2.4.1 SED-fitting	40
2.4.2 Measuring the SFRs	41
2.5 Dust extinction corrections	43
2.5.1 Differential extinction from $H\alpha$ to UV-based SFR indicators	45
2.5.2 Measurements of the continuum extinction	46
2.5.3 Extra extinction from the f -factor	47

2.5.4	Testing the dust correction: comparison between $\text{SFR}_{H\alpha}$ and SFR_{IR+UV} . . .	49
2.5.5	$A_{H\alpha}$ vs $M_{\star}$	50
2.5.6	Main sequence at $z \sim 1$	52
2.6	Caveats: the many faces of the f -factor	52
2.7	Summary and conclusions	55
2.8	Appendix A: Computation of the UV spectral slope	57
2.8.1	β from the best-fit SED	57
2.8.2	β from the observed photometry	57
2.8.3	β_{phot} vs β_{model}	58
2.9	Appendix B: main parameters of the sample	60
3	The Bright and Dark Sides of High-Redshift starburst galaxies from <i>Herschel</i> and <i>Subaru</i> observations	63
3.1	Introduction	63
3.2	The FMOS-COSMOS survey	64
65	section*.49	
66	section*.50	
3.3	Data set and sample selection	66
3.4	Spectral analysis	68
3.4.1	Emission line fitting on individual spectra	68
3.4.2	Stacking analysis	70
3.5	Results	71
3.5.1	Dust attenuation above the MS	71
3.5.2	Gas-phase metallicity above the MS: MZR and FMR	75
3.5.3	Constraining the ISM conditions of starbursts: preliminary results	77
3.6	Discussion and conclusions	78
3.7	Acknowledgements	81
3.8	Appendix: Different methods for measuring $M_{\star}$ and their impact on starburst statistics	81
4	Testing the Starburst/AGN sequence with AGN outflows	91
4.1	Introduction	91
4.2	Selecting AGN in the starburst region at $z \sim 1.6$	92
4.3	Average spectra for the AGN-starburst population	93
4.4	Optical morphology for the AGN-starburst population	94
4.4.1	A closer look: zooming on a merger with SINFONI	97
4.5	Dust attenuation properties	99
4.6	Discussion, preliminary conclusions and future developments	100
5	The SUPER survey and the role of IFS in outflow studies	101
5.1	Integral Field Spectroscopy	101
5.2	The SUPER survey	103
5.2.1	Observations and data reduction	106
5.2.2	A test case	107
5.3	Summary and future prospects	114
6	Conclusions	117
6.1	A critical analysis of the nebular dust attenuation on $z \sim 1$ MS galaxies	117
6.2	The first study of ISM properties of high- z MS outliers in light of their optically-thick attenuation	117

6.3	The role of AGN in the starburst region of the $z \sim 1.6$ MS	118
6.4	Benefitting of IFU resources for galaxy evolution studies	118
6.5	General considerations and future prospects	119
6.6	Concluding remarks	121
Acknowledgment		123
List of figures		125
List of tables		131
Bibliography		133

Abstract

Galaxies assemble their stellar mass mostly in long timescales at a moderate rate although stochastic episodes can trigger a starburst pushing the star formation rate to extreme values for short time. The evolution of galaxies then ends with the *quenching* of star-formation well below the average values, possibly because of the activity of the central black hole, capable of injecting large amount of energy into the galaxy interstellar medium via outflows. Understanding the details of galaxy growth, the modes in which stars are formed within galaxies and how galaxies are quenched are still hotly debated topics and studying the properties of star-forming galaxies and the connection with the activity of the central black hole can shed light on the different mechanisms shaping galaxies across cosmic time.

Star-formation episodes, black hole and outflow activity in galaxies are mainly constrained through observations in the UV-optical regime but this wavelength range is heavily affected by dust obscuration. As such, modeling the effect of dust on the galaxy spectrum is essential. This Thesis uses near-IR spectroscopic observations to study dusty star-forming galaxies at $0.7 \leq z \leq 2.5$ to analyze their dust attenuation properties and investigate their ionized gas features. The sample analyzed in this work includes galaxies representative of the average star-forming population at high redshift, starburst galaxies forming stars at an exceptional rate as well as galaxies hosting an active galactic nucleus (AGN).

For a sample of 79 *Herschel*-selected “normal” galaxies at $0.7 \leq z \leq 1.5$ I use HST slitless spectroscopy in the near-IR to study the attenuation on the $H\alpha$ emission line. I study the $H\alpha$ dust attenuation as a function of integrated parameters (i.e. $M_\star$, SFR_{FIR} and continuum dust attenuation) derived via spectral energy distribution fitting of the high-quality, ancillary photometric coverage from UV to far-IR. I show that the $H\alpha$ emission line and the continuum are attenuated by a similar amount, unlike in the local Universe. Furthermore, I show that the $H\alpha$ attenuation grows with stellar mass and this trend deviates from the local relation towards higher values of dust attenuation. Both results hint an evolution of dust attenuation properties with redshift and galaxy parameters.

I also analyze the near-IR spectra of twelve starburst galaxies at $z \sim 1.6$ using fiber spectroscopy from FMOS at Subaru. I measure the metal content showing that $z \sim 1.6$ starbursts are metal rich, suggesting a rapid enrichment and/or a negligible role of major pristine gas inflow from the cosmic web in enhancing the star-formation. I also show tentative indications of larger density than “normal” star-forming galaxies as well as a larger ionization parameter. Most importantly, I demonstrate that the effects of dust are dramatic in this class of objects. From a comparison between dust attenuation indicators, I show in fact that $\sim 90\%$ of star-formation is buried in heavily obscured cores so that rest-frame optical wavelengths do not provide a complete overview of starburst sources. I discuss the implications of these findings for the interpretation of distant dusty starbursts. I provide a toy model to describe the dust attenuation and distribution in these objects, warning that the metal content and interstellar medium (ISM) conditions of the most star-forming regions remain unconstrained.

To better understand the connection between black hole accretion and star-forming activity, I present a preliminary study of the AGN-dominated sources among starburst galaxies at $z \sim 1.6$. I use FMOS near-IR spectra to constrain their dust attenuation, finding indications that it is lower than in the star-forming parent sample. I discuss the detection of a blue-shifted component in the $[\text{OIII}]_{5007}$ emission observed in the near-IR spectrum of these AGN-starbursts at $z \sim 1.6$ indicating the presence of outflowing material. Furthermore, a visual inspection of the morphology reveals that AGN reside in interacting pairs more compact than star-formation dominated starbursts. If confirmed, all these preliminary results would provide strong support to the idea that AGN are cleaning their environment from dust after a buried star-formation dominated phase, a picture theorized since 30 years but not yet firmly proved.

Finally, I introduce Integral Field Spectroscopic techniques in the context of the SUPER survey, an ongoing large program with SINFONI designed to unveil the role of the AGN in the life-cycle of $z \sim 2$ star-forming host galaxies. IFS observations are key to add the geometrical information to the study of outflows as well as star-formation processes. I present the scientific analysis on a test case from preliminary SUPER observations, to discuss the potential of SUPER observations in obtaining a complete overview of the AGN-driven outflow physics, its link with the AGN and galaxy properties and its impact on the life of the latter.

Overall, this Thesis demonstrates that spectroscopic techniques are a powerful tool for constraining the properties of high- z dusty star-forming galaxies. This work also stresses the importance of a parallel, careful study of the multi-wavelength SED of galaxies spanning the electromagnetic spectrum from the UV to the far-IR. The results presented through this work have been possible thanks to the use of multi-wavelength techniques, the ultimate approach to tackle open problems in Galaxy Evolution studies.

Chapter 1

Introduction

In the local Universe we observe a wide variety of galaxy types displaying a broad range of structures, sizes and luminosities. Their structural properties are related to their physical properties like the gas, dust and stars content as well as the age or the star-forming activity and these properties give indications on their evolutionary stage and their formation. Explaining how galaxies were formed and evolved across the story of the Universe is the main aim of Galaxy Formation and Evolution and answering to this fundamental question is not an easy task. Galaxies are mostly made up of not visible cold dark matter which interacts only through gravitational forces and creates the potential well in which ordinary matter (baryons, i.e. the elements we are familiar with) in gaseous form condenses and collapses to form stars. This baryonic matter is only a minority percentage in the mass budget of a galaxy in form of dust, stars, gas, planets. Nevertheless, modeling its physics is extremely hard as baryons experience a series of complex processes including radiative, mechanical and chemical interactions. Those phenomena involve very different amount of energy so that we need observations across the whole electromagnetic spectrum to study them. Observations of either individual galaxies as well as large statistical samples in a wide range of wavelengths are crucial to improve our understanding of Galaxy Evolution and are important benchmarks to test the predictions of theoretical models which still fail to describe the precise physics regulating the star-formation and mass assembly in galaxies.

When looking at nearby galaxies, we discover that the most common class of objects is composed by round-shaped galaxies with a smooth light distribution: these elliptical or early-type galaxies are extremely massive objects (their typical stellar mass is $M_{\star} \sim 10^{12} M_{\odot}$) containing old stellar populations (with ages of ~ 10 Gyrs) and almost no gas and dust. Ellipticals do not show traces of recent star formation and are in a passive evolutionary status, but commonly host a super-massive black hole in the central regions that emits radiation in the X-ray and radio regimes. This black hole may have played a major role in ending the galaxy star-forming activity. The majority of star formation events are instead hosted in less massive ($M_{\star} \sim 10^{9-10} M_{\odot}$) disk galaxies: late-type galaxies host younger stellar populations, a larger gas and dust content with respect to ellipticals and are forming stars at a “gentle” rate in a disc. Violent star-formation episodes are finally observed in extremely compact regions of dust and gas rich galaxies, with irregular morphologies and/or in interacting pairs, commonly called “starburst galaxies”. Although these systems are capable of forming stars at a rate much higher than the average star-forming population, starburst galaxies are so rare that do not significantly contribute to the global star-formation events of the local Universe.

What is the relationship between different galaxy categories? Is there an evolutionary link between various morphological classes of galaxies? If yes, what are the processes that lead to morphological mutations in galaxies and how they influence their evolution? What processes are responsible for the extreme star formation events hosted in starburst galaxies? What is the role of interactions in the evolution history of galaxies? What phenomena conspire to shut down star formation in galaxies? Is it possible that the life of a galaxy is connected to the massive black hole hosted in its center? If this is the case, how the activity of this small but powerful black hole influences the surrounding galaxy and vice-versa? These are only few of the many puzzles that are still open in Galaxy Evolution studies. Answering to these questions will help to reconstruct a consistent description of galaxies since the collapse in the primordial Universe all the way to the present days through ~ 13 Gyr of evolution. The local Universe does not represent the ideal laboratory to conduct the observational tests required to answer these questions, as in the current epoch galaxies are forming a very small amount of stars on average. The main episodes of stellar mass assembly in the Universe occurred between $z \sim 1$ and $z \sim 3$ and this cosmic era is pivotal for our understanding of the galaxies life. At this stage, also the black hole accretion activity had a peak so that this is also the crucial epoch to assess the connection between black hole and star-forming activity.

Addressing some of the problems listed above is what motivated the work described in this Thesis. In these years, I combined a broad set of multi-wavelength photometric observations from UV to far-IR with optical rest-frame spectroscopy for star-forming galaxies at $0.7 \leq z \leq 2.5$, i.e. observed close to the star formation and black hole accretion rate density peaks of the Universe. This approach has been applied to different classes of star-forming galaxies (“normal”, starburst and AGN-hosts) to study their ionized gas properties and address some of the questions listed above. In the following of this chapter, before giving an overview of the work described in this Thesis (in Sect. 1.5), I provide a brief description of the main observational tools employed in my analysis (see Sect. 1.1). When presenting these tools, I will also devote some space to discuss the caveats behind them. The broad framework of the research presented in this Thesis will be discussed in Sections 1.2, 1.3 and 1.4.

1.1 Observational tools

To answer the hot questions of Galaxy Formation raised in the previous section, a careful characterization of the galaxy properties is required. In this section I will briefly introduce the principal techniques used in the literature to derive some of the main galaxy properties, focusing the discussion on those adopted in this manuscript.

1.1.1 Weighting a galaxy: measurements of the (stellar) mass

Estimating the mass of a galaxy is fundamental to define its evolutionary stage. In fact, several studies showed that the galaxy stellar mass is strictly related to other quantities such as the star formation rate, the chemical enrichment, the dust content, suggesting that the mass mediates all these processes in the galaxy itself. To measure the galaxy mass several techniques exist (see Conroy, 2013; Courteau et al., 2014, for reviews about the topic). Not all these techniques refer to measurements of the same mass content of a galaxy. For example, measurements of the rotational velocity or of the velocity dispersion allow to measure the gravitational potential of the galaxy itself and then derive the so-called *dynamical* mass M_{dyn} which includes stars, dark matter and ISM.

Measurements of M_{dyn} were mainly limited to the low-intermediate redshift Universe ($z \lesssim 1$) as they require high Signal-to-Noise (SN) spectroscopic and/or spatially resolved data. Recently, big spectroscopic surveys in the rest-frame optical/near-IR allowed to push these measurements up to $z \sim 3.5$ (e.g. Förster Schreiber et al., 2006; Cappellari et al., 2009; Onodera et al., 2010a,b; Gnerucci et al., 2011; van de Sande et al., 2013; Price et al., 2016; Swinbank et al., 2017; Turner et al., 2017). Nonetheless, the samples for which dynamical masses are available still remain statistically limited because of long integration times required. When cold gas emission is resolved (e.g. CO, Swinbank et al. 2015; Silverman et al. 2015a, or [CII], Capak et al. 2015), ALMA allows to derive M_{dyn} for galaxies up to $z \sim 5$, but also in this case the measurements are available for a restricted number of objects only. Alternatively, the mass of a galaxy can be evaluated through the gravitational lensing method that allows one to measure the mass of the lens from the shape of the lensed galaxy¹. Also in this case however, the measurements are limited to small samples because gravitational lensing phenomena are relatively rare (Hoekstra et al. 2013, but see also Negrello et al. 2017).

To estimate the *stellar* mass content of a galaxy $M_{\star}$ instead, the most common method is to compare the observed photometry to stellar evolutionary model, thus reconstructing the intrinsic stellar emission of the galaxy. This method is relatively cheap, as it requires the use of photometric data only, and allow to access large samples in broad redshift ranges thanks to the increasing availability of large multi-wavelength data-set (see e.g. GOODS-MUSIC, Grazian et al. 2006, COSMOS, Ilbert et al. 2009; Muzzin et al. 2013; Laigle et al. 2016). The basic idea of this technique is that the shape of the optical/near-IR spectral energy distribution of a galaxy is made up by the sum of the spectra of the stars it contains. Therefore, from the observed photometry, one can use stellar evolution models to infer the stellar content of the galaxy.

The main assumption behind this technique is that it is possible to treat stars in a galaxy as a linear combination of Simple Stellar Populations (SSPs), which are coeval generations of stars with homogeneous chemical and dynamical properties. The mass spectrum of a SSP is defined by the Initial Mass Function (IMF), while the energy spectrum of each star with a certain initial mass and chemical composition is defined in the spectral libraries. Since the evolution of each star depends on its mass and evolves with time, the full spectrum of each SSP evolves and its evolution is modeled through stellar evolution theories. Star formation episodes in galaxies occur in an extended time interval so that a simple linear combination of SSP is not a good approximation for the galaxy Star Formation History (SFH)². The galaxy SFH is unknown a priori and it is typically parametrized by an analytic function (constant, exponential, exponentially declining etc.). Eventually, it is also possible to define a chemical evolution history, that is the evolution of the metal content of a galaxy with time. This parameter is strictly related to the SFH, as the chemical enrichment is produced by stars. However, metallicity turns out to be of minor importance when deriving the stellar mass of a galaxy (Bolzonella et al., 2010; Pforr et al., 2012). Finally, one has to consider the presence of dust that absorbs light arising from young stars in the optical/UV wavelength regime (see Sect. 1.1.3). A dust attenuation curve has to be applied to the intrinsic stellar emission to obtain the “attenuated” spectrum of the galaxy itself. Once modeled the evolution of star formation events and known (through SSPs) the observed properties of each generation of stars in the galaxy it is possible to produce a synthetic spectrum of the intrinsic stellar emission of the galaxy, i.e. a Composite Stellar Population (CSP, see Fig. 1.1). By then comparing this CSP spectrum with the data it is possible to determine the best set of parameters (galaxy age, specific Star Formation Rate $sSFR$, dust attenuation and mass-to-light ratio M/L) that reproduces the observed data. From the best-fit M/L , known the luminosity, it is possible to derive the galaxy mass as $M_{\star} \sim L \times M/L$.

¹to be precise, the mass measured in this way is the one enclosed within the Einstein ring thus including part of the

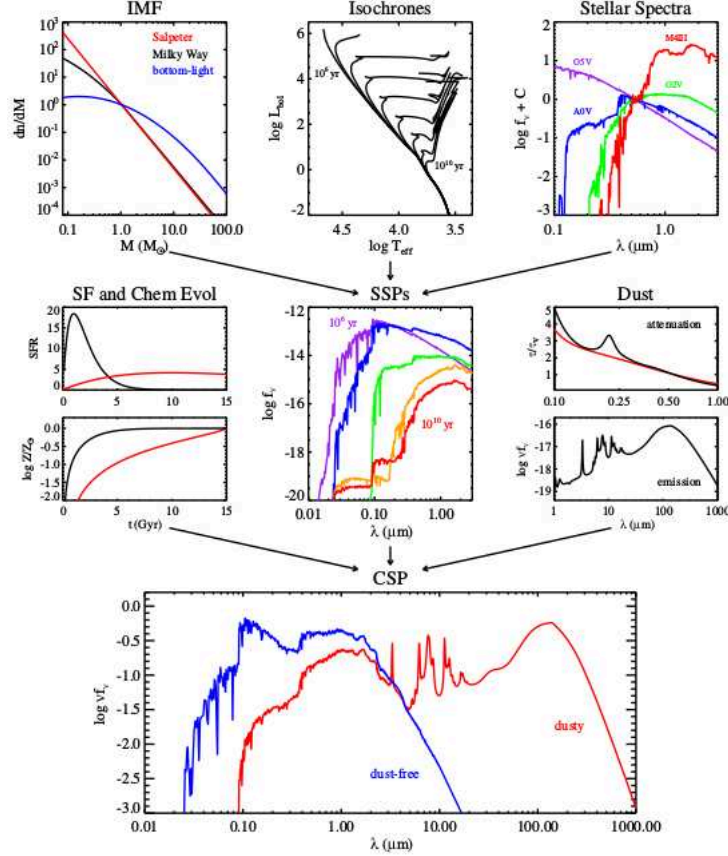


Figure 1.1: Overview of the stellar population synthesis technique. The upper panels highlight the ingredients necessary for constructing simple stellar populations (SSPs): an IMF, isochrones for a range of ages and metallicities, and stellar spectra spanning a range of effective temperatures T_{eff} , bolometric luminosity L_{bol} , and metallicity. The middle panels highlight the ingredients necessary for constructing composite stellar populations (CSPs): star formation histories and chemical evolution, SSPs, and a model for dust attenuation and emission (see also Sect. 1.1.3 and 1.1.4). The bottom row shows the final CSPs both before and after a dust model is applied. From Conroy (2013).

Several codes exist³ to perform such computations. These codes differ for many reasons: e.g. the adopted stellar libraries, the considered stellar evolution prescriptions, the fitting techniques, the wavelength range included in the fit, the dust attenuation recipes, the treatment of the AGN contribution when included, see Sect. 1.3 for more details about AGN) or the simultaneous fit of nebular emission lines.

The uncertainties of the SED-fitting derived parameters are usually estimated on mock galaxy catalogs, generated from real observed data. The typical uncertainties to derive $M_{\star}$ is $\sim 0.2 \text{ dex}$ (Mobasher et al., 2015). The SFH is the most uncertain parameter in the SED-fitting and, as a consequence, it produces an uncertainty in the computation of $M_{\star}$ also (Pforr et al., 2012; Ciesla et al., 2017). Another important source of uncertainty is the quality of the photometry and its wavelength coverage. Particularly important for an accurate estimate of the stellar mass is the inclusion of rest-frame near-IR data in the fit: the intermediate-low mass stars make up the bulk of the galaxy $M_{\star}$ and have the peak of emission in the near-IR so that including these bands in the SED-fitting is crucial for a proper derivation of $M_{\star}$ (Kannappan & Gawiser 2007; Maraston et al. 2010; Bolzonella et al. 2010

galaxy halo (Treu & Marshall, 2016).

²the Star Formation History, SFH, is defined as the evolution of star formation rate with cosmic time

³A thorough but not complete list of SED-fitting codes may be found at <http://www.sedfitting.org/SED08/Welcome.html>

but see Shapley et al. 2005 for opposite conclusions). In addition, the use of different codes, population synthesis models, attenuation law and the inclusion of emission lines can cause discrepancies in estimates of $M_\star$. In general, it is easier to recover $M_\star$ for a passive galaxy than a star forming one. In fact, when star-formation is ongoing, the bright youngest stellar populations can outshine the older and fainter stars which mainly contribute to the stellar mass content of the galaxy (Maraston et al., 2010). Furthermore, the presence of dust can be a major problem for heavily obscured objects, as it may heavily impact also the near-IR emission from intermediate-low mass stars (Lo Faro et al., 2013).

1.1.2 The Star Formation Rate

The Star Formation Rate (SFR) quantifies the rate at which a galaxy converts its gaseous mass in stars. The techniques used to derive the SFR for a galaxy are various and depend mainly on the distance of the target and the portion of the spectrum sampled by the data. All the methods share the same basic goal which is to identify the emission probing recently formed stars, avoiding as much as possible contamination from older stellar populations or other sources of emission. The only direct method available to quantify the SFR is by *counting* young stars or events tracing recent star formation (like supernovae remnants) but this method is currently applicable to our Milky Way and very few galaxies in its vicinity, as it requires to resolve objects on very small scales. For the vast majority of galaxies, the SFR can be derived from the integrated light, by applying calibrations that have been defined by assuming a certain IMF and a SFH. Several indicators have been adopted in literature, spanning a wide range of photometric and spectral observations from the UV up to radio wavelengths. Each of these indicators suffers of its drawbacks and it is sensitive to emission of stars with slightly different stellar masses, meaning that each indicator samples a slightly different star-formation timescale. This issue might have a minor impact on the SFR measurements with respect of other uncertainties but has to be taken into account when comparing different indicators (Kennicutt & Evans, 2012).

In the following of this section, I will briefly describe the three main SFR indicators adopted in this work, mentioning the main drawbacks behind each one of them and the time-scales to which they are sensitive.

- **SFR from the UV continuum emission**

The integrated spectrum of a galaxy in the wavelength range $\lambda \in [1200 - 2800] \text{ \AA}$ is dominated by the emission of young stars ($M_\star \sim 10 M_\odot$) so that the UV emission is proportional to the SFR. Calibrations to compute the SFR from the galaxy UV emission have been derived using spectrophotometric models that assume continuous SFH on a timescale of $\sim 10^8 \text{ yrs}$. This technique can be applied to star-forming galaxies in a wide redshift range, as it requires photometric data only which are relatively easy to obtain. However, UV emission is extremely sensitive to the form of the IMF, to dust absorption (see details in Sect. 1.1.3) and, to minor extent, also to the galaxy metal content, as metals efficiently absorb radiation in the UV part of the spectrum. Also, UV emission can be heavily contaminated by AGN emission.

- **SFR from the $H\alpha$ emission**

Massive young stars produce a large amount of energetic photons ($\lambda \sim 912 \text{ \AA}$) which ionize the surrounding gas and produce hydrogen recombination lines by cascade (Osterbrock & Ferland, 2006). The brightest of these lines, the $H\alpha$ emission, is widely used as a SFR indicator, mainly because it falls in the optical regime for local galaxies, but in principle all the hydrogen recombination lines can be used as a SFR tracer (see Kennicutt, 1998a, e.g.).

Since only extremely massive stars ($M_{\star} \sim 20 M_{\odot}$) produce an amount of high-energy radiation sufficient to ionize the hydrogen in the ISM, the $H\alpha$ emission is sensitive to the recent SFH probing timescales $\tau_{\text{SF}} \sim 20 \text{ Myr}$ and thus it provides an “instantaneous” measurement of the SFR. The calibration is valid for case B recombination (Osterbrock & Ferland, 2006)⁴ and it shares the uncertainties mentioned above for the UV indicator. In addition, it is sensitive to the presence of shocks and it can suffer from contamination of $[\text{NII}]_{6549,6583}$ to the $H\alpha$ emission, a major problem for low resolution spectra (see e.g. Chapter 2).

- **SFR from the FIR**

As anticipated above, a significant fraction of the optical/UV luminosity of a galaxy is absorbed by the interstellar dust and is re-emitted in the thermal IR at wavelengths of $\lambda \in [8 - 1000] \mu\text{m}$. Since in a star-forming galaxy most of the UV/optical emission arises from star formation, the infrared luminosity can be used as a SFR tracer. In this case, the calibration has to assume, in addition to an IMF and a SFH, a dust optical depth. The widest used calibration of Kennicutt (1998a) for example, assumes that an optically thick, compact dust component is heated by young stars in a continuous burst of $\sim 100 \text{ Myr}$ (i.e. the same timescale of SFR_{UV}). FIR observations provide a very suitable tool for deriving SFR without suffering dust biases. Therefore far-IR indicators are crucial when deriving the Star Formation activity of dust-rich star-forming galaxies. The presence of an AGN or an older stellar population may however contribute to dust heating (the so-called “*cirrus*” contamination, Kennicutt et al. 2009), causing the FIR luminosity to overestimate the SFR.

When a broad wavelength coverage is available, indicators may be combined to derive the obscured and un-obscured SFR, for example, by adding the bolometric FIR emission to the observed UV light (Papovich et al., 2007) or the $H\alpha$ emission (Kennicutt et al., 2009).

1.1.3 Dust attenuation

The presence of dust in a galaxy strongly influences its spectrum. While contributing marginally to the galaxy mass budget, being $\sim 1\%$ of the interstellar medium (ISM, a minor component of the total mass of the galaxy itself), dust efficiently absorbs radiation at UV/optical wavelengths. To precisely derive the SFR of the galaxy, or its SFH but also its $M_{\star}$, it is crucial to model with accuracy the effect of dust on its spectrum. In this section I will briefly summarize the effect of dust on UV/optical radiation and the main assumptions behind the computation of the dust attenuation and extinction curves. Moreover, I will list the main recipes used to compute the galaxy extinction and attenuation, as well as some of the well known empirical correlations holding among these recipes. I will focus in particular on the measurements that will be used and discussed in the main body of this Thesis.

Dust has two principal effects on the UV/optical emission: the absorption, which depends on dust composition and geometrical properties (shape and size); the scattering, which is related to the geometrical distribution of dust grains with respect to the radiating source. Considering a point source (e.g. a star) located behind a thin dust screen, the observed radiation will be lower because of dust absorption. This effect is defined as *extinction* and it depends only on the physical properties of dust. Measurements of dust extinction are possible only for resolved sources, therefore they are limited to local objects like the Milky Way or the Magellanic clouds.

⁴The Case B approximation corresponds to the assumption that every Lyman photon (i.e. a photon having an energy $E \geq 13.6 \text{ eV}$) is absorbed within the nebula or re-emitted

To quantify the capability of dust in absorbing the electromagnetic radiation, one can use the extinction curve $k(\lambda)$ which relates the total extinction (parameterized with the color excess $E(B - V) = A^0(B) - A^0(V)$, which is the difference between the extinction at B and V bands respectively, Calzetti 2001a) to the attenuation at a specific wavelength A_λ ⁵ as:

$$k(\lambda) = \frac{A_\lambda}{E(B - V)} \quad (1.1)$$

The extinction curve has been evaluated for example by Cardelli et al. (1989) and Fitzpatrick (1999). The Cardelli and Fitzpatrick curves are reported in Figure 1.2.

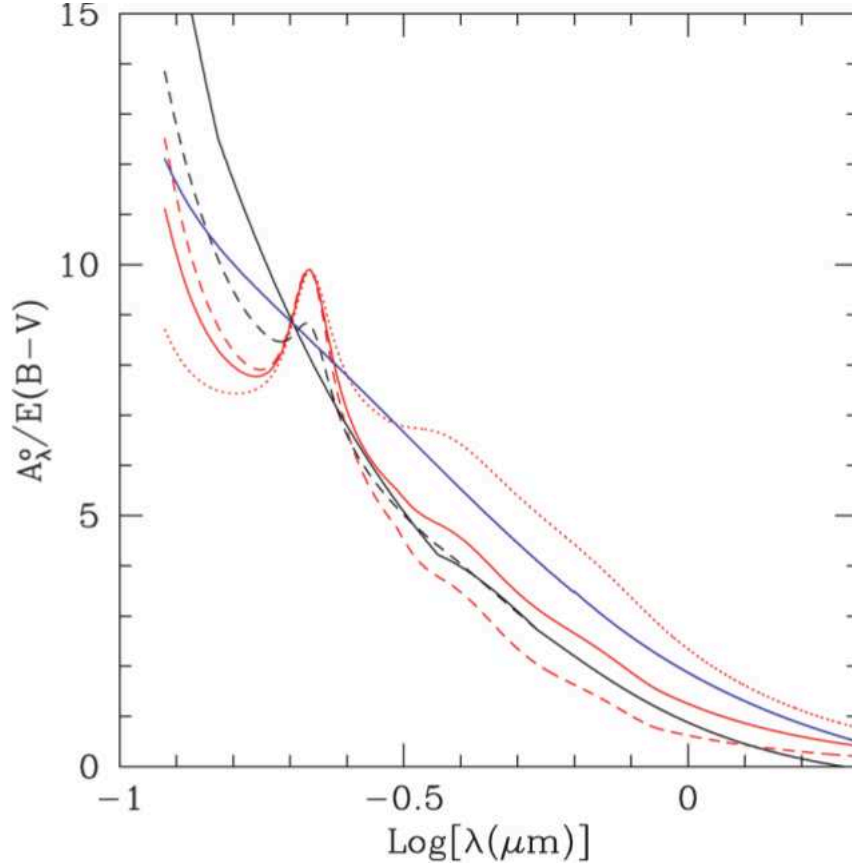


Figure 1.2: Extinction curves for local galaxies. The MW extinction curve is shown for three different values of R_V , 3.1 (solid red line), 5.0 (dashed red line), and 2.0 (dotted red line) (Cardelli et al., 1989; Fitzpatrick, 1999). The extinction curves of the Large Magellanic Cloud’s 30 Doradus region (dashed black line) and of the Small Magellanic Cloud’s bar (solid black line) are reported for $R_V = 2.7$ (Gordon & Clayton 1998; Misselt et al. 1999). The starburst obscuration curve (Calzetti et al., 2000, blue line) is shown here for a purely illustrative comparison because it refers to the dust obscuration of galaxies which is conceptually different from the dust extinction of stars. From Calzetti (2001a).

For the vast majority of extra-galactic observations, resolved measurements are not available and the effects of dust extinction are mixed with the effects of dust geometry. The net effect of dust in this case, which now is referred to as *attenuation*, is different and strongly depends on the spatial distribution of dust and stars.

⁵ As discussed in Calzetti (2001a), A_λ^0 and A_λ are two different terms which refer to two different concepts. The term $A_\lambda^0 = 1.086\tau_\lambda$ refers to the extinction at wavelength λ while $A_\lambda = m_{\lambda,a} - m_{\lambda,0}$ is the effective extinction and subsumes also the dependence of absorption on dust geometry. The equivalence $A_\lambda^0 = A_\lambda$ will hold only for a foreground, homogeneous and non-scattering dust screen (Calzetti, 2001a)

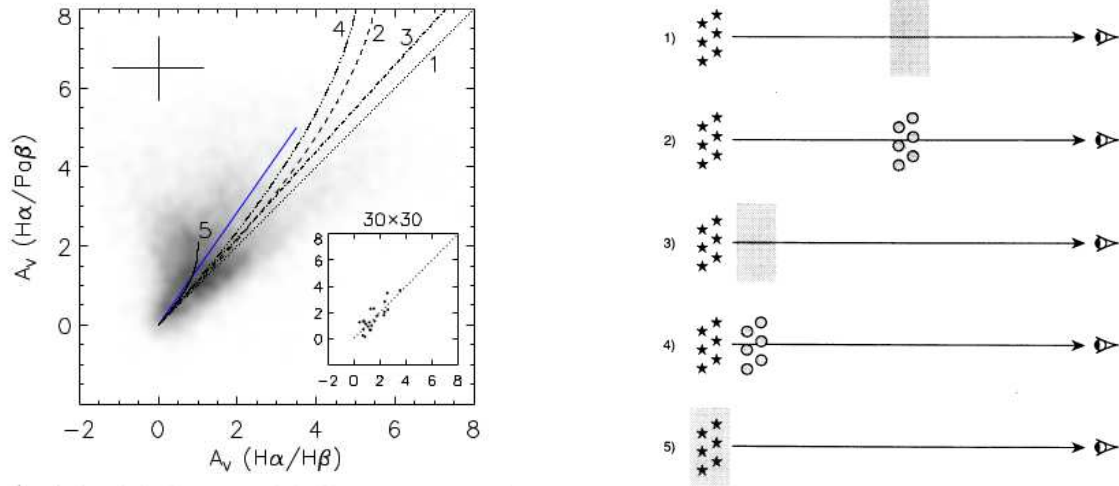


Figure 1.3: *Left:* relation between A_V derived from the Balmer Decrement ($H\alpha/H\beta$, x -axis) and from the $H\alpha/Pa\beta$ ratio (y -axis) in HII regions of M83, from Liu et al. (2013). Measurements are compared to five models considering different dust geometries (1-foreground screen; 2-clumpy dust screen; 3-uniform scattering slab; 4-clumpy scattering slab; 5-uniform mixture). The inset shows the same comparison but averaged over $\sim 180 pc$, corresponding to a 30×30 grid: all data points become consistent with model 1 because small scales fluctuations are averaged out. *Right:* Schematic view of the five configurations of dust/ionizing stars considered in Liu et al. (2013). Models are numbered in the same fashion as in the left panel. From Calzetti et al. (1994).

Two additional effects need to be taken into account in this case: the dust scattering into the line of sight and the differential optical depth, for which radiation at lower λ can effectively emerge from the dust cloud only if emitted in its external regions. Both effects compete to generate a grayer extinction than a foreground screen, which is the upper limit for dust attenuation at a fixed dust optical depth. Observations covering a broad wavelength range can help to constrain the geometry of the system, since they allow to measure the effect of differential dust optical depth (see e.g. Liu et al., 2013). The effect of dust geometry is exemplified in the left panel of Figure 1.3 where measurements of dust attenuation in resolved HII regions of M83 from hydrogen emission lines at different wavelengths are compared. The availability of different hydrogen lines allows to perform a crude estimate of the dust geometry by comparing the line ratios to models of the emitters/absorbers geometry. Only in the case of a foreground screen of non-scattering dust, any pairs of hydrogen line will yield the same A_V . For different geometries, schematized in the right panel of Fig. 1.3, the shortest wavelength line pairs will yield lower dust attenuation because of the differential optical depth.

A dust attenuation curve accounting for the effects of dust geometry was derived by Calzetti et al. (1994) on UV-selected blue compact starbursts in the local Universe. This curve, shown in Fig. 1.2, appears to be grayer with respect to the MW and LMC ones. This is expected if the distribution of dust and stars deviates from a foreground model. This curve has been largely applied to high redshift studies to correct UV/optical observations for dust, because it has been derived from spatially integrated measurements as is the case for studies of distant galaxies. In particular, it is widely adopted in SED-fitting codes to re-construct the intrinsic stellar SED of a galaxy (Ilbert et al., 2006; da Cunha et al., 2008; Noll et al., 2009; Bolzonella et al., 2000). However, it is not yet clear its universal validity and this topic is quite controversial, as I will further discuss in Chapter 2. Johnson et al. (2007); Reddy et al. (2015) for example, find good agreement with the local starburst attenuation curve while Buat et al. (2012) report variation in the attenuation curve slope up to $\sim 40\%$. These variations however, seem to be mostly related to variations in the dust attenuation curve between individual galaxies. The usage of this curve seems to be still appropriate to large samples, at least in local galaxies (Battisti et al., 2017).

Dust attenuation indicators

To quantify the effects of dust on a galaxy, several indicators can be used. These indicators are related to different dust effects and may refer to different galaxy component. Nonetheless, they are correlated between each other and this helps to constrain the dust effects on the galaxy spectrum when the wavelength information is limited. Here, I list the most widely used indicators to sample the effects of dust on a galaxy spectrum.

- **Dust attenuation/extinction from hydrogen recombination lines**

The effect of dust attenuation on the *ionized gas* can be evaluated from the ratio of hydrogen recombination line pairs sufficiently distant in λ . The intrinsic ratio of hydrogen emission lines is known with high accuracy, since it mainly depends on quantum effects and poorly varies with density and electron temperature (Osterbrock & Ferland, 2006). If three or more recombination lines are available in a wide wavelength range (e.g. $H\beta$, $P\beta$, $Br\gamma$) it is possible to both constrain the dust geometry and extinction (Calzetti et al., 2000, see also Fig. 1.3). If only two lines are available, typically $H\alpha$ and $H\beta$, it is necessary to assume a dust geometry configuration which usually is a foreground screen model. The color excess can be computed from the ratio between the observed hydrogen lines and their intrinsic value:

$$E_{\text{gas}}(B - V) = \frac{2.5}{k_{H\beta} - k_{H\alpha}} \log\left[\frac{H\alpha/H\beta}{2.86}\right] \quad (1.2)$$

where $k_{H\alpha}$ and $k_{H\beta}$ are the extinction/attenuation curve evaluated at $\lambda_{H\alpha}$ and $\lambda_{H\beta}$ respectively. The numerical value 2.86 in Eq. 1.2 is the intrinsic $H\alpha/H\beta$ ratio and it is derived assuming an electron temperature, an electron density and Case B recombination. Equation 1.2 refers to the case of the Balmer Decrement but it can be easily extended to other recombination lines by considering different values of the intrinsic ratio and the extinction/attenuation curve k_λ .

- **Reddening from the UV spectral slope β**

To measure the effect of dust on the *stellar continuum*, one can use the slope of the spectrum at UV wavelengths which is sensitive to dust reddening. In absence of dust, the shape of the continuum spectrum in a star-forming galaxy is nearly flat in L_ν in the range $\lambda \sim [1200 - 2800]$ Å (Kennicutt, 1998a). This is valid for two extreme assumptions for the SFH: an instantaneous burst of star formation and a constant star formation rate. For the first case, the typical duration of the burst is ~ 20 Myr, during which the stars contributing to the flux in the aforementioned wavelength range have had no time to evolve off the main sequence so that the shape of the intrinsic spectrum in the wavelength range of interest does not change. Considering instead a constant star formation, the continuous generation of new stars keeps the shape of the UV spectrum roughly constant (Calzetti et al., 1994). In presence of dust, absorbing radiation selectively, attenuation will be higher at shorter wavelength, thus producing a spectrum with a negative slope β .

The UV spectral slope was originally defined as the slope of the observed UV spectrum in ten spectral windows free of absorption features (Calzetti et al., 1994). However, it has been commonly measured from the UV colors (using the GALEX filters in the local Universe, Kong et al. 2004, or the $(B_J - z)$ color at $1.4 \leq z \leq 2.5$, Daddi et al. 2004) or from the galaxy modeled SED when lacking of a sufficient wavelength coverage (see e.g. Oteo et al., 2014; Puglisi et al., 2016).

- **Dust attenuation from the Infrared excess IRX**

The infrared excess IRX is defined as the ratio $L_{\text{FIR}}/L_{\text{UV}}$ (Meurer et al., 1999) and measures the dust attenuation of a star-forming galaxy, since L_{FIR} traces the bolometric luminosity of dust while L_{UV} quantifies the observed stellar emission. This parameter is not easy to measure given the difficulties to access to far-IR data, specially at high- z .

These quantities trace different effects of dust in different regions of the spectrum. Nevertheless, they appear to be correlated between each other through *empirical* relationship, calibrated mainly on local galaxy samples.

For example, $E_{\text{gas}}(B - V)$ measures the extinction of the *ionized gas* and is related to the stellar continuum extinction, through the relation:

$$E_{\text{star}}(B - V) = 0.44 \times E_{\text{gas}}(B - V) \quad (1.3)$$

with the $f = 0.44$ constant that was empirically derived by Calzetti et al. (1994). The existence of this correlation has been ascribed to geometrical effects. In particular, it has been interpreted as an evidence that HII regions (from which nebular lines are emitted) are more spatially correlated with the heavily obscured birth clouds (e.g. Charlot & Fall, 2000, see also Sect. 2.1 for more details). This relation has been derived from nearby blue starburst galaxies and it seems to hold for other classes of galaxies in the local Universe with a mild dependence on galaxy properties (Battisti et al. 2016, but see also Wild et al. 2011 for contrasting results). However, it is still not clear how $E_{\text{gas}}(B - V)$ and $E_{\text{neb}}(B - V)$ are related at high- z mainly because the dependence of this ratio on galaxy parameters or z as well as sample selection effects are still not understood (see e.g. Wuyts et al., 2011; Domínguez et al., 2013; Kashino et al., 2013; Reddy et al., 2015; Puglisi et al., 2016). Pursuing this problematic is the main goal of Chapter 2 and it will be discussed there with more details.

The β parameter measures the dust reddening, i.e. quantifies the absorbed radiation at short wavelength. Thus, it is not a measurement of the dust attenuation but rather represents an observational manifestation of it. The reddening is correlated to the total dust attenuation derived from the IRX as a large dust content produces in a galaxy SED both a higher reddening β and a higher total attenuation (indicated by the $L_{\text{IR}}/L_{\text{UV}}$ ratio, Calzetti et al. 1994; Meurer et al. 1999; Kong et al. 2004). This correlation is extremely handful for deriving the total attenuation of the galaxy in absence of far-IR data. If this correlation is universal, one could in principle infer the attenuation of the galaxy by simply having two UV colors. Of course, the real world is much more complex than that. The Meurer et al. (1999) IRX- β relation has been also calibrated on local blue-starburst galaxies, likely having homogeneous properties, but it does not work well for other galaxy samples such as ULIRGs⁶ (Goldader et al., 2002; Meurer et al., 2002; Howell et al., 2010) or normal (non starburst) galaxies (Seibert et al., 2003). Furthermore, the validity of this relation at high- z is still quite disputed (Reddy et al., 2010, 2012; Fudamoto et al., 2017). The physical origin of variations in the IRX- β relation are not yet fully understood. Several factors such as the age of the stellar population, dust geometry effects (including turbulence, patchy dust distribution, relative stars-dust distribution) or intrinsic variations in the dust type can compete to drive variations in a way that the IRX- β plane is broadly populated (Narayanan et al., 2017; Popping et al., 2017). Some of the possible effects leading to variations in the IRX- β relation are summarized in Fig. 1.4.

Understanding the behavior of dust is crucial for a complete understanding of the galaxy SED. Moreover, it is fundamental for deriving accurate relationships which allow to properly correct observations for dust attenuation when a restricted set of observations is available.

⁶Ultra Luminous Infrared Galaxies, i.e. galaxies with $L_{\text{FIR}} \geq 10^{12} L_{\odot}$

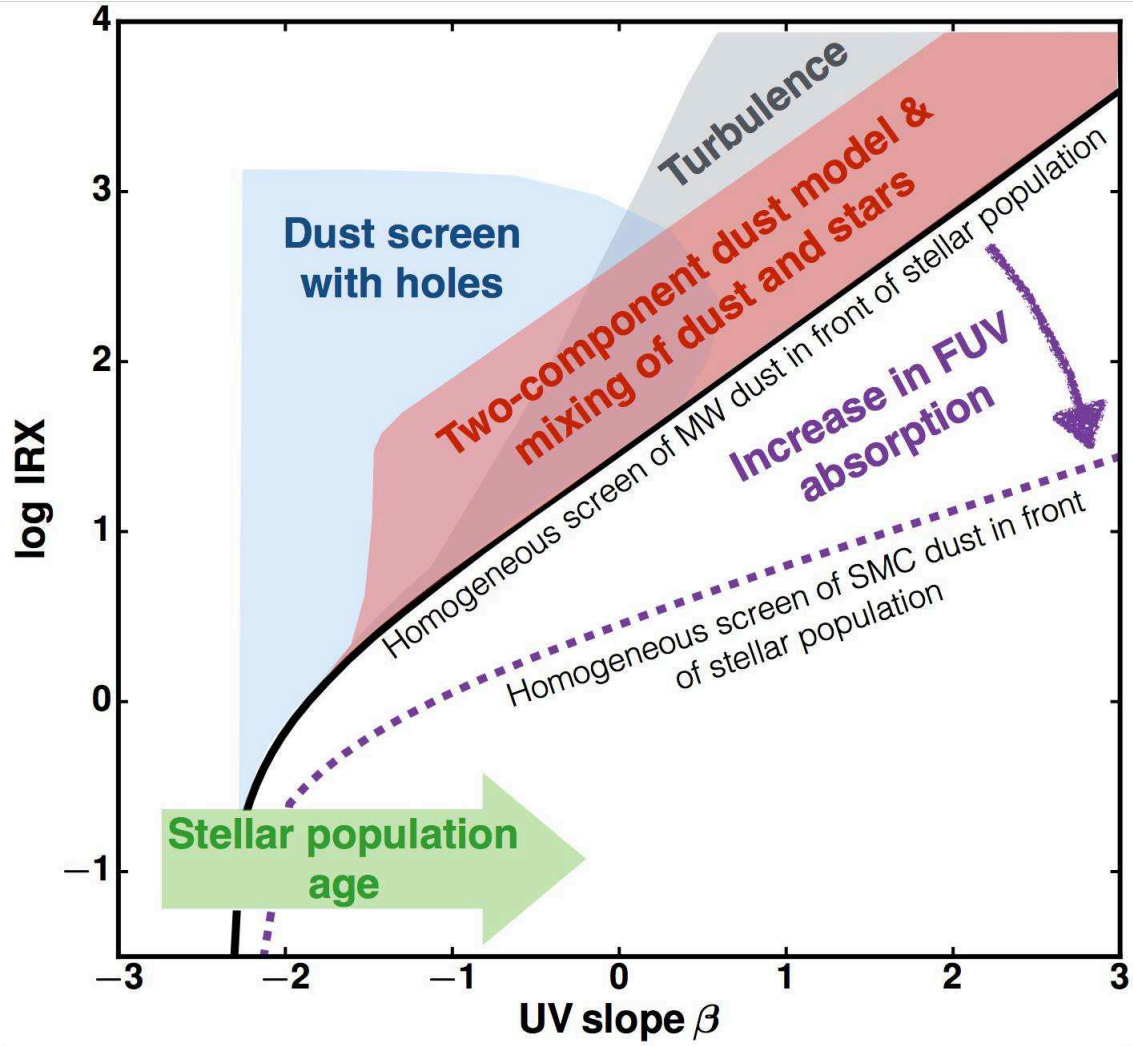


Figure 1.4: Schematic plot summarizing the physical effects driving variations in the IRX- β relation. Geometrical effects as turbulence in the dust screen, a patchy dust distribution, a different dust-stars distribution or a more realistic assumption of a two component dust model (Charlot & Fall, 2000) produce shift towards high IRX (dust attenuation) for a fixed β slope (dust reddening, above the black curve). Variations in the intrinsic properties of dust or in the stellar population age produce shifts below the black curve (i.e. towards redder β for a given IRX). From Popping et al. (2017).

For this purpose, it is necessary to test the validity of the local empirical calibrations in the distant Universe and to parametrize the effects that lead to deviate from the local relationship. Studies in the distant Universe were limited by the wavelength coverage, the statistics and the spatial resolution. Only recently thanks to the big spectroscopic surveys (e.g. 3D-HST, Brammer et al. 2012, MOS-DEF, Kriek et al. 2015, FMOS-COSMOS Silverman et al. 2015b as well as KMOS-3D, Wisnioski et al. 2015, or SINS, Förster Schreiber et al. 2009, for spatially resolved measurements), it has been possible to access to measurements of $H\alpha$ and $H\beta$ at $z \sim 1 - 3$, a crucial epoch for the studies of star formation of the Universe. On the other side, *Herschel* and ALMA allow nowadays to access to far-IR measurements for large samples of distant galaxies thus enabling measurements of dust up to very high redshifts (Reddy et al., 2017; Fudamoto et al., 2017).

Another limitation to overcome for a complete understanding of the dust attenuation issues is the sample selection, limiting the analyses to few classes of galaxies. Pathological objects as heavily obscured galaxies exist and they likely present peculiar dust attenuation properties (Chapman et al., 2005; Rodighiero et al., 2014; Casey et al., 2014b), so that they require dedicated studies.

Currently, few studies discuss this topic at high- z , mainly because these objects are hard to observe in the optical because of the large dust content. Here, I will address this problematic in more details. In particular I will study the dust attenuation properties of the average star-forming galaxy population at $z \sim 1$ in Chapt. 2 while I will discuss the dust attenuation characteristics of the starbursts population at $z \sim 1.6$ in Chapt. 3.

1.1.4 Dust emission

The galaxy ISM contains dust which is heated by stellar radiation: dust reprocesses the starlight and radiates it thermally in the far-IR. Studying the galaxy SED at long wavelengths is important for correcting the optical measurements for dust attenuation. Also, it is crucial for understanding the physical properties of the galaxy itself. By modeling the dust emission it is in fact possible to derive the dust bolometric luminosity L_{FIR} , the dust temperature T_{dust} and mass M_{dust} as well as its composition and geometrical features. The analysis of the far-IR SED is important also for improving our understanding of the evolution of galaxies as a whole. For example, the analysis of the far-IR SED of ULIRGs at $z \sim 1 - 2$ showed that these sources have $T_{\text{dust}} \sim 2 - 5 \text{ K}$ lower than local galaxies with similar L_{FIR} (Pope et al., 2006; Muzzin et al., 2010). This result has been interpreted as an evidence that the two population represent different systems and led to the discovery that $z \sim 2$ ULIRGs are rather the normal star-forming population at $z \sim 1 - 2$ (Daddi et al., 2004; Elbaz et al., 2011).

The typical IR spectrum of a galaxy is composed by features in the mid-IR, sampled by the IRAC bands in the local Universe ($\lambda \sim 4 - 8 \mu\text{m}$) and produced by Polycyclic Aromatic Hydrocarbons (PAH) whose intensity is related to the galaxy metallicity (Draine et al., 2007). In addition, the IR emission includes a modified black body thermal emission at longer wavelengths arising from the emission of dust grains. These dust grains are typically composed by silicate and graphite, even if other dust grain compositions have been considered in literature (see Draine & Li, 2007, and references therein). More complex models include two emitting components in the thermal FIR, a warm ($T_{\text{dust,warm}} \sim 40 \text{ K}$) and a cold one ($T_{\text{dust,cold}} \sim 20 \text{ K}$, e.g. da Cunha et al., 2008) Finally, the AGN dusty torus emits as a black body at mid-IR wavelengths, given that its typical temperature is warmer than dust heated by a stellar component ($T_{\text{torus}} \sim 60 \text{ K}$, Fritz et al. 2006 and see also Sect. 1.3.1). The contribution of this torus to L_{FIR} is typically minor in dusty star forming galaxies (Rodighiero et al., 2011).

The aforementioned models specify the dust physical properties and allow to derive properties as attenuation, scattering, polarization, depletion and FIR emission by comparing this emission to observed data. A good data coverage in the far-IR is important to break the degeneracies of the optical galaxy SED. For example, data covering the mid-IR SED are be important to identify the presence of an obscured AGN while (*Herschel*) photometry close to the peak of the thermal emission of the galaxy ($\lambda_{\text{peak}} \sim 100 \mu\text{m}$) is important when measuring T_{dust} . Finally, longer wavelength data sampling the Rayleigh-Jeans tail of the dust emission curve are fundamental when estimating M_{dust} because of the shallowest dependence on T_{dust} and because dust emission is optically thin at these wavelengths (see e.g. Casey et al., 2014a; Simpson et al., 2016). The far-IR coverage is also crucial when one wants to estimate L_{FIR} , so to have a dust-unbiased estimate of the galaxy SFR as well as strong constraints on its dust attenuation. This in particular may be crucial for specific classes of galaxies as far-IR bright starburst systems, as I will discuss in Section 1.2.2 and in Chapter 3.

1.1.5 Gas-phase metallicity

The metallicity Z , i.e. the abundance of heavy elements in ISM and stars, is a key parameter when interpreting Galaxy Evolution. The chemical enrichment is in fact produced by stellar nucleosynthesis so that measurements of the abundances give details on the recent SFH of the galaxy (see e.g. Belfiore et al., 2015; Ma et al., 2017, and references therein). Metallicity measurements refer to the stellar component when derived from absorption lines of the galaxy spectrum, and to the gas when measuring the element abundances through emission line ratios. In this work I will discuss measurements of the gas-phase metallicity of star-forming galaxies thus I will briefly summarize in the following the principal methods for deriving this quantity and I will ignore the metallicity of the stellar component. Hereafter I will use Z to refer to the gas-phase metallicity only unless specified otherwise.

Several indicators for measuring Z were presented in literature as well as several calibrations for each indicator. Most Z indicators are optical emission lines, even though indicators in the IR regime have been used (e.g. Maiolino et al., 2005). These Z indicators can be either direct and indirect.

Direct indicators measure the electron temperature T_e of HII regions which depends on the metal content of the gas, as metals favor the cooling of the nebula. Most used indicators consider Oxygen lines which is the most abundant element in a nebula, emits optical lines sensitive to T_e (e.g. [OIII] $_{4363}$) and is a primary nucleosynthesis product. Other elements, like Nitrogen, are also used. Direct methods are however biased towards high temperature, i.e. objects with low metallicity. In fact when metallicity is increasing the temperature decreases and collisional excitation phenomena became unefficient making the emission lines unobservable.

Indirect indicators aim to derive the metallicity from the ratio between forbidden transitions and hydrogen emission lines. These indicators are accessible in a wider redshift range because they are usually related to strong lines easier to detect, but are hard to calibrate. Calibrations against direct methods are available only in a narrow metallicity range thus indirect methods are usually calibrated using theoretical models (Kewley & Dopita, 2002).

The use of different indicators as well as different calibrations for the same indicator may cause different results on measurements of the absolute metallicity of a sample. However, the impact of different indicators and calibrators should be minor when considering relative metallicity measurements (Kewley & Dopita, 2002). In any case these effects can have a major impact on galaxy evolution studies, specially when attempting to highlight differences among different samples or to study evolutionary trends with redshift. Applying consistent calibrations and indicators is thus a fundamental requirement. Metallicity analyses at various redshifts and in different galaxy samples delivered so far interesting scaling relations that give insights on Galaxy Formation and Evolution processes. These scaling relations will be discussed in Section 1.2.1 and in Chapter 3.

1.2 The Main Sequence of star-forming galaxies

One of the pivotal results of the observational efforts carried out in the last decade has been the discovery that the majority of star-forming galaxies in a wide range of redshifts follow a correlation in the stellar mass $M_\star$ - SFR plane (see Figure 1.5). The existence of this correlation was firstly recognized by the work of Noeske et al. (2007) and has been confirmed from a large amount of subsequent works (Elbaz et al., 2007; Daddi et al., 2007; Pannella et al., 2009; Karim et al., 2011; Wuyts et al., 2011; Kashino et al., 2013; Rodighiero et al., 2014; Speagle et al., 2014; Whitaker et al., 2012, 2014; Pannella et al., 2014; Renzini & Peng, 2015, to mention a few).

The general analytic expression of this star forming galaxies Main Sequence (MS) is as follows:

$$\log(SFR) = \alpha \times \log(M_{\star}) + \beta \quad (1.4)$$

With α and β being two free parameters identifying the MS logarithmic slope and normalization respectively. The existence of this relationship and its observed properties have important implications for our understanding of galaxy formation and evolution.

In the widely accepted interpretation, the existence of the MS and its tight scatter, which varies between ~ 0.2 and 0.3 dex (Whitaker et al., 2012; Schreiber et al., 2015), implies that Star Formation in the vast majority of galaxies up to $z \sim 6$, (Speagle et al., 2014) is a fairly ordered process, occurring with long timescales in a quasi steady state mode of star formation. Galaxy mergers, which are instead a stochastic process, only represent a few percentage of the star-forming galaxy population and have a minor impact on the cosmic Star Formation History (e.g. Rodighiero et al., 2011; Schreiber et al., 2015).

The MS normalization β represents the absolute value of the $sSFR$ and sets the growth rate of individual galaxies (Renzini & Peng, 2015). It evolves with redshift such that star-forming galaxies in the distant Universe were characterized on average by a larger $sSFR$, mirroring the fact that the cosmic SFR density is a growing function of redshift (Renzini, 2016).

Finally, the MS slope α controls the relative growth of galaxies as a function of stellar mass. It can vary between ~ 0.8 and unity (Daddi et al., 2007), depending on the selection criterion and on the adopted SFR indicator (see Rodighiero et al., 2014, , e.g.). For example, selecting galaxies in a pass-band that is directly sensitive to the SFR (such as the rest-frame UV or the FIR) automatically induces a Malmquist bias in favor of low-mass galaxies with above average SFR, thus flattening the resulting $SFR - M_{\star}$ relation. However, Rodighiero et al. (2014) showed that a wide variety of SFR indicators all give consistent results when applied to mass-selected samples.

Recent studies have also shown that the MS tends to flatten at high stellar masses (see e.g. Whitaker et al., 2012; Magnelli et al., 2014; Whitaker et al., 2014; Ilbert et al., 2015; Schreiber et al., 2015, 2016; Gavazzi et al., 2015). This “MS bending” at the high masses is not yet understood. It has been explained as a gradually reduction of the star formation efficiency (slow quenching, see e.g. Ilbert et al., 2015; Schreiber et al., 2016) but it can be related also to the build up of bulges that can increase the differential rotation within the disk thus preventing the gas fragmentation (morphological quenching, Martig et al., 2009, but see also discussion and references in Schreiber et al. 2016), or simply not contributing to the star formation in the galaxy itself (Abramson et al., 2014; Schreiber et al., 2015; Tacchella et al., 2015). However, discussing the existence and the implications of the MS bending is beyond the scope of this work thus in the following the simplest form of the galaxy MS, i.e. a linear relation in the $\log - \log$ space, will be adopted.

1.2.1 Galaxies along the MS: observational properties and some outstanding questions

As already discussed in the previous section, most of the star-forming galaxies at least up to $z \sim 6$ produce a (main) sequence in the $M_{\star} - SFR$ plane indicating that these objects are experiencing continuous star-formation episodes on long time-scales. Since MS galaxies represent the dominant galaxy population in which star-formation is active, a large number of studies across the recent literature attempted to study their properties and to trace their global evolution with cosmic time. An important contribution to our understanding of the star-forming galaxy population comes from the most recent spectroscopic surveys which provide important constraints on the metal content, the dynamical properties, the attenuation and the ISM conditions of large samples of high- z galaxies, complementing

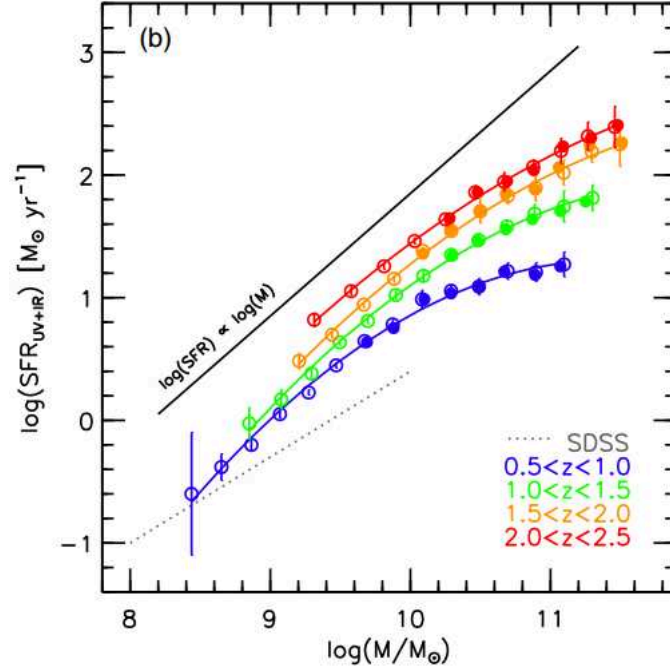


Figure 1.5: $M_\star - SFR$ plane and the star-forming MS as a function of redshift up to $z \sim 2.5$ from Whitaker et al. (2014).

the scenario depicted by the photometric surveys and allowing us to trace with unprecedented detail the properties of normal star-formers with time.

MS galaxies are typically disks (Wuyts et al., 2011; Wisnioski et al., 2015), even if the presence of clumps in these disks grows with redshift (Schreiber et al., 2015). These disks are supported by rotation (Förster Schreiber et al., 2009). The turbulence in these disks, traced by the velocity dispersion σ in spectroscopic measurements, seems to raise with redshift (e.g. Bournaud et al., 2007; Wisnioski et al., 2015, and references therein). A possible explanation for this increasing trend is that it is related to the increasing gas fractions, which are thought to be responsible of the increasing of SFR at high- z (Daddi et al., 2010b; Genzel et al., 2010, 2015). It seems that MS galaxies at a $z \sim 2$ are baryon dominated (Genzel et al., 2017), the baryon mass being mostly in gaseous form rather than in stars. There are also indications that these properties vary across the MS. Cosmological simulations suggest that the high-SFR galaxies in the upper envelope of the MS are compact, with high gas fractions and short depletion times (blue nuggets Zolotov et al., 2015), while the lower-SFR galaxies in the lower MS envelope have lower central gas densities, lower gas fractions and longer depletion times, consistent with observed gradients across the MS (Tacchella et al., 2016; Morselli et al., 2017).

It has been broadly shown that the gas-phase metallicity of MS galaxies depends on $M_\star$ with the most massive galaxies being more metal rich. MS galaxies therefore follow a correlation between $M_\star$ and Z , the so-called Mass-Metallicity Relation, MZR, which holds true both for the gas (Tremonti et al., 2004) and the stellar components (Panter et al., 2008). These two relations are shown in Fig. 1.6. Similarly to what observed for the MS, the MZR also shows a z evolution with low-mass galaxies in the past having a reduced metal content while the most massive ones being fully enriched even at high- z (Maiolino et al., 2008; Zahid et al., 2014; Kashino et al., 2017a; ?). The physical processes generating the MZR are not yet clear. It may arise by the fact that the chemical enrichment is less efficient in low-mass galaxies: low-mass galaxies may be less capable to retain reprocessed material in their small potential well, so that the enriched material can be easier removed via outflows. On the other side, the MZR and its redshift evolution might be an evidence of the so-called “chemical

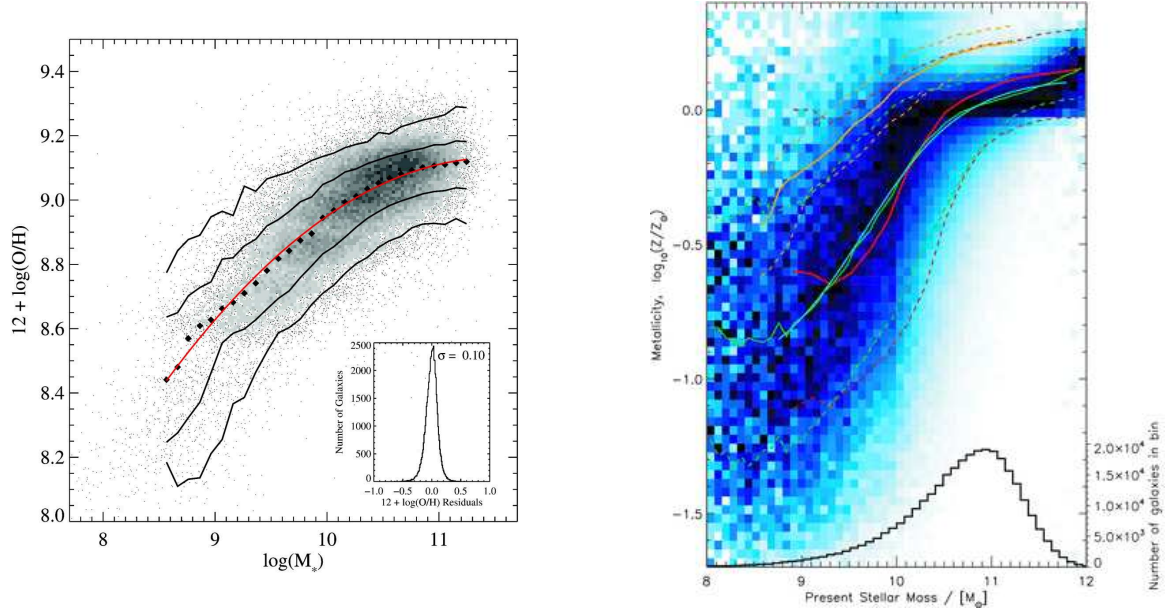


Figure 1.6: *Left:* Gas-phase metallicity as a function of M_* for local star-forming galaxies, from Tremonti et al. (2004). *Right:* M_* -metallicity relation for the stellar component in local galaxies. From Panter et al. (2008).

downsizing” (see e.g. Maiolino et al., 2008; Maier et al., 2016) according to which more massive objects are fully mature, while the chemical enrichment processes are still ongoing in low-massive systems.

The metal content of MS galaxies anti-correlates with their SFR: when fixing M_* , galaxies with the highest SFR have also a lower Z (the Fundamental Metallicity Relation, FMR Mannucci et al., 2010). It is not clear if this FMR is constant with redshift, and how it depends on the adopted indicators for either Z or SFR (Kashino et al., 2016, 2017a). This relation has been interpreted as an indirect evidence of gas-inflow processes and self-regulation. According to the general understanding, the FMR is the result of a delicate interplay between pristine gas inflow processes and Star Formation, with the former diluting the galaxy metal content and triggering the SFR at the same time (see for example the Lilly et al. 2013 bathtub model).

The study of these two correlations allow to derive important constrain on several galaxy evolutionary processes. For example, cosmological simulations are commonly calibrated in order to reproduce the local MZR and FMR, by tweaking free parameters as feedback efficiency (Maiolino et al., 2008).

The conditions of HII regions in which star-formation takes place, seem to evolve with cosmic time as well. For example, recent studies show that the most distant MS galaxies have, on average, a larger electron density n_e and a larger ionization parameter (that can be translated into a larger SFE or into a larger AGN contribution, Kashino et al. 2017a; Hirschmann et al. 2017).

Concerning the dust attenuation properties of these MS galaxies, it seems that in the local Universe they depends on galaxy integrated properties like M_* (Garn & Best, 2010) but also SFR and Z (Battisti et al., 2016). This seem to hold qualitatively also at high- z (Zahid et al., 2014; Tan et al., 2014; Pannella et al., 2014) but the details of these scaling relations are still not clear and, in particular, it is not clear whether these properties evolve with redshift or they rather depend on the galaxy conditions itself. These issues will be further addressed in Chapter 2.

In summary, MS galaxies show homogeneous properties but strongly evolving with redshift. This is in agreement with the observed trend for the cosmic SFR density which shows that the Universe is an evolving entity and stresses the fact that the physics of MS-galaxies has to be studied at each redshift to comprehend how the different conditions influence star-formation.

1.2.2 Starburst galaxies: known facts and open issues

The main implication of the galaxy MS is that SFH in the majority of star forming galaxies are very similar among each other, in contrast with a stochastic build up of the galaxy stellar mass. This means that galaxy mergers are relatively unimportant for the cosmic Star Formation History. On the other side however, outliers above the galaxy MS are known to exist. These off-MS objects are often referred as starburst galaxies (or simply starbursts), as they show exceptional SFRs given their stellar masses (see left panel in Fig. 1.7).

Galaxies on and above the MS seem to make up two distinct populations (Rodighiero et al., 2011; Bisigello et al., 2017; Caputi et al., 2017) and have been associated with different growth mechanisms (Daddi et al., 2010a; Elbaz et al., 2011). While MS galaxies are thought to grow on long timescales as a consequence of smooth gas accretion from the Intergalactic Medium (IGM), MS outliers seem to be experiencing a violent, starburst mode of star-formation with high efficiency (Daddi et al., 2010b; Sargent et al., 2014; Silverman et al., 2015a), although this view is currently debated (Narayanan et al., 2012; Kennicutt & Evans, 2012; Santini et al., 2014). The SB mode, being very rare, despite their high level of SFR, seem to contribute modestly to the cosmic star formation history SFH (Rodighiero et al., 2011).

Local outliers are mainly ULIRGs and are extremely dust-rich objects. This dust is mostly concentrated in extremely compact regions in the center hiding the light from the nuclear starburst to optical telescopes. As a consequence of the very high dust content, starburst galaxies appear as heavily obscured and present exceptionally high values of L_{FIR} , which dominates their bolometric luminosity. This extreme far-IR emission may arise either by an AGN or star formation or a combination of the two, but it is dominated by dust grains heated by intense star formation episodes in most of the cases (Sanders & Mirabel, 1996). In the current paradigm, the starburst occurs as a consequence of galaxy mergers (Sanders et al., 1988). The merger of two late-type galaxies produces molecular cloud collisions that dissipate orbital angular momentum, thus funneling the gas into the merger nucleus and increasing the efficiency of star formation (Scoville et al., 1986). The major merger picture is confirmed in the local Universe where nearly all the heavily obscured starbursts are found in interacting pairs (and sometimes in three-galaxy systems, see e.g. Väisänen et al. 2008). Furthermore, IFU spectroscopy has revealed that local SBs show major merger signatures as very complex kinematic structures like asymmetries, multiple components, heavily perturbed velocity fields, and complex gas properties, with evidence of strong nuclear outflows and shock dominated regions (Rupke et al., 2010; Westmoquette et al., 2012; Rich et al., 2015).

The question remains open for what triggers the starburst in high- z outliers, where the larger gas fractions cause major mergers to enhance weekly the SF (Fensch et al., 2017). Recent studies suggest that starbursts might be instead primordial systems caught in the act of starting their SFR process (Mancuso et al., 2016). Alternatively, other studies propose that the high SFR measured in starbursts are subained by high gas fraction (Scoville et al., 2015) rather than an enhanced SFE (as suggested in Silverman et al. 2015a and Sargent et al. 2014) or a combination of the two (Genzel et al., 2015; Scoville et al., 2016). The starburst at high- z could be produced by violent disk instabilities induced by the large gas inflows from the cosmic web (Dekel & Burkert, 2014; Narayanan et al., 2015).

Understanding the nature of star-formation in these starburst systems and what are the mechanisms driving such large SFR is a debated topic in modern Galaxy Evolution studies. Merger-driven starbursts are in fact the best candidate to be the progenitors of passive evolving ellipticals (e.g. Toft et al., 2014): the study of this minor population is thus crucial for a complete understanding of the processes regulating galaxy formation and evolution.

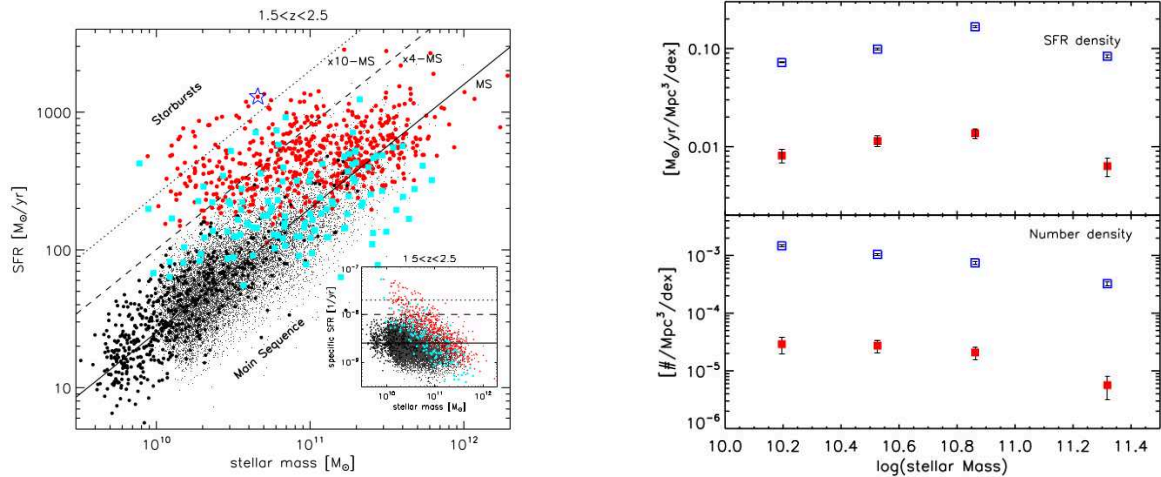


Figure 1.7: *Left:* $M_{\star} - SFR$ relation at $1.5 \leq z \leq 2.5$. The solid black line indicates the main sequence (MS) for star-forming galaxies at $z \sim 2$, while the dotted and dashed lines mark the loci 10 and 4 times above the MS, respectively. Sources above the $4\times$ MS are classified as starbursts. *Right:* SFR density (*top panel*) and number density (*bottom panel*) of on-sequence sources (blue open squares) and off-sequence sources (red filled squares), in four mass bins. MS outliers yield a minority contribution to the SFR. Both plots are from Rodighiero et al. (2011)

1.2.3 A galaxy life on the $M_{\star}$ -SFR plane

The interplay of the different mechanisms at play in galaxy evolution shapes the relation between the physical parameters that we observe at different cosmic epochs and, in particular, the dependence of SFR on $M_{\star}$. Thus, it is tempting to interpret the position of a galaxy in the $M_{\star}$ -SFR rate plane as a pointer to its evolutionary stage (see Figure 1.8). Different interpretations have been proposed to follow the life of sources assembling their $M_{\star}$ through different paths, with random episodes pushing them for short time scales above the MS, and eventually quenching the most massive sources to bury them in the graveyard of red and dead galaxies well below the MS. The situation is quite complex, with various teams proposing different evolutionary tracks (e.g. Dekel & Burkert, 2014; Mancuso et al., 2016; Tacchella et al., 2016; Ciesla et al., 2017). The evolutionary schemes have to deal with the shut down of SF, or its drop much below the MS regime, the so-called *quenching*: this is perhaps the most dramatic change taking place during the life of galaxies. The opposite process, rejuvenation, i.e. the return to an appreciable star formation rate, can also occur, possibly triggered by the capture of a gas-rich galaxy (Mancini et al. 2017, in preparation). But we know that over cosmic times the fraction of quenched galaxies steadily increases, approaching unity at $z \sim 0$ in the high mass and high overdensity (i.e. groups and clusters) extremes. Thus, quenching dominates over rejuvenation. Understanding the growth of galaxies and the physical nature of quenching has been a longstanding open issue and it is still one of the hottest topics in galaxy evolution (Renzini, 2016).

This complex story is also intimately linked to the presence of nuclear activity at the very center of massive galaxies: the accretion of gas onto the super-massive black hole (SMBH) is indeed one of the potential quenching mechanisms that are invoked by models (e.g. Hopkins et al., 2008). The accretion activity onto the SMBH can help us to build the bridge from an alive galaxy forming stars to an elliptical, red and dead system. Thus, a complete dissertation about the life cycle of a galaxy cannot miss out the interaction with its central black hole. I will discuss this aspect in the next sections.

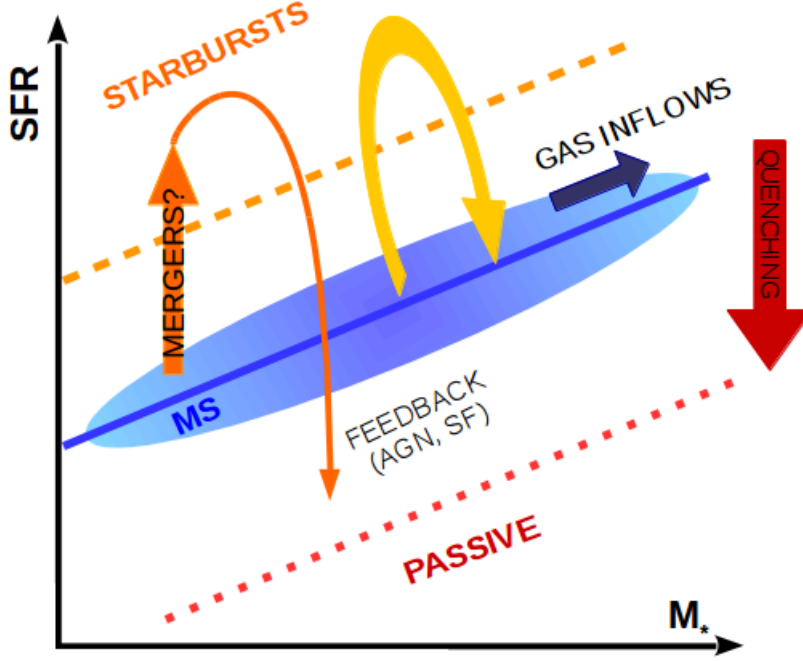


Figure 1.8: Summary of the episodes that a source could experience along the $M_\star - SFR$ plane. Rotationally supported star-forming galaxies on the MS could merge with similar systems and increase their “starburstiness”, i.e. being pushed above the MS. Similarly, disks through violent disk instabilities could reach similar high specific SFR. MS sources are continuously fed by pristine gas inflows that sustain their SFR on long timescales. Natural fading of SFR or AGN winds can eventually quench galaxies driving them on the elliptical situ situated below the MS.

1.3 Active Galactic Nuclei and their role in galaxy formation

An important ingredient in galaxy formation studies is the nuclear activity of the central black hole. SMBHs are in fact ubiquitous in all classes of galaxies and their activity is now postulated as having a major role in quenching star-formation in galaxies, specially at high redshift. Understanding the connection between the AGN and its host galaxy is currently one of the most active fields in galaxy formation and evolution studies.

In this section, after introducing the main physical properties of the AGN, I will summarize some of the evidences of its co-evolution with the host galaxy. I will then focus on this connection in a specific case, i.e. when driven by major mergers, which are believed to trigger, after a starburst phase, a luminous QSO. I will present arguments supporting the existence of this sequence and critically examine the difficulties in firmly demonstrating its existence via observations and/or simulations. Lastly, I will present models and observations of AGN-driven outflows which are the main mechanism of interaction between the central engine and the surrounding system. These outflows can play a major role in driving the clear-out phase of gas and dust in the aforementioned merger sequence, leading a galaxy to its death as a passive object.

1.3.1 AGN in a nutshell

Almost all galaxies host in their center a SMBH. The major growth phase of the SMBH produces intense nuclear activity, from which the name of Active Galactic Nucleus (AGN, Netzer 2013).

The engine of an AGN is a central black hole with typical masses of $M_{\text{BH}} \sim 10^6 - 10^9 M_{\odot}$ that is accreting mass from a geometrically thin yet optically thick disk of a scale of $\sim 0.01 - 0.1 \text{ pc}$ and it is embedded in a geometrically as well as optically thick torus composed by dust and molecular gas, extended on a scale of $\sim 1 - 10 \text{ pc}$.

The accretion disk is formed by material with high angular momentum, which spirals towards the BH loosing gravitational energy: the gravitational energy is converted in electromagnetic radiation with typical efficiencies ranging from $\sim 6 - 40\%$. The typical temperature of the accretion disk is $T_{\text{disk}} \sim 10^5 \text{ K}$ so that mostly emits X-ray and UV photons. The torus surrounding the accretion disk consists in dust grains at multiple temperature, whose convoluted black body emission peaks at mid-IR wavelengths (Mor & Netzer, 2012).

The high-energy photons produced in the accretion disk are able to ionize gas clouds with very high densities ($n_e \geq 10^8 \text{ cm}^{-3}$, Osterbrock & Ferland 2006) located in the vicinity of the black hole, producing extremely broad emission lines ($\text{FWHM} \sim 10^3 - 10^4 \text{ km s}^{-1}$) from permitted transitions (e.g. $\text{H}\beta$ or $\text{H}\alpha$): these emission lines define the so-called Broad Line Region (BLR) around the BH and may or not be observed depending on the orientation of the obscuring torus with respect to the line of sight.

The ionizing photons escaping the central regions of the AGN are capable of ionizing gas in low density regions ($n_e \leq 10^6 \text{ cm}^{-3}$) above and below the plane of the disk and extending $10^2 - 10^4 \text{ pc}$ in radius. Since these clouds are relatively distant from the BH, their speed is lower than in the BLR thus the emission lines produced are narrower (Narrow Line Region, NLR). Lines in the NLR can be produced either from permitted and forbidden transitions (e.g. the $[\text{NII}]_{6549,6583}$, $[\text{OIII}]_{4959,5007}$) due to the lower density. As the gas clouds producing the narrow emission are located outside the putative dusty torus, the capability to observe them does not depend on the orientation of the system.

Several sub-classes of AGN have been introduced in literature, according to their different observed properties and/or selection techniques and the connection between the various AGN sub-categories is still poorly understood (Padovani et al., 2017). In particular, it is still not clear whether these categories represent different manifestation of the same entity and the difference is purely due to geometrical effects (as proposed in the classical “unified” model, Antonucci 1993 and Urry & Padovani 1995) or they are simply caught in the act of different evolutionary phases (Hopkins et al., 2008, e.g.). Although these questions are intriguing and active research is ongoing to solve them, it is beyond the purpose of this work to enter into the details of this problematic as the main focus of this work is to discuss the connection of the AGN with the host galaxy itself. For the sake of simplicity, I will also avoid to enter in the similarly complex nomenclature of various AGN population. I will therefore simply refer in the following to “AGN host galaxies” to distinguish these objects from sources in which the emission is dominated by star formation.

1.3.2 Evidences of an AGN/Galaxy co-evolution and causal connection

It is reasonable to assume that AGN and Star Formation are strictly connected, as both processes require the same fuel, which is cold molecular gas. However, these processes involve completely different scales: the BH accretion takes place into an exceptionally small region of less than 1 pc around the galaxy center, while Star Formation is usually extended across the galactic disk thus involving scales of the order of $\sim 10 \text{ kpc}$. Moreover, the time-scales considered are extremely different: the AGN is a short-lived and highly intermittent phenomenon ($t_{\text{AGN}} \sim 10^8 \text{ Myr}$) while Star Formation is, on average, a secular process with a $\sim \text{Gyrs}$ time-scale duration.

Determining the existence of a causal connection between these events is not an easy task and any result from observational tests is subject to many-fold interpretations.

If we consider the binding energy of a BH ($\sim 0.1 M_{\text{BH}} c^2$, assuming 10% of radiative efficiency), we see that it is typically order of magnitudes larger than the one of the bulge ($\sim M_{\text{bulge}} c^2$): this means that even a small fraction of the energy released during the accretion onto the BH is sufficient to affect the gas content of the bulge itself. The interaction between the energy and radiation generated by accretion onto the SMBH and the gas in the host galaxy is usually referred as “feedback”. AGN feedback is believed to be at the origin of various scaling relation between AGN-related quantities and host parameters, like the correlation between central BH mass M_{BH} and the stellar velocity dispersion of the bulge σ_{bulge} (that is a proxy for the bulge stellar mass M_{bulge} , Kormendy & Ho, 2013). However, the existence of scaling relationships does not directly imply the existence of a co-evolution. For example, the $M_{\text{BH}} - \sigma_{\text{bulge}}$ correlation can also be produced by dry galaxy mergers (Peng, 2007). Additional hints supporting a star-formation/AGN causal connection come e.g. from studies of AGN-host galaxies in the color-color diagram (Schawinski et al., 2007) which reveal that the majority of local AGN are hosted in galaxies occupying the green valley, suggesting that AGN can play a role in quenching star formation and in morphological transformation of galaxies. Finally, BH and galaxy growth evolve in a remarkably similar way. Most of the galaxy growth occurs at $z \geq 1 - 2$, where the average star-forming galaxy population was more active in forming stars, and similarly nearly half of the integrated BH growth occurred at $z \geq 1 - 2$ (e.g. Marconi et al., 2004; Shankar et al., 2009; Aird et al., 2010). This similarity is evident looking at Fig. 1.9, which compares the BH accretion rate (BHAR) density with the cosmic SFR density: both quantities display the same trend increasing from $z = 0$ to 1 and declining steeply at high redshifts after a broad peak at around $z \sim 1 - 3$ (Madau & Dickinson, 2014).

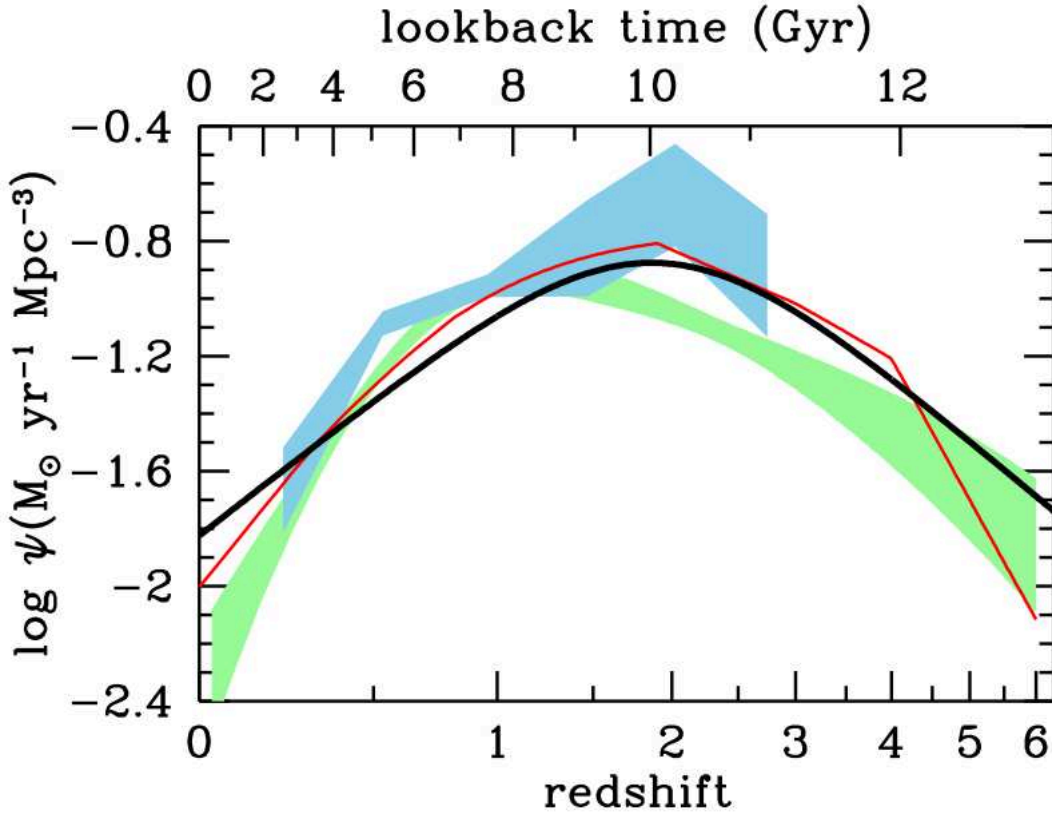


Figure 1.9: Cosmic SFH (black solid curve) compared with the SMBH accretion history from X-ray (red and light green curves) and infrared (light blue curve). From Madau & Dickinson (2014).

The idea of an AGN-SF causal connection is further supported by theoretical studies, that invoke the AGN to explain some observed galaxy properties. For example, the presence of an AGN heating the gas is required to explain why X-ray halos detected around ellipticals and cluster galaxies do not collapse to further form stars (Fabian, 1994). The ejection of enriched material from the host via strong winds is also required to explain the metal enrichment of the Intra-Cluster Medium (ICM) and Inter-Galactic Medium (IGM). Furthermore, semi-analytical models over-predict the galaxy mass function (see sketch in Fig. 1.10 from Silk & Mamon 2012): feedback from the AGN is required to prevent galaxies from overgrowing.

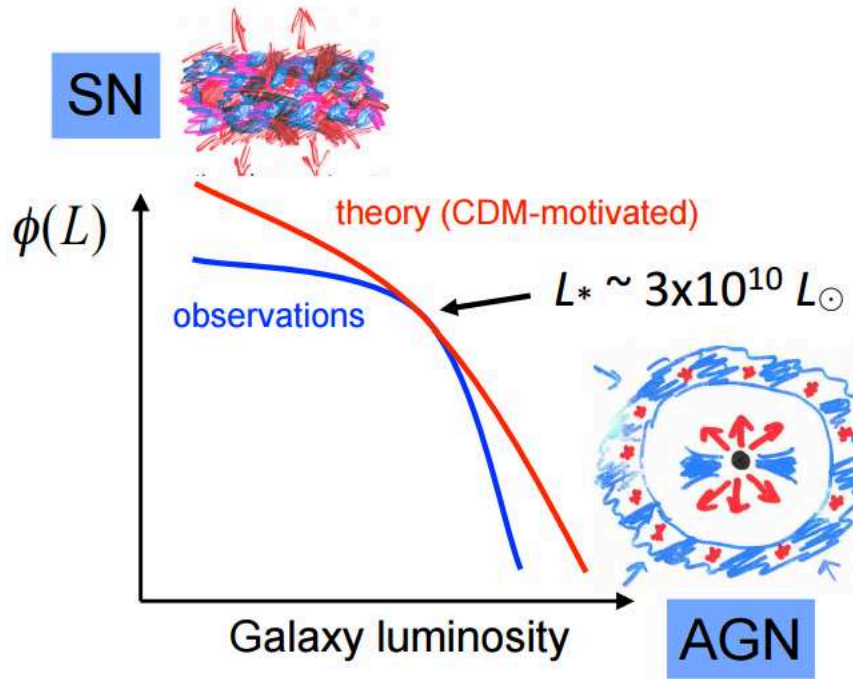


Figure 1.10: Role of feedback in modifying the galaxy luminosity function. From Silk & Mamon (2012).

The arguments listed above are intriguingly suggesting that a strong connection between AGN and star formation exists but these evidences are largely circumstantial and do not offer any observational proof of causal connection. In fact, as stated at the beginning of this section, the BH and galaxy growth are naturally related because they are both fueled by the cold gas content of the galaxy. Defining if a causal connection exist, how it proceeds and what are the physical mechanisms involved is still an open challenge for galaxy formation and evolution studies (see Harrison, 2017, for a recent review). A key question is, in particular, if the AGN is affecting the host galaxy properties and specifically, its SFR. Studying the AGN properties and star formation in actively star forming galaxies hosting an active BH and comparing these results with star formation properties of inactive galaxies represent an observational test that can help in answering this question. This is the experiment that we will conduct in this Thesis, to test the existence of an AGN-host galaxy causal connection in a specific population of galaxies, i.e. heavily obscured starburst galaxies above the MS (see Sect. 1.2.2), with the ultimate goal of probing the evolutionary sequence from inactive starbursts to optically bright QSO.

1.4 From MS to QSO via major mergers

As discussed in Section 1.2, the existence of the MS and of highly star forming MS outliers implies that two main processes of galaxy growth occur: a secular growth along the MS in a (quasi) steady state; stochastic episodes of major galaxy growth driven by major mergers that trigger short-lived and intense starbursts above the MS. Similarly, two different ways of BH growth seem to hold. Likely, secular processes dominate the growth of intermediate-low luminosity BHs, similarly to what concerns the growth of galaxies (see Sect. 1.2 and references therein). Instead, the most luminous population of AGN, defined as QSO⁷, may experience a different growth history strictly connected to the starburst activity in off-MS star forming galaxies.

According to the evolutionary picture firstly proposed by Sanders et al. (1988) and sketched in Fig. 1.11 in fact, the bright QSO activity can be the final stage of the major merger of two late-type galaxies. The galaxy merger firstly induces molecular cloud collisions that dissipate orbital angular momentum, thus funneling the gas into the merger nucleus and increasing the efficiency of star formation (Scoville et al., 1986) resulting in a heavily obscured nuclear SB (see also Sect. 1.2.2). The gas inflow towards the center also furnish the fuel for the SMBH that will initiate a phase of moderate growth during the nuclear starburst. Then, at the end of the starburst, the SMBH will start a phase of exceptional growth at the Eddington limit. During such phase of violent growth, the SMBH will launch powerful winds removing dust and gas from the surrounding. At this “blow-out” stage, the SMBH reveals itself as an optically bright QSO. The winds generated in this phase can also expel the remaining gas from the system thus leading it to its end as a passive spheroid (Sanders et al., 1988; Di Matteo et al., 2005). The QSO phase therefore represents a key stage in the major-merger evolutionary sequence as the fast winds triggered by the intense BH growth are required to clear the galaxy from the dust cocoon in which the starburst was initially embedded and to swept up the residual gas content, not consumed during the previous phases.

QSO-driven outflows play a negative feedback action in this sequence, abruptly quenching star formation in the starbursting host because of gas removal, leading the system to its final end as a passive elliptical.

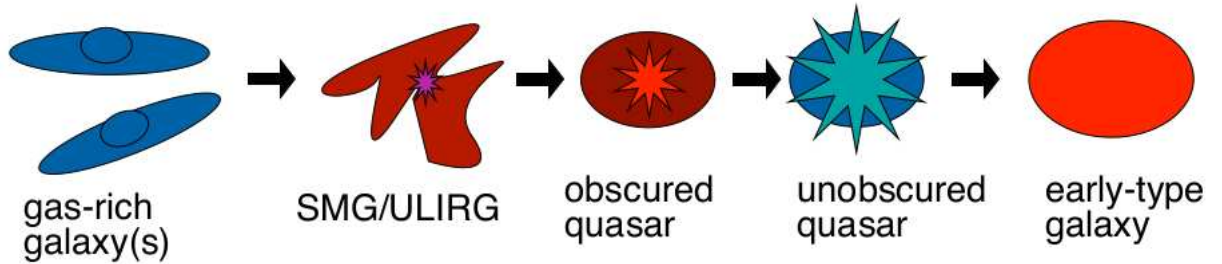


Figure 1.11: The standard evolutionary scenario for the formation of a passive elliptical galaxy: two disk-like, gas-rich galaxies undergo a major merger triggering a nuclear starburst (SMG/ULIRG phase) that will further evolve in a obscured QSO. At the final stage of the evolution, the QSO clears the surrounding from dust (blow-out stage) revealing itself as an optical bright QSO. The powerful winds from the QSO can couple with the host ISM, thus removing the residual gas and lead the system as a passive evolving elliptical. From Alexander & Hickox (2012).

According to the picture sketched above, starburst and QSO are strongly connected phenomena both representing two keystones for the formation of massive spheroids in which the majority of the present-day stellar mass is enclosed. Probing the existence of such sequence, studying the properties of galaxies at all its stages, evaluating the causal connection between different systems

⁷with QSO are usually indicated AGN with $L_{\text{bol}} \geq 10^{45} \text{ erg/s}$

(starburst galaxies and QSOs respectively) and understanding the details of their evolution make one of the main, yet open challenges in Galaxy Formation and Evolution.

The existence of a starburst/QSO connection has been supported by several studies. One of the simplest observational tests of this strong connection is to compare the percentage of AGN on and off the MS, because this quantity gives an idea of the amount of time the AGN is active in starbursts. The AGN fraction among starbursts is high either in the local universe (up to $\sim 50 - 80\%$ local starbursts host an AGN, Alexander & Hickox 2012) and at high- z , where nearly all of the extremest SBs host heavily obscured AGN (Rodighiero et al., 2011) and show an X-ray luminosity enhancement (Rodighiero et al., 2015). AGN host galaxies on the MS are instead $\sim 10\%$ (see e.g. Kashino et al., 2017a): this implies that the AGN duty cycle is higher above the MS. In low z ULIRGs/QSOs, the AGN contribution to the bolometric luminosity increases when L_{FIR} increases as well as the nuclear separation tracing the merger stage (Veilleux et al., 2009), meaning that the contribution of QSO emission in starbursts seem to increase towards the end of the merger sequence.

In addition, it has been observed that the nuclear obscuration mildly increases with the AGN contribution and the merger stage. Although this correlation is very weak, it may suggest that from early to intermediate stage of the merger both nuclear obscuration and AGN fraction are increasing. For late-stage mergers close to coalescence, showing also the highest AGN contribution, the nuclear obscuration decreases, consistent with the picture in which, towards the end of the sequence, the AGN clears the surrounding and shows up as an optical bright QSO. Conversely, Su et al. (2013) do find no significant difference between the properties of stellar populations in local ULIRGs with or without AGN components, against an evolutionary link among starbursts and QSOs.

The QSO stage corresponds to the “clear-out” phase of the sequence, in which the system becomes visible in the optical. As a signature of this transition phase, we therefore expect to see traces of QSO-driven winds in starbursting QSO systems. Indeed, dust-obscured QSO at high redshift show an high occurrence of strong outflows (outflows will be discussed in details in Sect. 1.4.1): these outflow are not commonly observed to affect the spectra of UV-luminous quasars, providing evidence that the reddened quasars are in a phase of expelling their gas and dust (Banerji et al., 2012).

Moreover, the strength of these outflows anti-correlates with the starburst L_{FIR} , indicating that they can have a negative impact on the host star formation in obscured star-forming galaxies (Farrah et al., 2012). High- z galaxies hosting an AGN seems also to have lower gas fraction than the average non-active star forming galaxies, as an additional indication that the gas content of the host has either been consumed and/or removed via outflows (even if these results are mostly related to objects sitting on the MS Kakkad et al., 2017; Carniani et al., 2017). Finally, simulations broadly support the existence of such evolutionary sequence showing that a merger generates a powerful QSO in addition to a burst of star formation (see e.g. Di Matteo et al., 2005; Hopkins et al., 2008) but the details of this evolution are still poorly constrained. This mainly is because the considered processes are probing very different scales and short-lived phenomena, making extremely difficult to constrain the interaction between the AGN and starburst phases from theoretical studies (see e.g. Alexander & Hickox, 2012).

To conclude, several evidences support the existence of an evolutionary path from starburst to optically bright QSO, with this sequence triggered by a major merger of two “normal” MS galaxies, as predicted by Sanders et al. (1988). However, these results are not trivial to interpret as these studies probe very short-lived phenomena and usually are able to sample only one specific phase of the sequence. Moreover, a large scatter usually affects the measurements further complicating the interpretation of the results. This scatter may arise from observational effects: for example, characterizing the merger stage through optical imaging is challenging given the extreme obscuration. But the scatter may be due to intrinsic differences as the details on the initial conditions of the merger or the details on the feedback physics (Veilleux et al., 2009).

Also, it can be related to the indicator adopted for tracing starburst and AGN activity as different indicators are probing different timescales, thus different evolutionary stage of the system (Lanzuisi et al., 2017). Unambiguous confirmations of the validity of the SB-QSO sequence are still lacking and it is not clear whether this scenario holds at the peak of SF and BH activity.

To test the evolution paradigm, it is crucial to characterize objects in different stages of the (presumed) sequence. An important test is to study outflows in starburst systems with and without an AGN in the center: as described above, outflows are a key signature of the transition phase from star-forming to passive galaxies. Detecting and characterizing outflow in AGN hosts above the MS; analyze in parallel their host properties (dust extinction, SFR, M_*) and compare these results with a parent sample of non-AGN starbursts can help us to address presence of evolutionary links between the two classes of systems.

1.4.1 Probing the Starburst-QSO evolutionary sequence through outflows

As introduced in the previous section, strong winds are required to clear an heavily obscured quasar from dust and gas, reveal it as an optically bright QSO and eventually lead it to its death as a passive early-type galaxy. Studying the occurrence and the features of powerful winds in starburst galaxies with and without AGN can therefore provide indications on the evolutionary sequence described in Sect. 1.4. In particular, it is of primary importance to study the features of these winds (spatial extension, geometry, energetic) in connection with the host galaxy properties (like dust attenuation, SFR, ISM conditions) in order to properly understand the interplay between the wind and the system and also attempting to constrain its time evolution.

In the following, before summarizing the main techniques to detect outflows, I will discuss a model from King & Pounds (2015) to describe the outflow properties and its interaction with the galaxy ISM.

Models for AGN-driven outflows

Fast, nearly isotropic winds from the AGN are one of the possible ways in which feedback may proceed: they couple with the galaxy ISM to reach galaxy wide scale thus they can have an important role in shaping the host galaxy ISM itself. AGN driven winds are qualitatively similar to stellar driven winds interacting with the surrounding ISM. The wind arising from the BH is strongly slowed in a zone of reversed shock at the interface with the host ISM. This wind removes the ISM in the host galaxy as the contact discontinuity is moving through it: the motion of this discontinuity is supersonic and drives a shock front in the inside. The dominant interaction is the reverse shock that slows the BH wind and inject energy into the ISM. The nature of this shock depends on the timescale of the shock-heated gas cooling with respect of its “flow time”. Depending on the cooling timescale we can have two kind of winds: a momentum-driven flow, if the cooling process is efficient; an energy-driven flow when the cooling processes are negligible. Figure 1.12 schematizes the momentum and energy driven outflows (*top* and *bottom* panel respectively)

In the case of a *momentum-driven* wind, the cooling process is rapid and the kinetic energy accumulated before the shock is dissipated. The fast cooling implies that the shocked gas is highly compressed and the post-shock region is geometrically thin and behaving as a discontinuity (isotherm shock). Since the momentum is conserved, the post-shocked gas transmits only the ram-pressure to the host ISM. The process is not violent so that it has a minor impact on the host galaxy. It has been postulated that momentum-driven winds may be responsible of the $M_{\text{BH}} - \sigma_{\text{bulge}}$ relation.

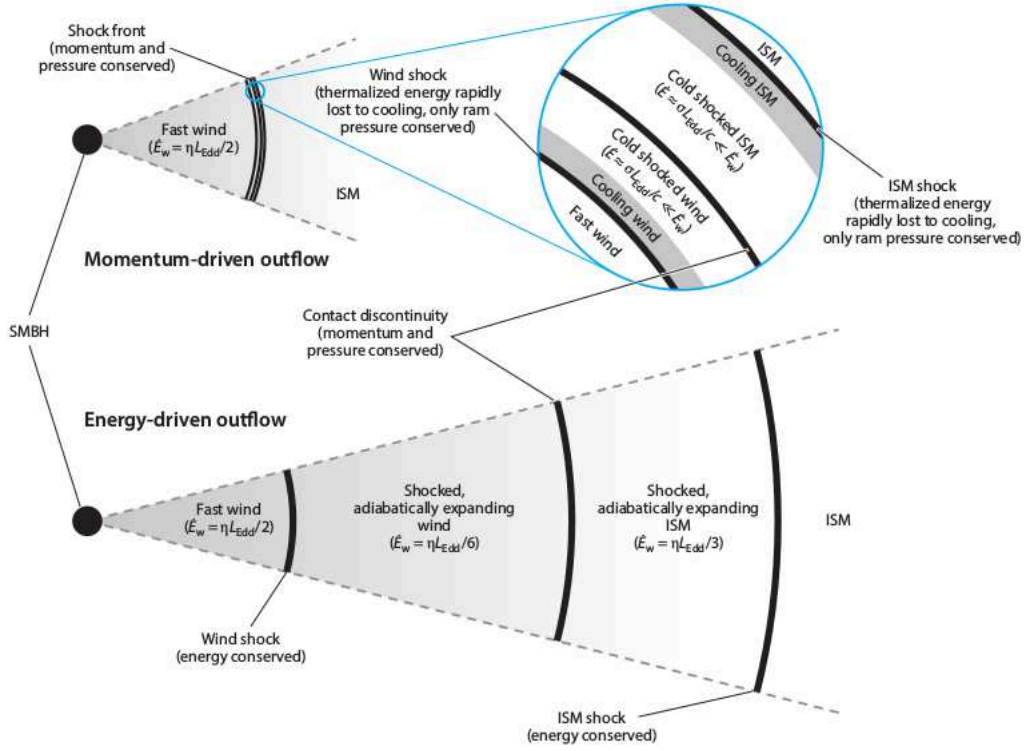


Figure 1.12: Shock pattern of a (top) momentum-driven and a (bottom) energy-driven outflows impacting the host-galaxy ISM from King & Pounds (2015). For more details about the outflow models see the main text.

However, these winds involve small amount of energy only thus they are not capable of removing gas from the host. As such, the mass growth of the galaxy is unaffected. When instead the cooling is negligible, the shocked gas can retail all the mechanical luminosity thermalized during the shock and it expands adiabatically into the ISM. This adiabatic expansion results in a geometrically extended wind.

The discontinuity at the front shock between the outflow and the ISM is highly unstable because the wind is highly expanded and its mass density is much lower than the gas of the ISM outside the shell. These *energy-driven* outflows are much more violent and can involve a huge fraction of the galaxy ISM so that they have a major impact on the host galaxy. It is believed that these process hold when the BH reached a critical mass. Energy-driven outflows are thought to be responsible of the large-scale outflows, capable of removing the gas from the galaxy.

The occurrence of one of the two processes depends on the cooling efficiency which is related to the radial distance of the shock front with respect to the SMBH. The distance from the SMBH, in fact, determines the intensity of the radiation field regulating the cooling process. The BH radiation field accreting at an Eddington limit has a temperature $T_{\text{field}} \sim 10^7 \text{ K}$, while the wind temperature after the shock is $T_{\text{wind}} \sim 10^{10}-10^{11} \text{ K}$. Because $T_{\text{wind}} \geq T_{\text{field}}$, the electrons in the shocked gas loose energy giving it to the BH radiation field through inverse Compton scattering. If the wind shock is located close to the BH, the radiation field is strong enough that this effect cools the wind in a timescale t_{cool} lower than the time $t_{\text{flow}} \sim R/\sigma$ the wind is propagated. Since the radiation field scales as R^{-2} , the cooling time increases as R^2 . On the other side, t_{flow} increases with R only therefore, after a critical radius R_{crit} , the cooling time will be higher than the flow time and the expansion is adiabatic: this will result in an energy-driven wind.

To summarize, the nature of AGN-driven outflows depends on the cooling efficiency of the outflowing gas and determines the extension and the energetic of the outflow itself.

Different outflows have different impact on the host. Momentum-driven outflows are confined within $\sim 1\text{ kpc}$ scales and they are likely ruling the interaction between the SMBH and the bulge. On the other hand, large scale interaction up to $\sim 10\text{ kpc}$ scales are due to energy-driven outflows.

Detecting outflows

Outflows have been observed either in the local Universe and at high redshift from spectroscopy, through blue- and/or red-shifted lines either in absorption or emission (Fabian, 2012; Harrison et al., 2014; Talia et al., 2016). These phenomena can be observed in various regions of the electromagnetic spectrum from the X-ray to the sub-mm, depending on the ionization state of the outflow itself. For example, X-ray and UV absorption lines revealed the presence of fast winds (Ultra Fast Outflows, UFO, see Fabian 2012 for a review) in few luminous AGN in the nearby Universe. In addition, outflows have been detected thorough optical emission lines for their ionized component as well as in near-IR and sub-mm emission lines in the molecular form (Maiolino et al., 2012; Ciccone et al., 2014). One of the major results of these studies is that outflows seem to be a common phenomenon in AGN spectra. However, this does not directly imply that AGN-driven outflows have actually an impact on the host galaxy life. To fulfill this task, AGN winds have to be extended to galactic scales.

The majority of outflow episodes detected in the X-ray, tracing the pre-shock phase in the King & Pounds (2015) model, seem to be concentrated within the nuclear regions (within less than 1 pc scale, e.g. Tombesi et al., 2012) so that the surrounding galaxy is not affected by them. On the other hand, molecular and ionized outflows (potentially connected with the X-ray wind, (?)) are detected on kpc scales.

The major interest for studies of AGN and galaxy interactions (as is the case for the work presented in this manuscript) are outflows extended of $\sim 1 - 10\text{ kpc}$ scales which can reach the galaxy disk and thus potentially interact with the host ISM. An useful tracer to detect extended outflows is the $[\text{OIII}]_{5007}$ emission line.

This line is sufficiently bright to be easily observed up to high- z (Cano-Díaz et al., 2012; Harrison et al., 2014; Cresci et al., 2015a). Most importantly, this forbidden line cannot be produced within the BLR because of the high densities and it traces the NLR, extended on $\sim\text{ kpc}$ scales (see Sect. 1.3). The presence of broad components in this emission lines is a clear signature of outflowing material on large scale: the velocity of this gas, measured from the $[\text{OIII}]_{5007}$ line, is one of the fundamental ingredients to determine the outflow energetic and studying the effect of the outflow on the system (see discussion in Perna et al. 2015; Kakkad et al. 2016; Brusa et al. 2016). The $[\text{OIII}]_{5007}$ emission line have been used to identify wide outflow either in the local Universe and at high redshift. This diagnostic tool will also be used to define the presence of outflow in our sample of AGN above the MS in Chapter 4.

The vast majority of works in literature have used so far long-slit or fiber-based spectroscopy to detect AGN-driven outflows at different redshifts. Although these techniques represent a powerful and quick tool to spot the presence of strong outflow, they do not provide sufficient information to study in detail the interaction between AGN and host galaxy. In fact, they do not provide constraints on the outflow geometry and spatial extension but these two parameters are crucial to properly define the outflow energetic and thus determine the impact of the outflow on the host (for a through discussion see e.g. Husemann et al. 2016). A useful tool to derive the outflow geometry is Integral Field Spectroscopy (IFS) that provides a spectrum for the whole object enabling to map the outflow extension. In addition, spatially resolved spectroscopy allows to study the star-formation geometry. The latter is another important ingredient to understand the interplay between the AGN and the galaxy .

The capabilities of integral field instruments have been exploited to study outflows in the ionised, atomic and molecular phases, revealing the presence of massive outflowing gas with velocity $v \sim 1000 \text{ km s}^{-1}$ that cannot be due to supernovae-driven winds (see Liu et al., 2014; Cano-Díaz et al., 2012; Cresci et al., 2015a,b; Kakkad et al., 2016). These studies however are focused on small AGN samples, biased towards the bright population for the vast majority. Therefore they are hard to be interpreted in a broad context to define the impact of AGN-driven outflow on the whole star-forming galaxy population. Major step forward in this regard will be possible thanks to the SUPER survey, which I will discuss in Chapter 5.2.1.

1.5 This work: overview

The broad aim of this Thesis is to use spectroscopic data in the near-IR observed frame to study several properties of far-IR selected star-forming galaxies, also including AGN hosts, located in different position with respect to the Star-Forming MS at the peak of the star-formation and AGN activity of the Universe. This analysis allows to pinpoint their dust attenuation, gas-phase metallicity, ISM conditions as well as the role of the embedded AGN including a characterization of outflows processes. I corroborate this analysis with a careful reconstruction of the multi-wavelength SED to robustly constrain the SFR and $M_\star$ of these galaxies and study their properties as a function of their MS position. This allows to study the aforementioned properties as a function of their evolutionary stage.

In Chapter 2, adapted from Puglisi et al. (2016), I discuss the dust attenuation properties of a sample of star-forming galaxies representative of the MS population at $0.7 \leq z \leq 1.5$. In this case, I combine near-IR data from the 3D-HST survey with *Herschel* observations to measure the differential attenuation between $H\alpha$ emission and continuum, parametrized by the ratio $f = E_{\text{neb}}(B - V)/E_{\text{star}}(B - V)$. I compare these measurements with results from the literature, either in the local Universe and at high redshift, to have insights on the processes driving the evolution of dust attenuation properties with redshift. I also discuss the effects that can cause discrepancy between various studies of dust attenuation corrections.

In Chapter 3, which is an extended version of the work presented in Puglisi et al. (2017), I discuss the properties of a sample of star-forming galaxies located at least $4\times$ above the MS at $z \sim 1.6$. In this work I use high-resolution fiber spectra in the near-IR from the FMOS-COSMOS survey to study the dust attenuation, gas-phase metallicity and ISM conditions of these MS outliers. I discuss these results in comparison with the properties of the MS sample analyzed in the companion papers from the FMOS-COSMOS collaboration. This comparison allows to place these results in the context of the average population of star-forming galaxies at the same redshift. I also present a simple model to describe dust attenuation in these heavily obscured sources when only spatially integrated measurements are available. Moreover, I provide a toy model to interpret the metallicity evolution of the system experiencing a burst of star-formation.

In Chapter 4 I discuss the properties of AGN-dominated star-forming galaxies above the $4\times$ MS at $z \sim 1.6$, mostly identified from optical diagnostics in the sample studied in Puglisi et al. (2017). I briefly discuss the properties of these systems, such as their morphology, SFR, dust attenuation in comparison with the parent population of star-forming dominated sources above the MS. I also present the detection of an ionized outflow on the average spectrum of this population from a blue-shifted tail in the $[\text{OIII}]_{4959,5007}$ emission lines. I interpret and discuss the ensemble of these early findings in the context of a merger-driven evolutionary sequence from starbursts to AGN (Sanders et al., 1988). Future investigations with higher SN data will allow to confirm these preliminary results.

In Chapter 5 I introduce the IFS techniques and their crucial role for galaxy evolution studies, focusing in particular on their importance for studying galaxy wide outflows.

I present in this context the SUPER survey, an ongoing large program with SINFONI to map the AGN and SF activity of X-ray selected AGN at $z \sim 2$. I describe the sample selection, the observations and the data analysis on XN_115_23, a type-1 AGN selected as a test case from the SUPER observations. I present the computation of the energetic of an ionized outflow detected in the the $[\text{OIII}]_{4959,5007}$ emission from the SINFONI integrated spectrum. I then discuss possible future developments with data from this survey that will certainly allow a major step forward in our understanding of the role of AGN in shaping galaxy evolution.

Finally, in Chapter 6 I summarize the main findings from this Thesis, I draw my conclusions and I present future developments of the work presented in this manuscript.

Chapter 2

Dust attenuation in $z \sim 1$ galaxies from Herschel and 3D-HST $H\alpha$ measurements

Abstract

We combined the spectroscopic information from the 3D-HST survey with *Herschel* data to characterize the $H\alpha$ dust attenuation properties of a sample of 79 main sequence star-forming galaxies at $z \sim 1$ in the GOODS-S field. The sample was selected in the far-IR, at $\lambda=100$ and/or $160 \mu\text{m}$, and only includes galaxies with a secure $H\alpha$ detection ($S/N>3$). From the low resolution 3D-HST spectra we measured the redshifts and the $H\alpha$ fluxes for the whole sample (a factor of 1/1.2 was applied to the observed fluxes to remove the [NII] contamination). The stellar masses ($M_\star$), infrared (L_{IR}) and UV luminosities (L_{UV}) were derived from the SEDs by fitting multi-band data from GALEX near-UV to SPIRE $500 \mu\text{m}$. We estimated the continuum extinction $E_{\text{star}}(B - V)$ from both the $\text{IRX}=L_{\text{IR}}/L_{\text{UV}}$ ratio and the UV-slope, β , and found an excellent agreement between the two. The nebular extinction was estimated from comparison of the observed $\text{SFR}_{H\alpha}$ and SFR_{UV} . We obtained $f=E_{\text{star}}(B - V)/E_{\text{neb}}(B - V) = 0.93\pm0.06$, i.e. higher than the canonical value of $f=0.44$ measured in the local Universe. Our derived dust correction produces good agreement between the $H\alpha$ and IR+UV SFRs for galaxies with $\text{SFR} \gtrsim 20 M_\odot/\text{yr}$ and $M_\star \gtrsim 5 \times 10^{10} M_\odot$, while objects with lower SFR and $M_\star$ seem to require a smaller f -factor (i.e. higher $H\alpha$ extinction correction). Our results then imply that the nebular extinction for our sample is comparable to that in the optical-UV continuum and suggest that the f -factor is a function of both $M_\star$ and SFR, in agreement with previous studies.

¹

2.1 Introduction

The rate at which a galaxy converts gas into stars, the Star Formation Rate (SFR), is a fundamental quantity to characterize the evolutionary stage of the galaxy. The SFR can be measured in several ways, e.g. from the UV luminosity, the far-IR emission, the recombination lines or the radio-continuum (Kennicutt, 1998a; Madau & Dickinson, 2014), although each of these SFR tracers suffers from some uncertainties.

¹This Chapter is adapted from Puglisi et al. (2016)

2.1. INTRODUCTION

Concerning the UV and optical indicators, the main source of uncertainty in the estimate of the SFR is due to the dust extinction, that strongly absorbs the flux emitted by stars at UV and optical wavelengths and re-emits it in the far-IR. Hence, an accurate quantification of the impact of dust on the galaxy integrated emission is crucial to precisely evaluate the SFR. The dust distribution inside a galaxy can be described by a two component model (Charlot & Fall, 2000, e.g.), including a diffuse, optically thin component (the Inter-Stellar Medium, ISM) and an optically-thick one (the *birth cloud*) related to the star forming regions. The birth clouds have a finite lifetime ($\tau_{\text{BC}} \sim 10^7$ yr) and consist of an inner HII region ionized by young stars and bounded by an outer HI region. This model assumes that the stars are embedded in their birth clouds for some time and then disrupt them or migrate away into the ambient ISM of the galaxy. In this model the emission lines are produced only in the HII regions of the birth clouds as the lifetime of the birth clouds is in general greater than the lifetimes of the stars producing most of the ionizing photons ($\sim 3 \times 10^6$ yr). The emission lines and the non ionizing continuum from young stars are attenuated in the same way by dust in the outer HI envelopes of the birth clouds and the ambient ISM but, since the birth clouds have a finite lifetime, the non ionizing continuum radiation from stars that live longer than the birth clouds is attenuated only by the ambient ISM (Charlot & Fall, 2000).

This two component model was conceived to explain the higher extinction observed on the nebular lines with respect to the UV/optical stellar continuum in the local Universe (e.g. Fanelli et al., 1988; Mas-Hesse & Kunth, 1999; Mayya et al., 2004; Cid Fernandes et al., 2005; Calzetti et al., 1994, 2000).

The relation between the color excess of the nebular regions and that of the stellar continuum derived by Calzetti et al. (1994, 2000), i.e. $f = E_{\text{star}}(B - V)/E_{\text{neb}}(B - V) = 0.44$, has proven to be successful for local star-forming galaxies, while it is still unclear if it holds true in the high redshift Universe.

The most secure method to quantify the amount of dust extinction in the HII regions is by directly measuring the Balmer decrement (i.e. the $H\alpha/H\beta$ line ratio).

Nevertheless, such measurements are very challenging at $z \gtrsim 0.5$ since the $H\alpha$ line is shifted to the less-accessible near-infrared window so indirect methods are often needed to infer the attenuation related to the nebular lines.

Current studies on dust properties in high redshift galaxies lead to contrasting results. In fact, while some authors claim that the extinction related to the emission lines and to the stellar continuum are comparable in $z \sim 2$ galaxies (e.g. Erb et al., 2006; Reddy et al., 2010, using UV-selection), other authors confirm the validity of the Calzetti et al. local relation (e.g. Förster Schreiber et al., 2009; Whitaker et al., 2012; Yoshikawa et al., 2010, for samples of mainly optical and/or near-IR selected sources). Some recent works also suggested that the factor $f = E_{\text{star}}(B - V)/E_{\text{neb}}(B - V)$ required to reconcile the various SFR measurements is higher than those computed in the local Universe (e.g. Kashino et al., 2013; Pannella et al., 2014, on sBzK selections). These contrasting results found in the literature are not surprising, given the different and indirect methods used and/or the small and sometimes biased samples of most of these studies. Direct measurements of the Balmer Decrement would be required on statistical samples of sources at high redshift to clarify dust properties of distant star forming galaxies.

In the present paper we used near-infrared spectroscopic data from the 3D-HST survey (Brammer et al., 2012) and multi-wavelength photometry to derive the differential attenuation on a sample of 79 star forming galaxies at z between 0.7 and 1.5, selected in the far-IR within the GOODS-South field. The presence of the far-IR photometry for the whole sample is very important, as these data allow us to robustly constrain the integrated dust emission.

This kind of approach has been often applied to galaxies in the local Universe (see for example Domínguez Sánchez et al., 2014), but only very occasionally at higher redshifts.

The paper is organized as follows. In Section 2.2 the properties of the sample and the data-set are described. Section 2.3 presents the spectral analysis. Section 2.4 illustrates the computation of the physical quantities for the galaxies in the sample. Section 2.5 describes the measurement of dust extinction on the H α emission. Section 2.6 presents a critical discussion about the results with careful attention to the assumption behind our analysis and Section 2.7 summarizes the results.

We adopt throughout this work a standard cosmology ($H_0 = 70 \text{ km/s/Mpc}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$) and assume a Salpeter (1955) IMF.

2.2 Sample and data-set

Our sample is selected in the far-IR using the *Herschel* observations from the PACS Evolutionary Probe survey (PEP, Lutz et al., 2011) in the GOODS-South field, that has the deepest sampling with PACS-*Herschel* photometry. The far-IR data are a key ingredient for the purpose of this work, as they allow us to strongly constrain the thermal emission by dust and therefore to infer robust estimates of the continuum dust attenuation for all the galaxies in the sample. The *Herschel* selected sample has been matched with objects at $0.7 < z < 1.5$ from the 3D-HST survey catalog (Brammer et al., 2012; Skelton et al., 2014) for which the H α line is observable with the G141 grism. For the cross-correlation procedure we took advantage of the GOODS-Multiwavelength Southern Infrared Catalog (*GOODS-MUSIC*, Grazian et al., 2006), that collects the available photometry from ~ 0.3 to $8 \mu\text{m}$ for the objects detected in the GOODS-S field. In the following we briefly describe the catalogs used and the sample selection procedure.

2.2.1 The *Herschel*/PEP survey

The PEP survey is a deep extra-galactic survey based on the observations of the PACS instrument at 70, 100 and $160 \mu\text{m}$. The GOODS-South field is the deepest field analyzed by the PEP survey and it is the only one observed also at $70 \mu\text{m}$. The 3σ limit in the GOODS-S field is 1.0 mJy , 1.2 mJy and 2.4 mJy at 70, 100 and $160 \mu\text{m}$ respectively.

PACS photometry has been performed with a PSF fitting tool, adopting the positions of *Spitzer* MIPS $24 \mu\text{m}$ detected sources as priors. This approach has been applied to maximize the depth of the extracted catalogs, to improve the deblending at longer wavelengths, and to optimize the band-merging of the *Herschel* photometry to the available ancillary data in the UV-to-near IR. As described in Berta et al. (2011, 2013), the $24 \mu\text{m}$ have been used as a bridge to match *Herschel* to *Spitzer*/IRAC (3.6 to $8.0 \mu\text{m}$) and then to the optical bands. PACS priors source extraction followed the method described by Magnelli et al. (2009). The completeness of the catalogs have been estimated through extensive Monte-Carlo simulations and it turns to be on the order of 80%, with flux limits of 1.39, 1.22 and 3.63 mJy at 70, 100 and $160 \mu\text{m}$, respectively (see PEP full public data release ²). We defer to Lutz et al. (2011) for further information on the PACS source extraction performances.

²<http://www.mpe.mpg.de/ir/Research/PEP/DR1>

2.2.2 Multi-wavelength photometry

The GOODS-MUSIC catalog

The GOODS-MUSIC catalog reports photometric data for the sources detected in z and Ks bands in the GOODS-South area and it is entirely based on public data. The catalog was produced with an accurate PSF matching for space and ground-based images of different resolutions and depths and it includes 14847 objects. The photometric catalog was cross-correlated with a master catalog³ released by the ESO-GOODS team, that summarizes all the information about the spectroscopic redshifts collected from several surveys in the GOODS area. For the sources lacking a spectroscopic measurement, Grazian et al. (2006) computed a photometric redshift using a standard χ^2 technique with a set of synthetic templates drawn from the PEGASE2.0 synthesis model (Fioc & Rocca-Volmerange, 1997). The MUSIC catalog was extended by Santini et al. (2009) with the inclusion of the mid-infrared fluxes, obtained from MIPS observations at $24\ \mu\text{m}$. This catalog was also used for the computation of the Spectral Energy Distributions (SED, see Section 2.4.1 for more details about the SED-fitting).

GALEX, IRS-*Spitzer* and SPIRE observations

In order to increase the spectral coverage of the final sample, we added to the MUSIC photometry also the GALEX near-UV observations at $\lambda = 2310\ \text{\AA}$ acquired from the online catalog Mikulski Archive for Space Telescopes (MAST), the IRS observations at $16\ \mu\text{m}$ (Teplitz et al., 2005) and the SPIRE data at 250, 350 and $500\ \mu\text{m}$ (Oliver et al. 2012; Roseboom et al. 2010; Levenson et al. 2010, see also Viero et al. 2013 and Gruppioni et al. 2013).

Both the GALEX and the SPIRE observations are extremely important for the scope of this work. The GALEX data allow us to better constrain the SED at UV wavelengths, enabling a more accurate estimate of the UV spectral slope β (see Section 2.5.2 and Appendix 2.8 for details). On the other hand, the SPIRE data improve the spectral coverage in the far-IR, thus allowing us to derive a robust estimate of the bolometric infrared luminosity (see Section 2.4.1).

The SPIRE catalog is also selected with positional priors at $24\ \mu\text{m}$. SPIRE fluxes were obtained with the technique described in Roseboom et al. (2010). Images at all Herschel wavelengths have undergone extractions using the same MIPS prior catalog positions.

For the GALEX data we used publicly available photometric catalog from MAST⁴, and rely in this case on a simple positional association.

The ancillary photometry was included by cross-correlating the above mentioned catalog using a positional association with a matching radius of $1\ \text{arcsec}$. About 28 % of the galaxies in the final sample have a near-UV observation, the 82 % of these sources have a $16\ \mu\text{m}$ counterpart, while 87 %, 62 % and 23 % of the galaxies have a SPIRE 250, 350 and $500\ \mu\text{m}$ detection, respectively. This fast decreasing fraction with λ is due to the degrading of the PSF in the SPIRE diffraction-limited imager.

³www.eso.org/science/goods/spectroscopy/CDFS_Mastercat

⁴<http://archive.stsci.edu/index.html>

2.2.3 The 3D-HST survey

The 3D-HST near-infrared spectroscopic survey (Brammer et al., 2012; Skelton et al., 2014) covers roughly 75% of the area imaged by the CANDELS ultra-deep survey fields (Grogin et al., 2011; Koekemoer et al., 2011). In this work we used the observations in the GOODS-S field from the preliminary data release, that covers an area of about 100 square *arcminutes*. The WFC3/G141 grism is the primary spectral element used in the survey. The G141 grism covers a wavelength range from 1.1 to 1.65 μm , thus can detect the $H\alpha$ emission line in a redshift interval between 0.7 and 1.5. The mean resolving power of this grism is about $R \sim 130$, insufficient to deblend the $H\alpha$ and [NII] emissions. Our measured $H\alpha$ flux is then affected by contamination from [NII], that we took into account and removed as described in Section 2.4.2.

Because no slit is used, and the length of the dispersed spectra is larger than the average separation of galaxies down to the detection limit of the survey ($F_{\text{obs}}(\lambda) \sim 2.3 \times 10^{-17} \text{ erg/s/cm}^2$ at 5σ), there is a significant chance that the spectra of nearby objects could be overlapped. This “contamination” by the neighbors must be carefully accounted for in the analysis of the grism spectra. To evaluate the contribution to the flux from nearby sources, we considered the quantitative model developed by Brammer et al. (2012). For a complete description of the instrumental set-up, the data-reduction pipeline and the contamination model we defer to Brammer et al. (2012). Further details about the contamination issue are discussed in Sections 2.2.4 and 2.3.

2.2.4 Cross correlation and cleaning of the sample

The use of the MUSIC catalog is fundamental for the association between the *Herschel* and 3D-HST observations, as the *Herschel* beam is not directly matchable to the high resolution imaging of HST: the spatial resolution of PACS at short and long wavelengths is $\sim 5 \text{ arcsec}$ and $\sim 11 \text{ arcsec}$ respectively, while the WFC3 camera has a spatial resolution of 0.13 *arcsec*. The inclusion of the MIPS data at 24 μm was very useful for the association with the *Herschel* data, due to the *Spitzer* - MIPS intermediate resolution between optical instruments and the *Herschel* Space Telescope.

The PACS-MUSIC catalog includes 591 sources, selected at 100 and/or 160 μm above the 3σ flux limits of 1.1 *mJy* and 2 *mJy*, respectively. About 40% of these objects have ground-based spectroscopic redshift in the MUSIC catalog. We then cross-correlated the PACS-MUSIC and 3D-HST catalogs, using a matching radius of 2 *arcsec*, and found that 378 PACS-MUSIC objects have a counterpart in the 3D-HST catalog. The choice of the adopted near-search radius, 2 *arcsec*, to cross-match the PACS-MUSIC sample and the 3D-HST is the best compromise between the 24 μm beam size (5.6 *arcsec*) and the IRAC ones (from 1.7 to 2 *arcsec* going from the 3.6 μm to the 8.0 μm channel). We have however verified that using a slightly smaller (1 *arcsec*) or larger (3 *arcsec*) search radius does not affect the statistics of our final sample. Of these 378 sources, we only considered the 144 galaxies with a MUSIC redshift between 0.7 and 1.5, for which the $H\alpha$ emission line is expected to fall in the WFC3-G141 grism spectral range. The spectra of these sources have been visually inspected to discard faint or saturated objects or sources without emission lines. We excluded also sources that are strongly contaminated by nearby objects, carefully evaluating by eye the 2D and 1D spectra of each galaxy, also considering the quantitative contamination model of Brammer et al. (2012). Galaxies whose spectra are strongly contaminated were discarded from the final sample. To avoid mis-identification of the lines, we also discarded objects with $|z_{\text{MUSIC}} - z_{\text{3D-HST}}| \geq 0.2$.

The X-ray luminous AGN population

We used the Chandra 4Ms catalog from Xue et al. (2011) to identify and discard the AGN from our sample. Following Xue et al. (2011), we classified as AGN only those objects with an absorption-corrected rest frame 0.5-9 keV luminosity $L_{X-ray} \geq 3 \times 10^{42} \text{ erg/s}$: we found that 8 objects match this criterion. We cannot confirm the presence of the AGN relying on the 3D-HST data alone, as they do not have neither the required resolution to deblend the [NII] and H α lines, nor the adequate spectral coverage to detect other emission lines entering the BPT diagram (Baldwin et al., 1981), e.g. [OIII]₅₀₀₇ and H β .

We note here that with this AGN-identification criterion, we might miss a population of heavily obscured “Compton thick” AGN with large column densities of gas and dust ($N_H \sim 1.5 \times 10^{24} \text{ cm}^{-2}$, see Comastri, 2004, for a review). These Compton-thick AGN might be identified through their excess in mid-IR Spitzer bands due to re-emission of the absorbed energy by the circumnuclear dust (cfr. introduction in Georgantopoulos et al., 2011, and references therein). The sources in our sample however are consistent with being dominated by star formation also when adopting mid-IR colors diagnostics (Fadda & Rodighiero, 2014) to identify the presence of an AGN.

2.2.5 The final sample

To summarize, since we wanted to study galaxies with detections in the far-IR and in the H α emission line, we considered only the 144 galaxies in the range $0.7 \leq z \leq 1.5$ from the full sample of PACS objects with 3D-HST counterparts. The spectra of these sources were then visually inspected to discard the faint, noisy, saturated or strongly contaminated ones, removing AGN as explained in the previous section.

The final sample includes 79 sources, i.e. $\sim 55\%$ of the 144 PACS-selected objects at $0.7 \leq z \leq 1.5$ with a counterpart in the 3D-HST catalog. The sample galaxies have observed H α luminosities $L_{H\alpha,obs} \in [1.4 \times 10^{41} - 5.6 \times 10^{42}] \text{ erg/s}$ and bolometric infrared luminosity $L_{IR} \in [1.2 \times 10^{10} - 1.3 \times 10^{12}] L_{\odot}$. An overlay showing the spatial distribution of our source sample is reported in Figure 2.1.

Due to the adopted selection criteria, our sources are not fully representative of the whole Main Sequence (MS) population at $z \sim 1$ (Elbaz et al., 2007; Noeske et al., 2007). This effect is visible in Figure 2.2, showing the distribution of our sample in the $M_{\star}$ -SFR plane with respect to the 3D-HST galaxies at $z \in [0.7 - 1.5]$. The stellar masses and SFR for the overall 3D-HST population are derived from SED fitting (Skelton et al., 2014). The SFR for the galaxies analyzed in this work are instead estimated from the IR+UV luminosities and the stellar masses $M_{\star}$ are computed using the MAGPHYS software (da Cunha et al., 2008), as detailed in Sections 2.4.1 and 2.4.2. Fig. 2.2 offers a qualitative comparison of the two selections, and has the only purpose of showing the effects of the used selection criteria on the global properties of our sample. Our objects occupy the upper part of the MS of “normal” star-forming galaxies at $z \sim 1$, due to the adopted far-IR selection (corresponding to a selection in SFR, cfr. Rodighiero et al., 2014). Only one galaxy lies 4 $\times$ above the MS, i.e. the starburst region (Rodighiero et al., 2011). However, the presence of this outlier does not influence our results, hence we did not remove it from the sample. The SFR and mass ranges spanned by our sample are $3 \leq SFR_{IR+UV} \leq 232 M_{\odot}/\text{yr}$, $2.6 \times 10^9 \leq M_{\star} \leq 3.5 \times 10^{11} M_{\odot}$, respectively.

Figure 2.3 shows the dependence of the total infrared luminosity as a function of the redshift for the PACS-MUSIC sources that are located inside the area observed also by the 3D-HST survey: 97 % of these objects have a 3D-HST counterpart.

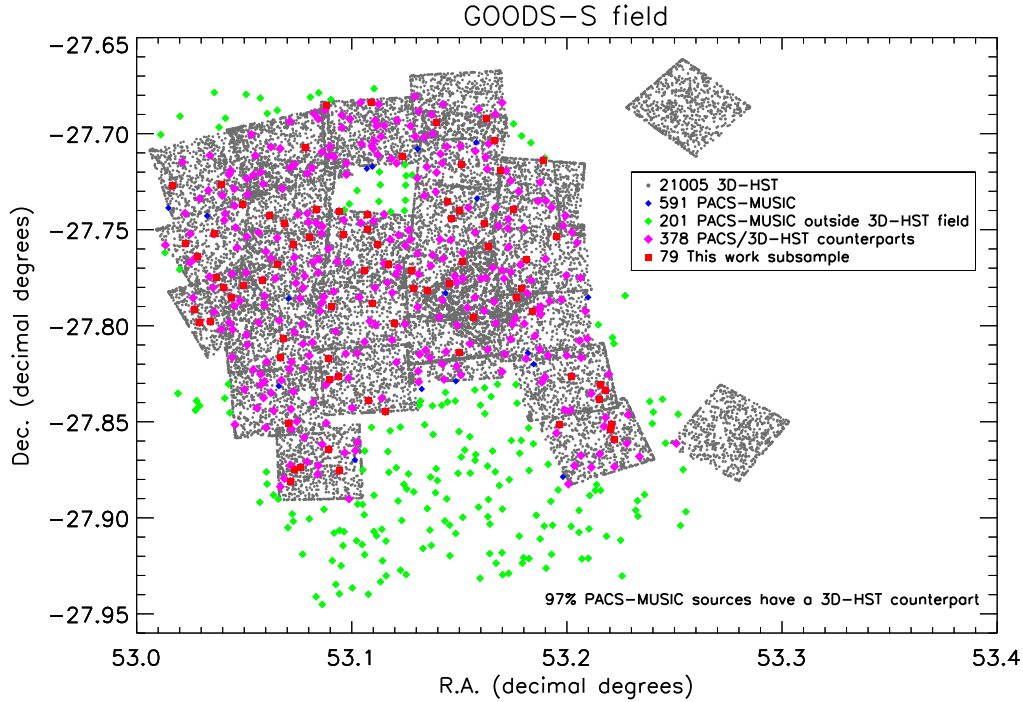


Figure 2.1: Overlay showing the spatial distribution of the PACS/MUSIC/3D-HST source sample.

In Figure 2.3 the 79 sources of our final sample, namely the PACS-MUSIC/3D-HST sources with an $H\alpha$ emission and a “clean” spectrum, are also highlighted.

2.3 Spectral analysis

We extracted the 1D spectra by collapsing the 2D spectra inside specific apertures, adapting an IDL procedure which also applies the calibration files by Brammer et al. (2012). Figure 2.4 shows the grism spectrum and the extracted 1D spectrum for one of the sources in our sample. The upper panel displays the cutout of the grism exposure: the 2D spectrum of the object is located in the central part of the frame.

The extraction of the 1D spectrum (lower panel of Figure 2.4) is done inside a frame region called “virtual slit” (inside the two red horizontal lines in the upper panel of Figure 2.4). The width and the position of the virtual slit are adjusted ad hoc on each object to maximize the S/N ratio and to minimize the contribution to the flux from other spectra. The flux contribution from other sources is negligible in the extracted spectra, as we defined the position of the virtual slits to minimize this effect. Furthermore, for the majority of galaxies in our final sample, this confusion usually affects the flux at all wavelengths, so the contamination, if present, is mostly removed by the flux correction to the spectrum as discussed in Sect. 2.3.2. For 9 sources out of 79, we found that the flux is strongly contaminated at the edge of the spectrum but the spectral range around the $H\alpha$ and the closeby continuum are not affected by this contamination. We accounted for this problem in these 9 sources by carefully selecting the portion of the continuum near the $H\alpha$ emission when rescaling the spectrum to the observed broad-band photometry (i.e. to derive the aperture correction factor) and excluding the part of the continuum affected by the contamination.

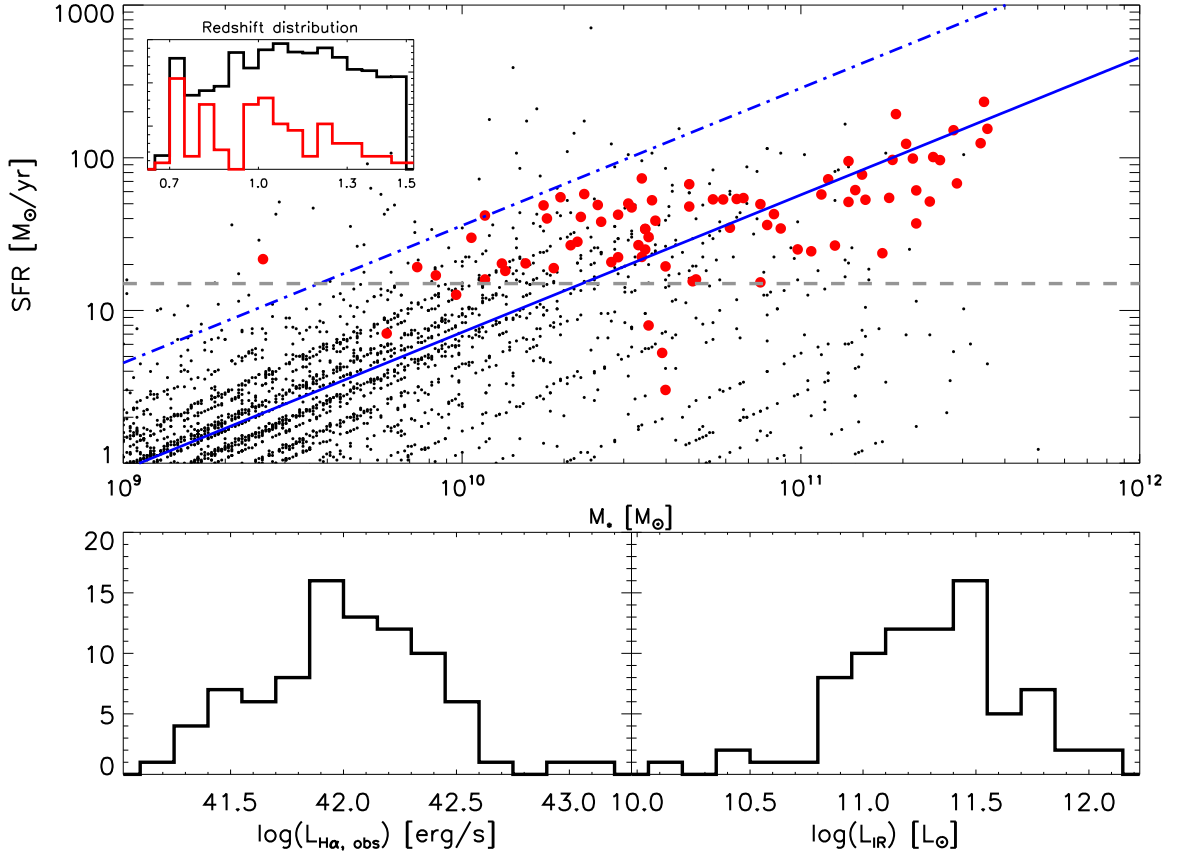


Figure 2.2: Location of our sample (red filled circles) in the SFR- M_* space, compared with the distribution of the all 3D-HST galaxies (black dots) in the same redshift range. The blue solid line represents the Main Sequence at $z \sim 1$ (Elbaz et al., 2007) and the dot-dashed blue line is the $4\times$ MS. The grey dashed line represents the SFR corresponding to the 3σ flux limit at $160\,\mu\text{m}$ ($f_{\lambda}=2.4\,\text{mJy}$) for a typical main-sequence galaxy, derived using the median SEDs of Magdis et al. (2012). The inset shows the redshift distribution for this work sample (red curve) compared to the complete 3D-HST sample in the same redshift range (black curve). The lower panel on the left is the distribution of the observed $\text{H}\alpha$ luminosities for our sample (not corrected for dust attenuation), the lower panel on the right shows the distribution of L_{IR} .

2.3.1 $\text{H}\alpha$ fluxes and redshift measurements

We measured the redshift and the integrated $\text{H}\alpha$ flux from the extracted 1D spectra by fitting the emission lines with a Gaussian profile based on the IRAF tool *splot*, even if the spectral line profile is dominated by the object shapes (the so-called “morphology” broadening, Schmidt et al., 2013) and the grism line shape may not be well described by the Gaussian profile. For part of the sample sources we re-measured the fluxes by simply integrating the area under the line, without fitting any profile, and found that the flux measurements are in agreement with those obtained with the Gaussian fit. The errors on the redshift and on the $\text{H}\alpha$ integrated flux were estimated using Monte Carlo simulations with random Gaussian noise. The measurements of the observed $\text{H}\alpha$ luminosities and the redshifts are listed in Tab. 2.4 in Appendix 2.9.

The redshifts are distributed between $z \sim 0.7$ and 1.5 as shown in Figure 2.5, as a result of the combined transmission of the grism G141 + F140W filter. Our measurements are in good agreement with the pre-existing redshift measurements. Figure 2.6 shows the excellent correlation between the MUSIC spectroscopic (black dots) and photometric (red dots) redshifts and our redshifts measured from 3D-HST spectra. The median absolute scatter $\Delta z = |z_{\text{3D-HST}} - z_{\text{MUSIC}}|$ is 0.0040 , while the median relative scatter $\Delta z / (1 + z_{\text{3D-HST}}) \simeq 0.0022$.

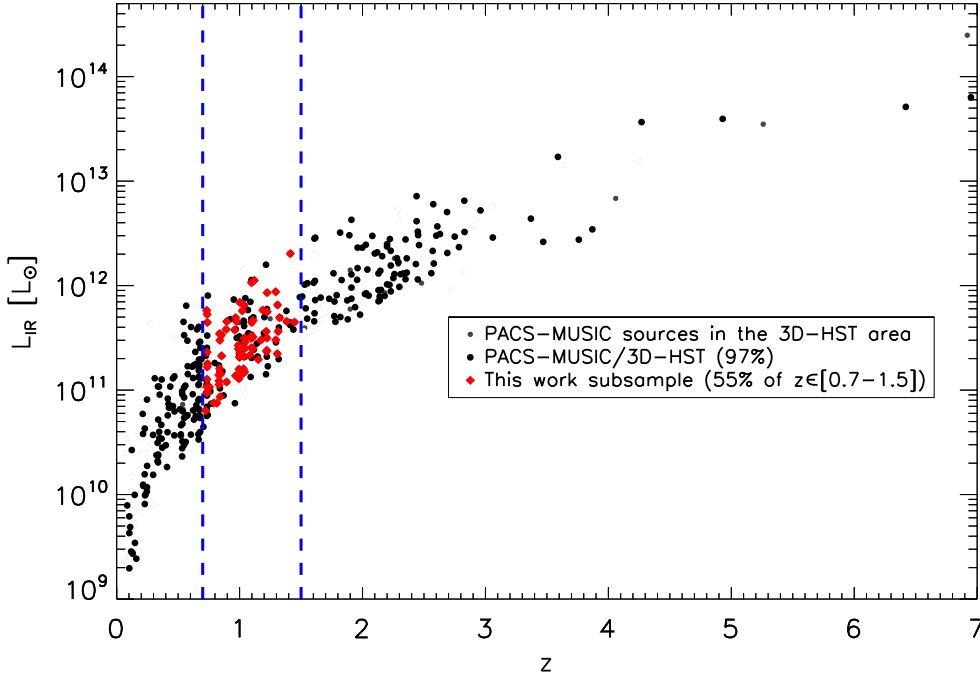


Figure 2.3: Total infrared luminosity L_{IR} as a function of redshift for the PEP sample. The magenta filled circles are the 378 PEP sources with a counterpart in the 3D-HST observations. The blue filled circles highlight the 79 sources of our final sample, located in the redshift range $z \in [0.7 - 1.5]$

We also compare our redshifts with those from the recent catalog of Morris et al. (2015), measured also from 3D-HST spectra: also in this case a very good agreement is found ($\Delta z = |z_{3D-HST} - z_{Morris}| \simeq 0.0051$, $\Delta z / (1 + z_{3D-HST}) \simeq 0.0027$).

2.3.2 Flux correction by SED scaling

The position and the width of the virtual slit used to extract the 1D spectrum were adjusted for each object in order to maximize the S/N ratio and minimize the contamination from nearby sources. We applied corrections to the measured $H\alpha$ fluxes to account for flux losses outside the slit. For each 1D spectrum the correction factor was derived as the ratio between the average continuum flux in the 1D spectrum (F_{spec}) and on the galaxy SED (F_{SED} , see Sect. 2.4.1 for details about the SED fitting), measured in the same wavelength range. The average value of the correction factor is $F_{SED}/F_{spec} \sim 1.41$, ranging from $F_{SED}/F_{spec} \sim 0.39$ up to $F_{SED}/F_{spec} \sim 8.24$.

Once this flux correction is applied, all the objects show an excellent agreement between the 1D spectrum and the near-IR part of the SED. An example is shown in Figure 2.7.

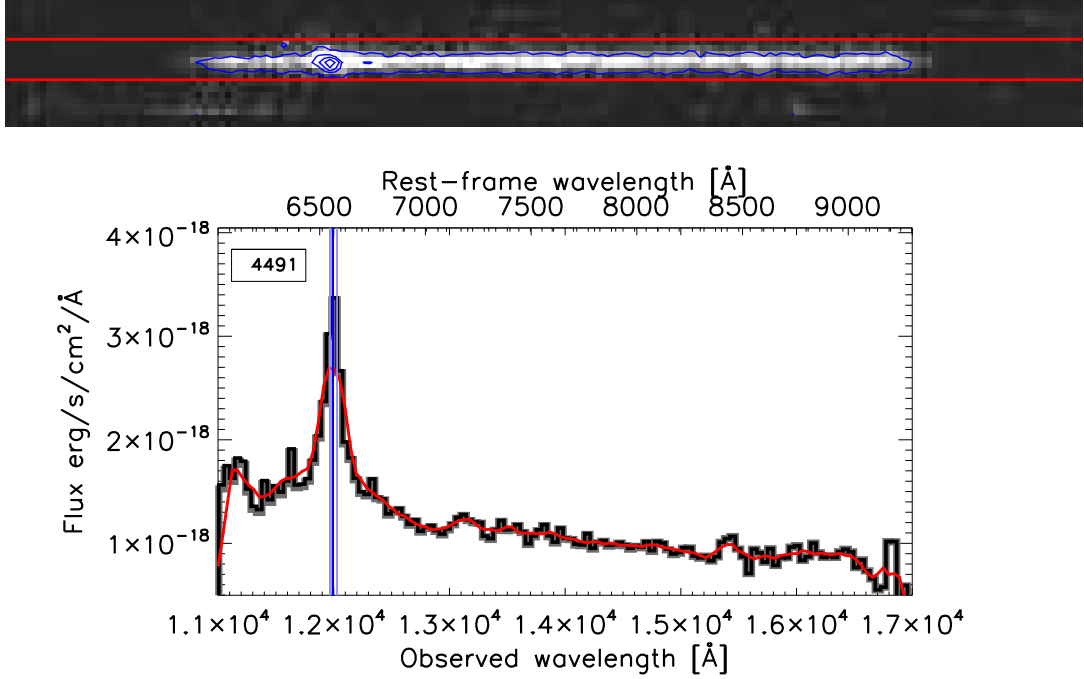


Figure 2.4: *Upper panel:* image of the 3D-HST bi-dimensional spectrum for source 4491 (ID-MUSIC), as displayed by the IDL routine. The red horizontal lines define the “virtual slit”. *Lower panel:* 1D spectrum of source 4491, obtained collapsing the 2D spectrum along the columns inside the virtual slit. The flux is in $\text{erg/sec/cm}^2/\text{\AA}$. The black thicker histogram is the observed spectrum, the red curve is a spline interpolation to the observed spectrum. The grey thin histogram, almost overlapping the black one, represents the “decontaminated spectrum”, i.e. the contamination model by Brammer et al. (2012) subtracted to the observed spectrum. The overlap between the observed and the decontaminated spectrum highlight the fact that the contamination flux in the region defined by the virtual slit is negligible. The vertical blue line highlights the position of the $\text{H}\alpha$ emission while the pale blue lines correspond to the position of the [NII] doublet.

2.4 Derivation of the main physical quantities of the sample galaxies

2.4.1 SED-fitting

We fitted the Spectral Energy Distributions with the MAGPHYS package (Multi-wavelength Analysis of Galaxy Physical Properties, da Cunha et al., 2008). This software has the main advantage of fitting the whole SED from the UV to the far-IR, relating the optical and IR libraries in a physically consistent way. To compute the SEDs, we ran MAGPHYS in the default mode, using the stellar-population synthesis models of Bruzual & Charlot (2003). For the SED fitting we used 21 photometric bands, i.e. from the near-UV (GALEX) to the SPIRE $500\,\mu\text{m}$. The filters used for the SED fitting are listed in Table 2.1. The errors of the photometric data points were set to be 10% of the measured flux and were then adjusted ad hoc. The best-fit SEDs were obtained by fixing the redshifts to the spectroscopic values that we measured from the 3D-HST spectra.

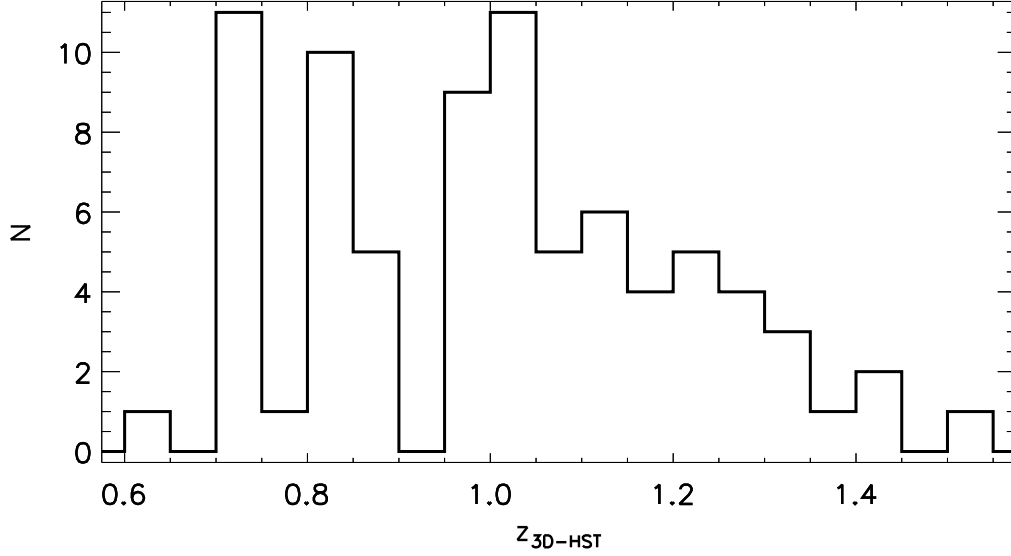


Figure 2.5: Redshift distribution for the 3D-HST sources in the GOODS-South field. The sources are distributed in a redshift interval $z \in [0.65 - 1.53]$, according to the features of the WFC3/G141 grism.

Figure 2.8 shows an example of a best-fit SED as output by MAGPHYS.

In addition to the best-fit SED, MAGPHYS returns several physical parameters of the observed galaxy together with their marginalized likelihood distributions. We used in particular the stellar masses $M_\star$ and the bolometric infrared luminosity L_{IR} , considering the values at the 50th percentile of the likelihood distribution. The errorbars at 68% for these quantities were derived from the PDFs computed by MAGPHYS. Since MAGPHYS adopts a Chabrier (2003) IMF, we converted the stellar masses to a Salpeter IMF by multiplying by a constant factor of 1.7 (e.g. Cimatti et al., 2008).

2.4.2 Measuring the SFRs

We derived for all the sources in the sample the SFR from several indicators, thanks to the availability of a wide multi-wavelength photometric coverage and the near-IR spectra. In particular, we computed the SFRs from the $H\alpha$ luminosity, the UV luminosity and the IR luminosity, adopting the classical calibrations of Kennicutt (1998a).

The $H\alpha$ luminosity is derived from 3D-HST near-IR spectra. The measured $H\alpha$ flux is aperture corrected as described in Section 2.3.2 while the [NII] contribution was removed by scaling down the $H\alpha$ flux by a factor 1.2, following Wuyts et al. (2013). The contamination by [NII] could produce some uncertainties in the estimate of $L_{H\alpha}$ since the ratio [NII]/ $H\alpha$ may vary object by object as a function of the stellar mass and the redshift (Zahid et al., 2014). To validate our choice of using a constant factor, we then computed the [NII] correction factor as a function of $M_\star$, using the evolutionary parametrization of the ISM metallicity by Zahid et al. (2013).

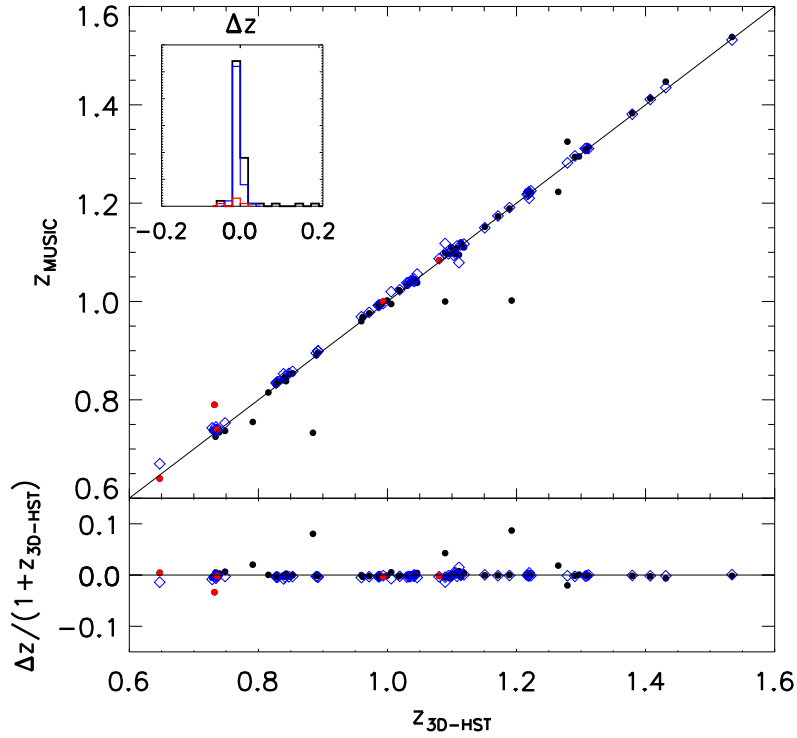


Figure 2.6: *Upper panel:* relation between 3D-HST spectroscopic redshifts (x-axis) and MUSIC redshifts. In the inset, the distribution of the absolute scatter $\Delta z = (z_{3D-HST} - z_{MUSIC})$ is shown. The standard deviation for this distribution is $\sigma = 0.031$. The red histogram highlights the absolute scatter for photometric MUSIC redshifts. The blue histogram represents the absolute scatter between our measurements and the redshifts from Morris et al. (2015). *Lower panel:* relative scatter $(z_{3D-HST} - z_{MUSIC}) / (1 + z_{3D-HST})$. The data points in red are the photometric redshifts in the MUSIC catalog, the black dots are the sources with spectroscopic redshift also in the MUSIC catalog from ground based measurements. The blue open diamonds are the redshifts measured by Morris et al..

We found that the use of a more accurate [NII] correction does not change our results about the dust extinction corrections (i.e. Figures 2.10 and 2.12). Results of our later analysis (like the f -factor and the comparison between SFR indicators) are not affected by the choice of a mass-dependent [NII] correction or of a constant scaling factor.

In order to account for both the unattenuated and the obscured Star Formation, we measured the “total” SFR combining the L_{IR} and the observed L_{1600} (the same procedure was adopted by Nordon et al., 2012):

$$SFR_{IR+UV} = (1.4L_{1600} + 1.7L_{IR}) \times 10^{-10} [L_{\odot}] . \quad (2.1)$$

We estimated the luminosity at $\lambda_{rest-frame} = 1600\text{\AA}$ from the best-fit SED, and used the IR luminosity L_{IR} derived by MAGPHYS (cfr. Section 2.4.1). The SFR_{IR+UV} is the best estimate of the SFR for our objects, considering the wide photometric coverage in the far-IR, and will be used as a benchmark to verify the validity of our dust extinction correction. The errors for the various estimates of the SFR are computed via MC simulation by randomly varying $L_{H\alpha}$, L_{1600} and L_{IR} within the errorbars, assuming that these quantities are Gaussian distributed.

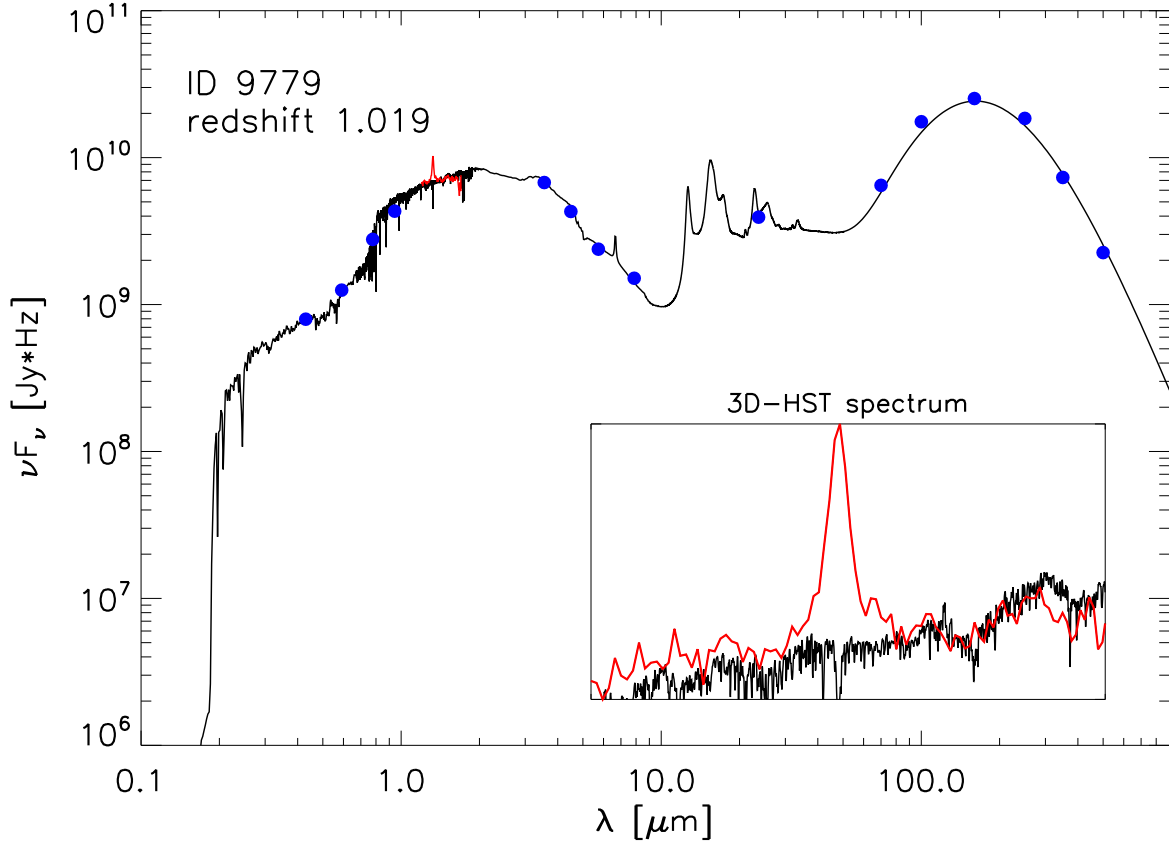


Figure 2.7: Spectral Energy Distribution from MAGPHYS (black curve) with the observed photometry (blue filled circles) and the 3D-HST spectrum (red line). The 3D-HST spectrum is corrected for the flux loss outside the slit, as described in the text. The plot also reports the MUSIC ID of the source and its redshift, measured from the near-IR spectrum. The inset shows a zoom on the 3D-HST spectrum, close to the $H\alpha$ emission line.

2.5 Dust extinction corrections

In order to precisely evaluate the SFR and to reconcile the various SFR estimates, we need to accurately quantify the effect of dust on the integrated emission of our galaxies. According to Calzetti (2001b), the action of dust on starlight for starburst galaxies in the local Universe can be parametrized as:

$$F_{\text{obs}}(\lambda) = F_{\text{int}}(\lambda) \times 10^{-0.4A_\lambda} = F_{\text{int}}(\lambda) \times 10^{-0.4E_{\text{star}}(B-V)k(\lambda)} \quad (2.2)$$

where $F_{\text{obs}}(\lambda)$ and $F_{\text{int}}(\lambda)$ are the dust-obscured and the intrinsic stellar continuum flux densities, respectively. A_λ and $E_{\text{star}}(B-V)$ are the dust attenuation and the color excess on the stellar continuum respectively, while $k(\lambda)$ parametrizes the Calzetti et al. (1994) starburst reddening curve.

As already stated in the introduction, Calzetti et al. (2000) found that exists a differential attenuation between the stellar continuum and the nebular lines by measuring both the hydrogen line ratios and the continuum reddening in a sample of local star-forming galaxies.

2.5. DUST EXTINCTION CORRECTIONS

Table 2.1: Filters used for the SED fitting and respective effective wavelengths λ_{eff} (μm).

Filter	λ_{eff} [μm]
GALEX_NUV	0.2310
U	0.346
ACSF435W	0.4297
ACSF606W	0.5907
ACSF775W	0.7774
ACSF850LP	0.9445
ISAACJ	1.2
ISAACH	1.6
ISAACK	2.2
IRAC1	3.55
IRAC2	4.493
IRAC3	5.731
IRAC4	7.872
IRS16	16
MIPS24	23.68
PACS70	70
PACS100	100
PACS160	160
SPIRE250	250
SPIRE350	350
SPIRE500	500

This differential attenuation is parametrized by a f -factor of 0.44, as defined by :

$$E_{\text{star}}(B - V) = f \times E_{\text{neb}}(B - V) \quad (2.3)$$

with $f = 0.44 \pm 0.03$.

We note that in the original calibration of eq. (3) two different reddening curves were used to measure the continuum and the nebular extinction (Fitzpatrick 1999 and Calzetti et al. 2000, respectively). If the Calzetti reddening curve is used to measure both the nebular and continuum extinction components, as done in this work, the local f -factor becomes $f=0.58$, instead of the canonical $f=0.44$ (Pannella et al., 2014; Steidel et al., 2014). Hence, hereafter we refer to $f=0.58$ as the “local” f -factor.

Equation 3 implies that the ionized gas is about two times more extinguished than the stars. The applicability of such relation in the high redshift Universe is still not clear, as already mentioned in Sect. 1. Several authors (e.g. Pannella et al., 2014; Kashino et al., 2013; Erb et al., 2006; Reddy et al., 2010; Price et al., 2014; Wuyts et al., 2013) found that the use of this equation implies to overestimate the intrinsic line flux, i.e. the $\text{H}\alpha$ line is less attenuated in the high redshift galaxies with respect to the local Universe.

To shed some light on this issue, we investigated the differential extinction between nebular lines and continuum at high- z by using the ratio between the observed $SFR_{\text{H}\alpha}$ and SFR_{UV} , thus uncorrected for dust attenuation. To validate the derived dust correction we compared our measurements of $SFR_{\text{H}\alpha}$ to the $SFR_{\text{IR+UV}}$, that we assume as the “true” SFR estimator.

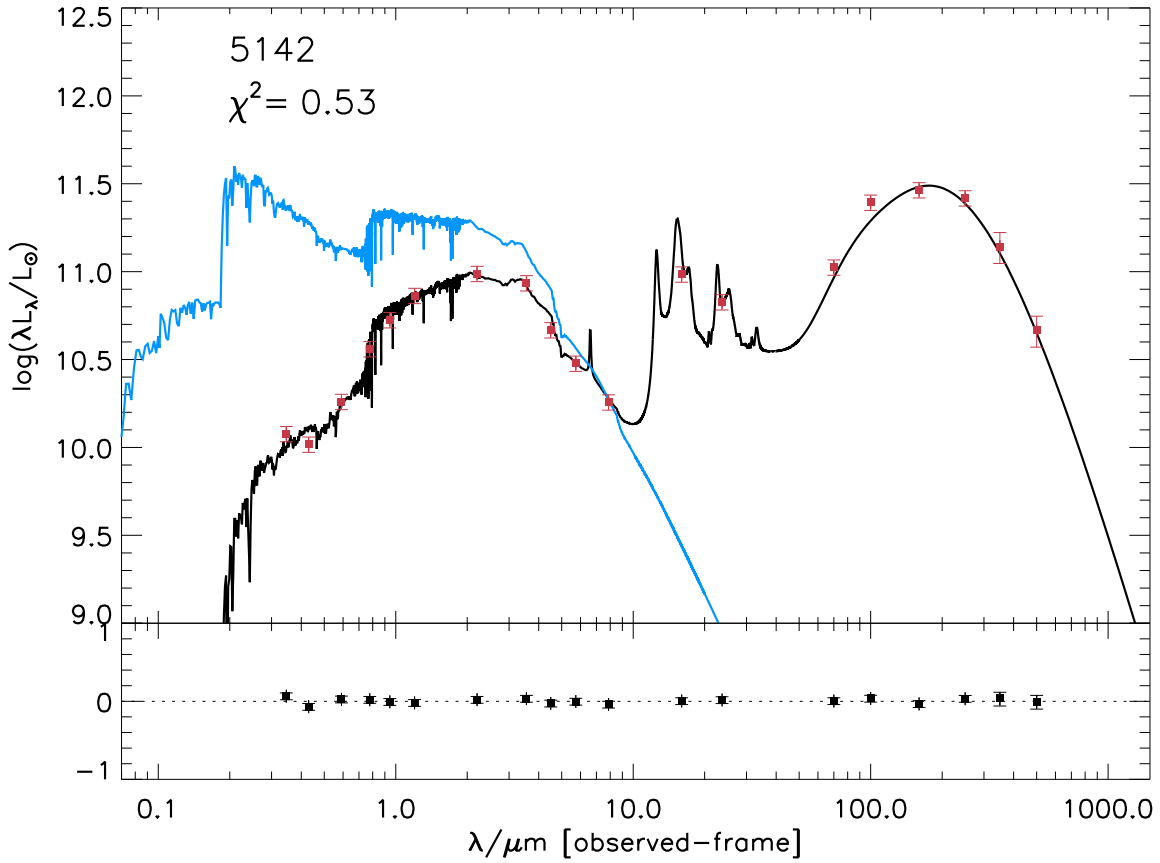


Figure 2.8: Example of a Spectral Energy Distribution in output from MAGPHYS. The black solid line is the best-fit model to the observed SED (data-points in red). The blue solid line shows the unattenuated stellar population spectrum. The bottom panel shows the residuals $(L_\lambda^{\text{obs}} - L_\lambda^{\text{mod}}) / L_\lambda^{\text{obs}}$.

In the following section we present the formalism and the methods to derive the $H\alpha$ differential attenuation.

2.5.1 Differential extinction from $H\alpha$ to UV-based SFR indicators

We use the $H\alpha$ and UV luminosities, both uncorrected for dust extinction, to derive the extra correction factor associated with the nebular lines as a function of the color excess on the continuum emission. For the reader's convenience, we report in this Sect. the relevant formalism.

We assume that the total Star Formation Rate SFR_{tot} is proportional to luminosity:

$$SFR_{\text{tot}} = \text{const} \times L_{\text{int}}(\lambda) \quad (2.4)$$

where, in the case of UV-optical wavelengths, the intrinsic luminosity $L_{\text{int}}(\lambda)$ is related to the observed $L_{\text{obs}}(\lambda)$ through the attenuation A_λ (eq. 2.2). Combining equations 2.2 and 2.4, we obtain for the observed SFR:

$$SFR_{\text{uncorr}} = \text{const} \times L_{\text{obs}}(\lambda) = 10^{-0.4A_\lambda} \times SFR_{\text{tot}}. \quad (2.5)$$

2.5. DUST EXTINCTION CORRECTIONS

Considering the UV and the $H\alpha$ SFR tracers and assuming that the intrinsic SFRs in absence of dust attenuation are the same ($SFR_{H\alpha} = SFR_{UV}$), we obtain that the ratio between the observed SFRs is related to the differential extinction in the $H\alpha$ emission line:

$$\begin{aligned} \frac{SFR_{H\alpha, \text{uncorr}}}{SFR_{UV, \text{uncorr}}} &= \frac{10^{-0.4A_{H\alpha}} \times SFR_{\text{tot}}}{10^{-0.4A_{UV}} \times SFR_{\text{tot}}} = \\ &= 10^{-0.4E_{\text{star}}(B-V) \times [\frac{k(H\alpha)}{f} - k(UV)]} \end{aligned} \quad (2.6)$$

or in logarithmic units

$$\log\left[\frac{SFR_{H\alpha, \text{uncorr}}}{SFR_{UV, \text{uncorr}}}\right] = -0.4 \left[\frac{k(H\alpha)}{f} - k(UV) \right] \times E_{\text{star}}(B - V). \quad (2.7)$$

We can then quantify the differential extinction of nebular lines through a linear fit in the plane $E_{\text{star}}(B - V)$, $\log[\frac{SFR_{H\alpha, \text{uncorr}}}{SFR_{UV, \text{uncorr}}}]$ from eq. 2.7.

We stress here that in this analysis we impose that the intrinsic $H\alpha$ and UV luminosities are tracing the same stellar populations and this condition could be in principle not satisfied, as these two SF tracers are sensitive to different star formation timescales. In fact, the UV luminosity is dominated by stars younger than 10^8 yr while only stars with masses higher than $10 M_{\odot}$ and lifetimes lower than ~ 20 Myr contribute significantly to the ionization of the HII regions, i.e. to the $H\alpha$ luminosity (Kennicutt, 1998a). However, our assumption seems to be reasonable from a statistical point of view, as we would need to observe a galaxy when the formation of stars with ages $< 10^7$ yrs (i.e. the star formation traced by $L_{H\alpha}$) is already exhausted, while the formation of stars with ages $10^7 < t < 10^8$ yr is already in place (i.e. sources that produce L_{UV} but do not contribute significantly to $L_{H\alpha}$), to have $L(H\alpha)$ substantially different from L_{UV} .

2.5.2 Measurements of the continuum extinction

After we have parametrized the f -factor and measured the ratio $SFR_{H\alpha, \text{uncorr}}/SFR_{UV, \text{uncorr}}$, we need to estimate the continuum color excess $E_{\text{star}}(B-V)$.

Taking advantage of the far-IR measurements available for our sample, we derived the continuum attenuation A_{IRX} from the ratio $L_{\text{IR}}/L_{UV, \text{uncorr}}$ (Nordon et al., 2012):

$$A_{\text{IRX}} = 2.5 \log\left[\frac{SFR_{\text{IR}+UV, \text{uncorr}}}{SFR_{UV, \text{uncorr}}}\right]. \quad (2.8)$$

We can independently infer the continuum attenuation also from the UV spectral slope β because it is a sensitive indicator of dust attenuation. The intrinsic shape of the UV continuum spectrum for a star-forming galaxy is nearly flat in $F(\lambda)$, even considering two extreme situations: an instantaneous burst of star formation and a constant star formation rate. For the case of the instantaneous burst, the usually assumed burst duration is typically ~ 20 Myr. During the first 2×10^7 yr, the stars contributing to the flux in the range $\lambda \in [1200 - 3200] \text{ \AA}$ have had no time to evolve off the main sequence, so that the shape of the intrinsic spectrum in the UV wavelength range of interest has not changed. Considering instead a region of constant star formation, the continuous generation of new stars keeps the shape of the UV spectrum roughly constant. In conclusion, we can reasonably assume that the intrinsic shape of the UV spectra of star-forming galaxies is constant so each deviation from this intrinsic shape is produced by dust (Calzetti et al., 1994).

We then computed the continuum attenuation at 1600 Å (A_{1600}) from β using the calibration from Meurer et al. (1999), derived on a local sample of starburst galaxies:

$$A_{1600} = 4.43 + 1.99\beta . \quad (2.9)$$

Here the UV-slope parameter β is defined as the linear interpolation of the observed spectrum (or in the lack of it from the photometric data) in the rest-frame wavelength range $\lambda \in [1250 - 2600]\text{Å}$. The applicability of the Meurer relationship in different ranges of redshift has been demonstrated by several authors (e.g. Reddy et al., 2012; Buat et al., 2012; Talia et al., 2015).

In our case, since we lack observational data in this wavelength interval for the majority of the sample, we estimated β from a linear interpolation of our best-fit MAGPHYS spectral model discussed in Sect. 4.1, as done e.g. in Oteo et al. (2014). To test the robustness of this slightly model-dependent estimate of the UV-slope, we also computed β from the UV rest-frame photometry, when available (i.e. for 13 objects), and found that the two measurements are in good agreement. For more details see Appendix 2.8.

The attenuation is related to the color excess $E_{\text{star}}(B-V)$. Assuming the reddening curve of Calzetti et al. (2000) we have:

$$E_{\text{star,IRX}}(B - V) = \frac{A_{\text{IRX}}}{k(UV = 1600)} \quad (2.10)$$

$$E_{\text{star},\beta}(B - V) = \frac{A_{1600}}{k(UV = 1600\text{Å})} . \quad (2.11)$$

These two quantities are consistent to each other, as displayed in Figure 2.9. The correlation between $E_{\text{star},\beta}(B - V)$ and $E_{\text{star,IRX}}(B - V)$ is very good, confirming the reliability of our estimate of continuum dust extinction, and has an intrinsic scatter, i.e. not accounted for by the experimental errors (?), of $\sigma_{\text{intr}} \sim 0.061$, that represent 95% of the total scatter ($\sigma_{\text{tot}} \sim 0.064$). Estimates of σ_{intr} and σ_{tot} are obtained with the IDL routine MPFIT (Markwardt, 2009).

Note that, since our UV-slope β is measured from SEDs computed with MAGPHYS, which consistently accounts for both the UV and far-IR emission, this could partially explain the high correlation degree between $E_{\text{star},\beta}(B - V)$ and $E_{\text{star,IRX}}(B - V)$. In any case, this comparison is useful to verify the accuracy of our continuum extinction measure.

Both measurements of $E_{\text{star}}(B - V)$ will be considered in the subsequent analysis to evaluate the differential extinction, i.e. the f -factor.

The errors for $E_{\text{star},\beta}(B - V)$ were derived by propagating those on β (see Appendix 2.8 for the calculations of the errors on the UV slope β), while the errorbars for $E_{\text{star,IRX}}(B - V)$ are estimated via MC simulations, by varying L_{IR} and L_{UV} within the 1σ errorbars.

2.5.3 Extra extinction from the f -factor

Following the formalism of section 2.5.2, we evaluated the f -factor as a function of the color excess on the continuum by using the ratio $SFR_{\text{H}\alpha,\text{uncorr}}/SFR_{\text{UV,uncorr}}$ and the two measurements of the color excess on stellar continuum, $E_{\text{star},\beta}(B - V)$ and $E_{\text{star,IRX}}(B - V)$. To derive the f -factor we fitted a linear function $y = s \times x$ to the data points through a minimization of a weighted χ^2 (i.e. a least square fit obtained by weighting each data point for its error, both in the x and y axes), where $y = \log(SFR_{\text{H}\alpha,\text{uncorr}}/SFR_{\text{UV,uncorr}})$ and $x = E_{\text{star}}(B - V)$.

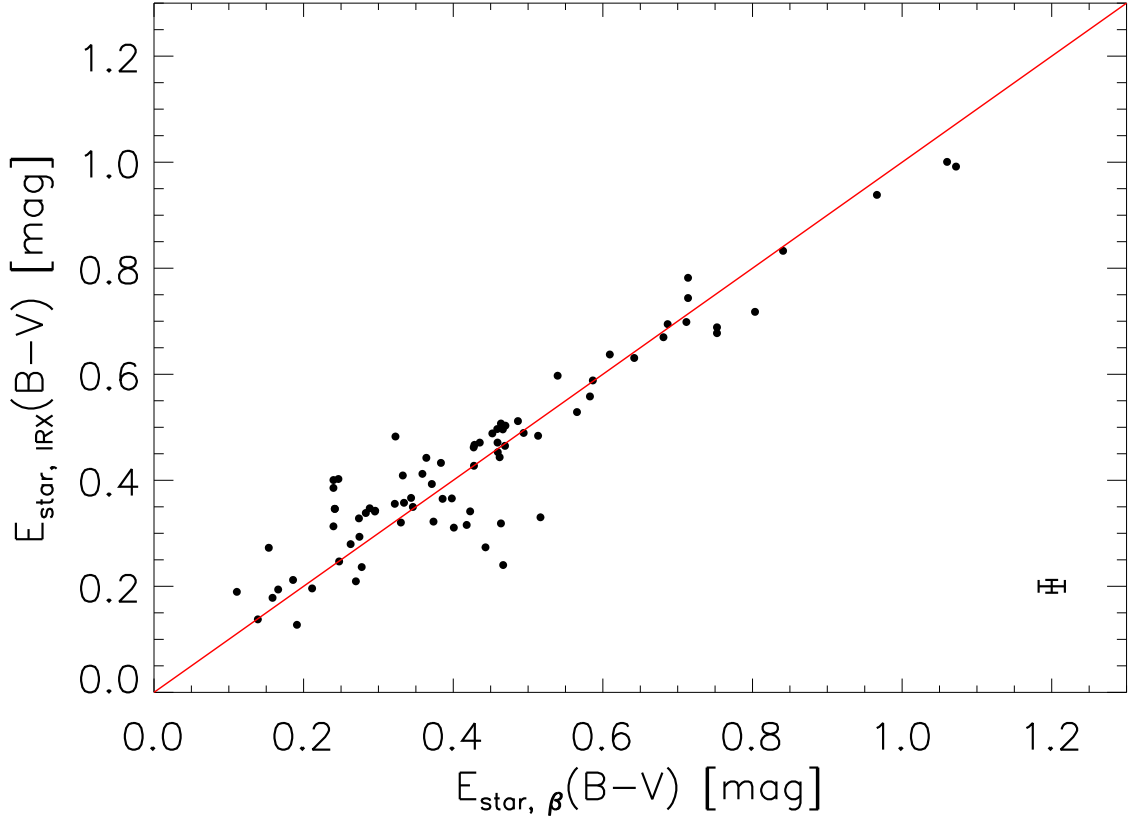


Figure 2.9: Comparison between the continuum extinction $E_{\text{star}}(B - V)$ derived from the UV spectral slope β (x -axis) and the continuum extinction derived from the infrared excess IRX (y -axis). The red line is the 1:1 correlation relationship. In the lower part of the plot on the right are indicated the typical size of the errorbars.

To obtain this fit we used the routine `MPFIT`, and took care of checking the result by a MC simulation by inserting a scatter in the x -coordinate value for each data-point. The f -factor is then finally obtained from the slope s of the best-fit line as

$$f = \frac{0.4 \times k(H\alpha)}{0.4 \times k(UV) - s}. \quad (2.12)$$

The uncertainty for the f -factor was estimated by propagating the error on the best-fit parameter s .

Figure 2.10 reports $SFR_{H\alpha, \text{uncorr}}/SFR_{UV, \text{uncorr}}$ as a function of the continuum color excess. The red solid line in Figure 2.10 corresponds to Equation 2.7 with $f=0.93 (\pm 0.065)$ that is the best-fit value from our data distribution. Hence we found that the f -factor required to match $SFR_{H\alpha}$ and SFR_{UV} in our sample is larger than the local value ($f=0.58$, blue dashed line in Fig. 2.10) and turns out to be also higher than the values computed by Kashino et al. (2013) on a sample with slightly higher z and different selection criteria ($f=0.69$ and 0.83 , black dot-dashed and green dot-dot-dashed lines in Fig. 2.10 respectively).

The value of the f -factor does not change using either $E_{\text{star}, \beta}(B - V)$ or $E_{\text{star}, \text{IRX}}(B - V)$: this result is in line with the high correlation of these two measurements, as seen in Fig. 2.9. We further show the $SFR_{H\alpha, \text{uncorr}}/SFR_{UV, \text{uncorr}}$ as a function of $E_{\text{star}}(B - V)$ in Fig. 2.11. In this plot we color-code our data-points according to their $M_{\star}$.

From this plot, it seems that low $M_\star$ galaxies require $f \sim 0.58$ while higher $M_\star$ galaxies are more consistent with $f \sim 0.93$.

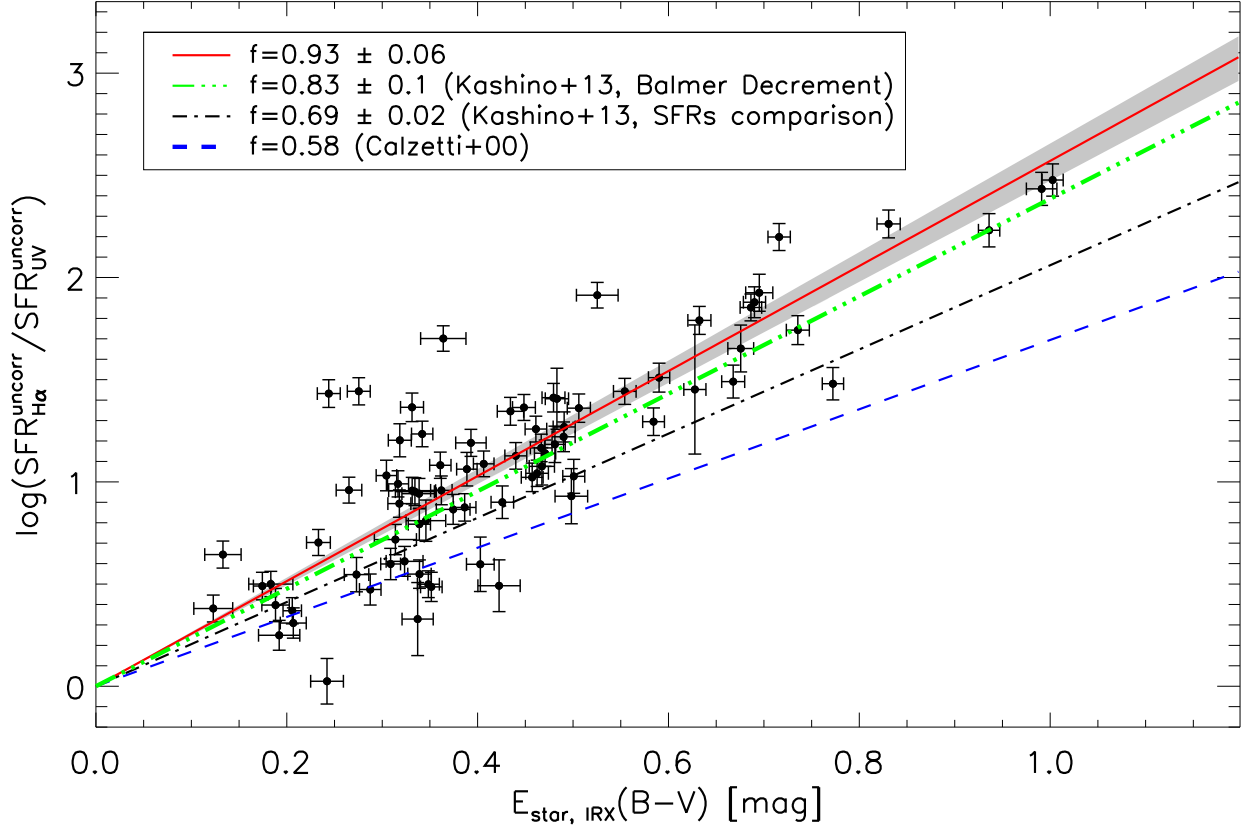


Figure 2.10: Ratio of $H\alpha$ to UV-based SFRs (not corrected for dust extinction) as a function of $E_{\text{star}, \text{IRX}}(B-V)$ derived from the IRX ratio. The lines are the equation 2.7 with different values of f from Kashino et al. (2013) and Calzetti et al. (2000), as the legend indicates. The grey shaded area marks the confidence interval for our estimate of the f -factors.

2.5.4 Testing the dust correction: comparison between $SFR_{H\alpha}$ and $SFR_{\text{IR}+\text{UV}}$

We tested the reliability of our extinction correction in Figure 2.12, where we compare the $SFR_{\text{IR}+\text{UV}}$ with the $SFR_{H\alpha}$, corrected for dust extinction using both the prescription derived in this work (i.e. $E_{\text{star}, \text{IRX}}(B-V)$ and $f=0.93$, upper panel), and that derived by Calzetti et al. (2000) for local galaxies ($E_{\text{star}, \text{IRX}}(B-V)$ and $f=0.58$, lower panel). The results show that a better agreement between $SFR_{H\alpha}$ and $SFR_{\text{IR}+\text{UV}}$ is obtained by applying our correction factor, with a median ratio $SFR_{H\alpha}/SFR_{\text{IR}+\text{UV}}=0.88$ and a median relative scatter $|SFR_{\text{IR}+\text{UV}} - SFR_{H\alpha}|/(1 + SFR_{\text{IR}+\text{UV}})=0.38$. On the contrary, the Calzetti et al. prescription would lead to overestimate the $SFR_{H\alpha}$ by a factor up to 3.3 above $SFR_{\text{IR}+\text{UV}} > 50 M_\odot/\text{yr}$. We emphasize that our recipe for the nebular dust attenuation seems to “fail” for the tail of objects with $SFR_{\text{IR}+\text{UV}} \in [10 - 20] M_\odot/\text{yr}$ and $M_\star \sim 10^{10} M_\odot$ (light blue points in Fig. 2.12). For these sources our dust correction underestimates the $SFR_{H\alpha}$ with respect to $SFR_{\text{IR}+\text{UV}}$, while using the Calzetti prescription the two SFRs are in slightly better agreement. This could imply that the f -factor is an increasing function of SFR and $M_\star$.

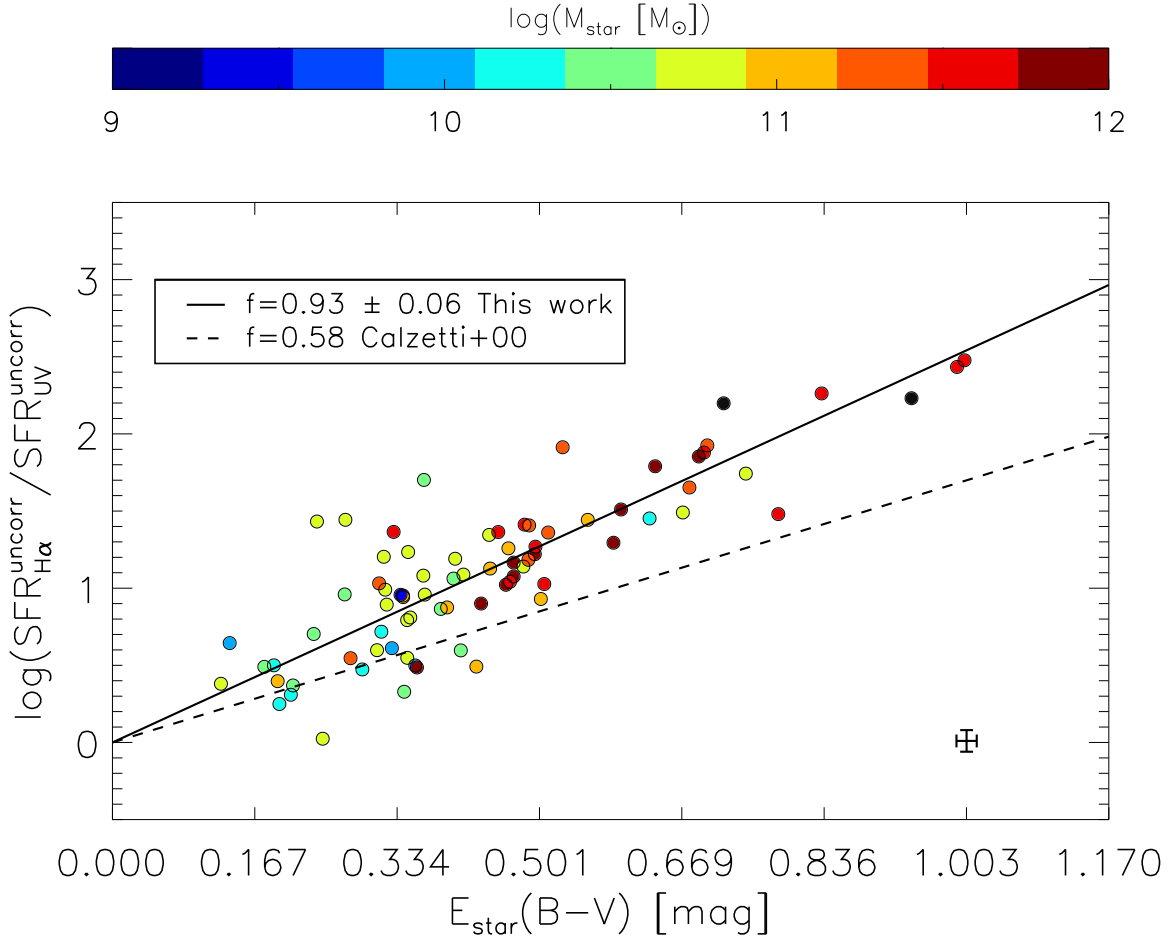


Figure 2.11: Same as Fig. 2.10. Here our data-points are color-coded by $M_\star$. A trend seems to emerge for which galaxies with the lowest $M_\star$ are in agreement with the Calzetti et al. (2000) local relation, while galaxies at the highest $M_\star$ require a larger f -factor to reconcile the H α and UV SFR indicators.

However, the disagreement between SFR indicators at $SFR_{IR+UV} \lesssim 20M_\odot/\text{yr}$ can be due also to an overestimate of SFR_{IR+UV} rather than a problem of the dust correction. At lower $M_\star$ and SFRs in fact, the contamination to the heating of dust by an older stellar population (the so-called “cirrus” component, e.g. Kennicutt et al., 2009) became not negligible and can cause to overestimate L_{IR} . Finally, the trend seen in Figure 2.12 could also be a consequence of the selection criterion used in this work, considering that $SFR_{IR+UV} \sim 15M_\odot/\text{yr}$ is the value that corresponds to the 3σ flux limit at $160\mu\text{m}$ at $z \sim 1$ as estimated using the median SEDs of Magdis et al. (2012) (see also Fig. 2.2 of section 2.2.5).

2.5.5 $A_{H\alpha}$ vs $M_\star$

Figure 2.13 shows the relationship between the attenuation $A_{H\alpha}$ and stellar masses. Here we converted the continuum attenuation $E_{\text{star,IRX}}(B - V)$ to $A_{H\alpha}$ by using $f=0.93$ and the $k(\lambda)$ from Calzetti et al. (2000). Despite the high dispersion of the data, we can observe an excess of $A_{H\alpha}$ at the highest masses with respect to the local relationship of Garn & Best (2010) (green dashed line in Figure 2.13). We report also the relationship of Kashino et al. (2013), derived at $z \sim 1.6$ (blue solid line).

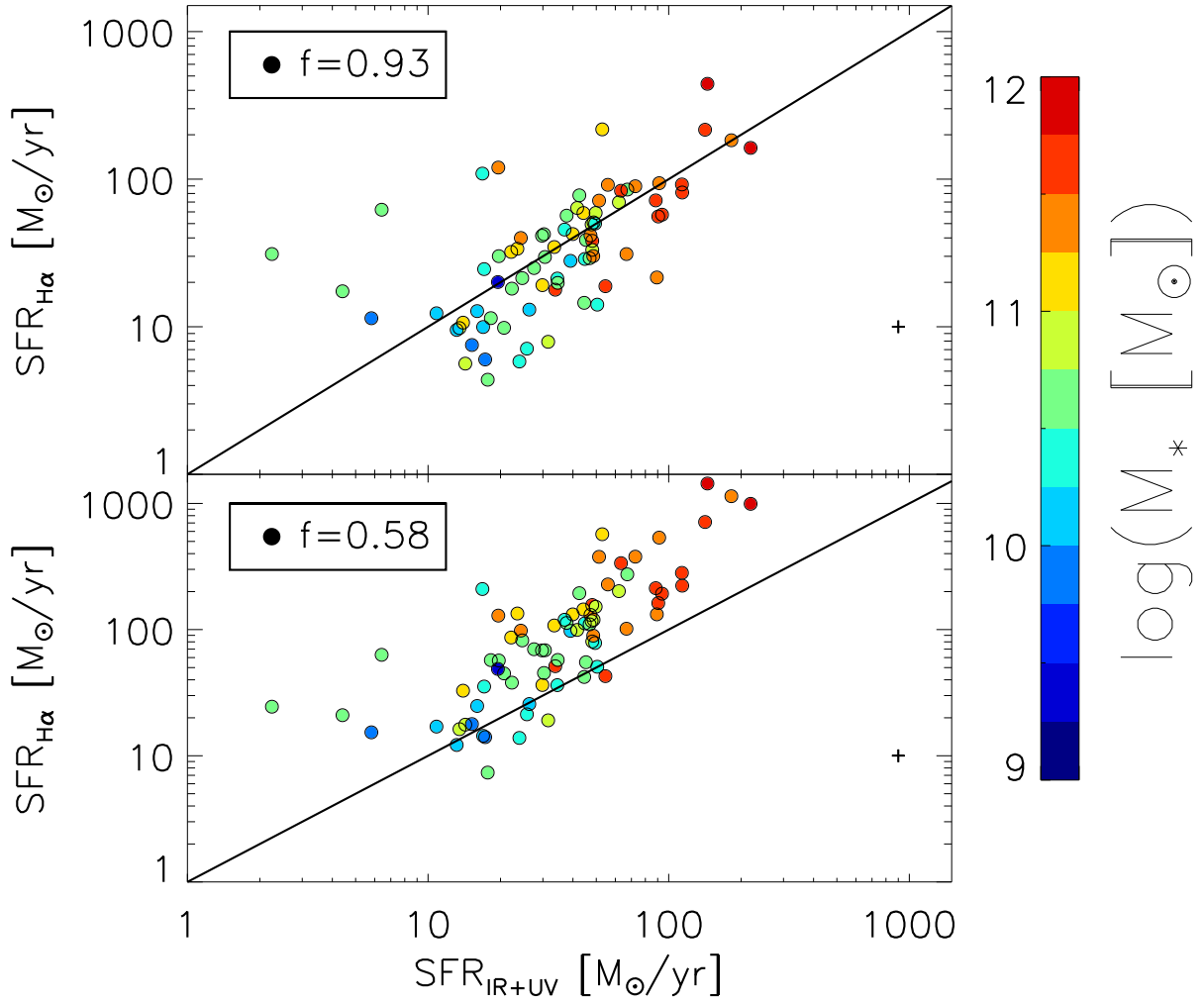


Figure 2.12: Comparison between SFR_{IR+UV} and $SFR_{H\alpha}$ when varying the dust correction for the $H\alpha$ emission. The lower panel shows the case in which $L_{H\alpha}$ are corrected for dust attenuation by using the classical prescription of Calzetti ($f=0.58$) while in the upper panel the $H\alpha$ luminosities are corrected with our dust correction ($f=0.93$). The black solid line is the 1:1 correlation line and the different colors mark the stellar masses, as indicated in the vertical color-bar. In the lowest part of each panel are also shown the median errors on the SFR measurements.

The grey filled dots of Figure 2.13 represent the median values of $A_{H\alpha}$ obtained in three M_* bins as reported in the figure. The errorbars are the median scatter of $A_{H\alpha}$ and M_* in each bin. Within the large scatter in the data, the median values in each bin are consistent with both the local and the higher- z relationship, in agreement with the results of Ibar et al. (2013). Of course, there may be selection effects in operation in the graph disfavoring the detection of galaxies with high values of $A_{H\alpha}$, that may be more important for the lower mass objects with intrinsically faint $H\alpha$ flux. Our combined selection requiring detection of the $H\alpha$ line may be somewhat exposed to such an effect. To confirm if an evolution with z exists in the dust properties of star forming galaxies it would be necessary to have deeper observations for the most attenuated galaxies. This aspect of the analysis will be investigated in a further paper.

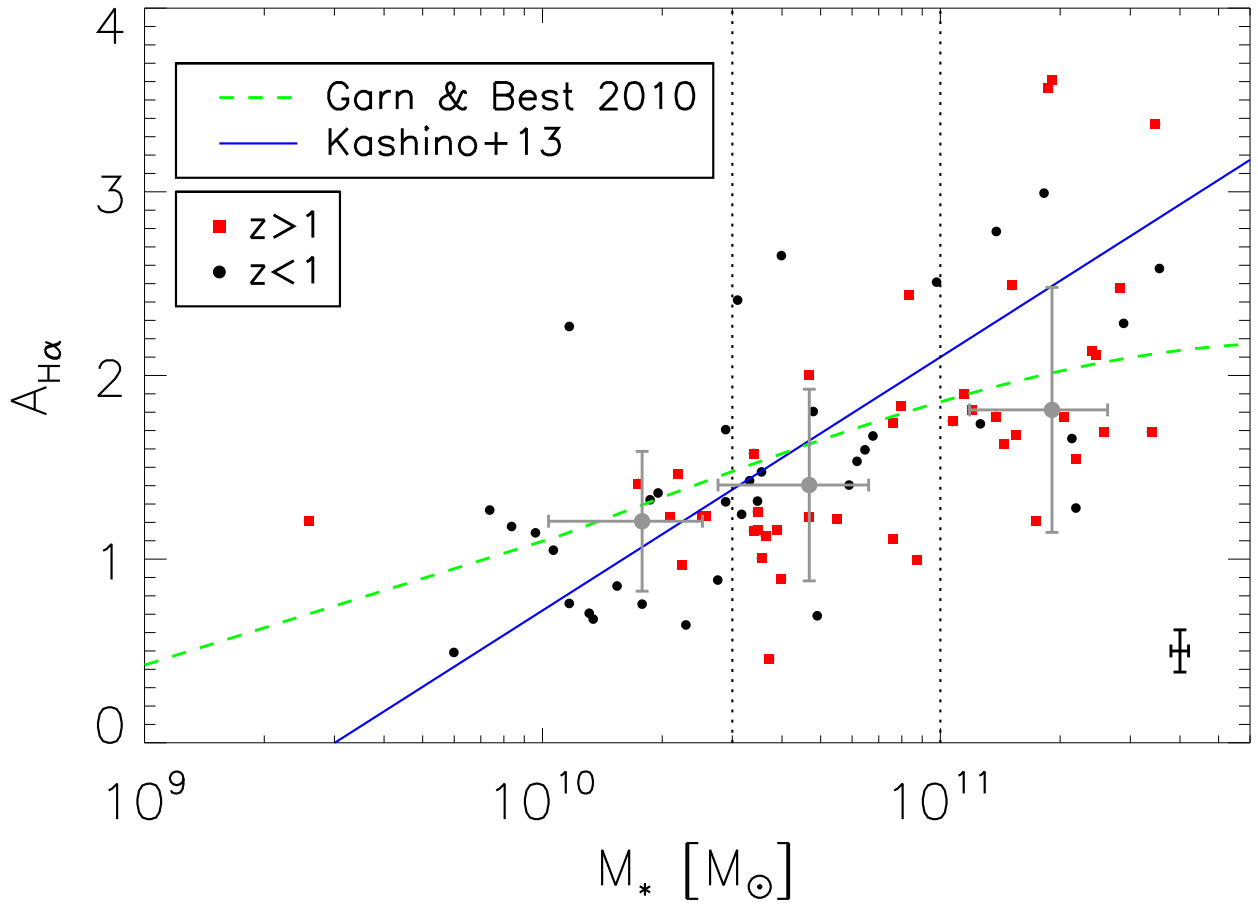


Figure 2.13: $A_{\text{H}\alpha}$ as a function of stellar masses. The black filled circles are the sources at $z < 1$ while red filled squares are objects with $z > 1$. The attenuation is computed from $E_{\text{star,IRX}}(B - V)$ by using $f=0.93$. The grey filled circles are the median values of $A_{\text{H}\alpha}$ in three mass bins ($M_{\star} < 3 \times 10^{10} M_{\odot}$, $3 \times 10^{10} \leq M_{\star} < 1.7 \times 10^{11} M_{\odot}$, $M_{\star} \geq 1.7 \times 10^{11} M_{\odot}$) and the errorbars are the median scatter for $A_{\text{H}\alpha}$ and $M_{\star}$ in each mass bin. The two vertical dashed lines highlight the mass bins ($M_{\star} < 3 \times 10^{10} M_{\odot}$, $3 \times 10^{10} \leq M_{\star} < 1.7 \times 10^{11} M_{\odot}$, $M_{\star} \geq 1.7 \times 10^{11} M_{\odot}$).

2.5.6 Main sequence at $z \sim 1$

In Figure 2.14 we report an updated version of the relation between the stellar mass and the SFR, already presented in Figure 2.2, where SFR is now computed from the $\text{H}\alpha$ luminosities, corrected for dust extinction according to our reference dust correction. As already mentioned in Section 2.2.5, our sources do not span the overall range covered by the star-forming Main Sequence population at $z \sim 1$, since our far-IR selection favor the detection of sources with $\text{SFR} > 10 - 20 M_{\odot}/\text{yr}$. However, we note that above stellar masses on the order $3 \times 10^{10} M_{\odot}$, our sample is basically representative of a mass-selected sample that traces the underlying MS at the same redshift.

2.6 Caveats: the many faces of the f -factor

Values of the f -factor estimated in the literature range from 0.44 to ~ 1 , as shown in Table 2.3, and in this section we briefly discuss the likely origins of these differences. An f -factor less than unity is currently interpreted as implying more average obscuration affecting the line emitting regions (HII regions) compared to the average obscuration affecting the hot stars emitting the UV continuum,

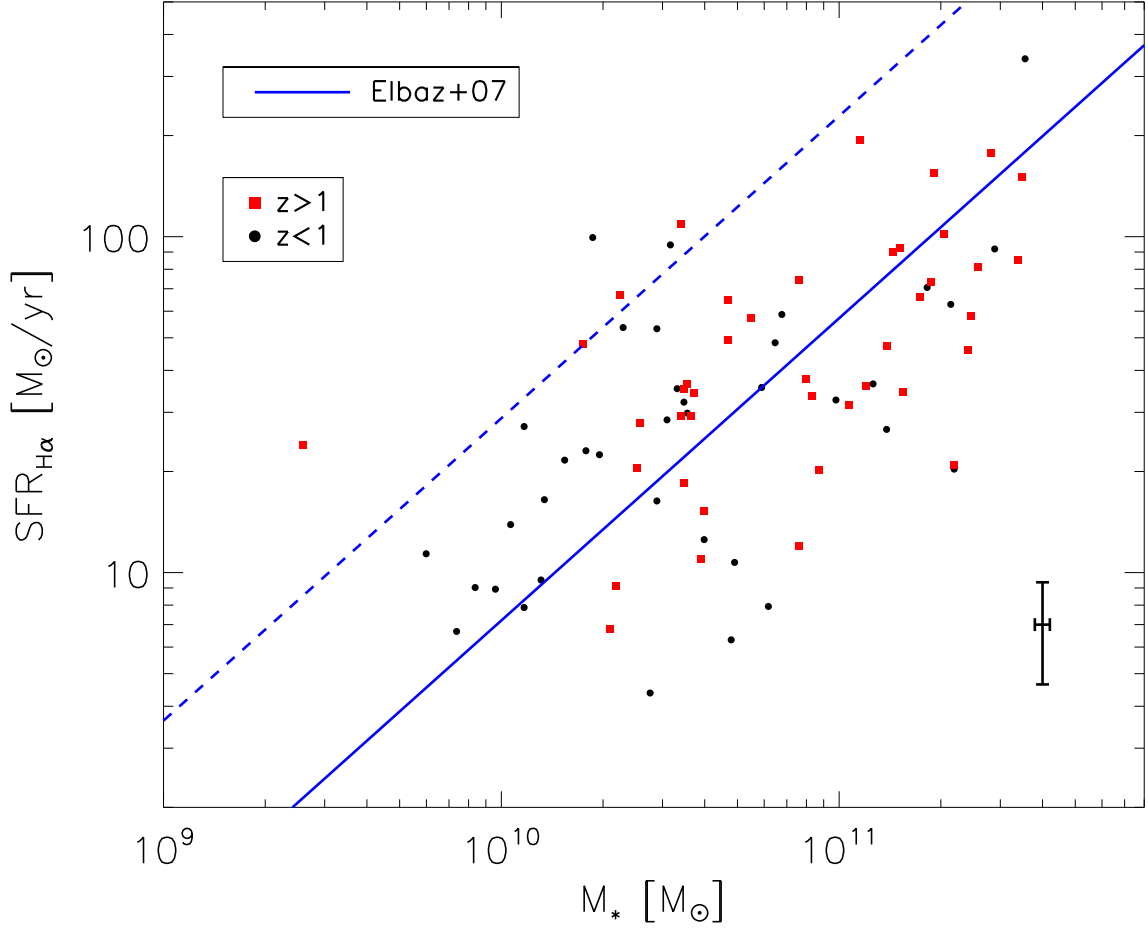


Figure 2.14: $SFR_{H\alpha}$ versus M_* with $L_{H\alpha}$ corrected by dust with our recipe. The blue solid line reports the MS relationship from Elbaz et al. (2007) at $z = 1$ and the blue dashed line is the corresponding $4 \times MS$. The black filled circles are the sources at $z < 1$ while the red filled squares are the objects at $z > 1$. The median errors for M_* and $SFR_{H\alpha}$ are reported in the lower part of the plot on the right.

i.e., $f \neq 1$ would be the result of a geometrical effect with the spacial distribution of line emitting regions being different from that of continuum emitting stars. Actually, the reality may be somewhat more complicated.

First of all, the f -factor can be derived in two radically different ways: either by comparing two extinctions or two SFRs. In the former case the $H\alpha$ extinction derived from the Balmer decrement is compared to the extinction in the UV as derived from either the UV slope or from Equation (10). Then one has to adopt one specific reddening law $k(\lambda)$. In the latter case, the f -factor is estimated by enforcing equality between the SFR derived from the $H\alpha$ flux with the SFR derived from another indicator, such as $SFR(UV)$, $SFR(UV+IR)$ or SFR from SED fitting, etc.

2.6. CAVEATS: THE MANY FACES OF THE f -FACTOR

When the f -factor is derived by comparing $H\alpha$ and UV extinction, then the result depends on the adopted reddening law $k(\lambda)$, hence it reflects at once both the mentioned geometrical effect and possible departures from the adopted reddening law. As well known, the reddening law is not universal, not even within the Local Group. These two contributions to determine the value of f can barely be disentangled. When the f -factor is derived by forcing agreement between $SFR_{H\alpha}$ and the SFR from another indicator, then it becomes a fudge factor to compensate for the relative biases of the two SFR estimators, neither of which will be perfect.

Moreover, the measured $H\alpha$ flux is subject to dust absorption in two distinct ways: first, each $H\alpha$ photon has a probability $10^{-0.4A_{H\alpha}}$ to escape the galaxy, but, second, dust absorption in the Lyman continuum reduces the number of produced $H\alpha$ photons by a factor $10^{-0.4A_{\text{Lyman-cont.}}}$, where $A_{\text{Lyman-cont.}}$ is the extinction in the Lyman continuum. With few exceptions (e.g. Boselli et al. 2009), this second aspect is generally ignored, in the hope that an empirical calibration of SFRs may subsume in it also this part of the involved physics. In any event, the resulting f -factor depends on the actual extinction law of each galaxy, extending from the optical all the way to the Lyman continuum, on the geometry of the emitting regions, as well as on the relative systematic biases in the relations connecting SFRs to observables.

Besides these aspects, derived f values can also depend on the specific galaxy sample from which it is derived. For example, in our approach the far-IR selection criterion leads to select objects with strong levels of dust obscuration in the UV. The other requirement is to select objects with a strong $H\alpha$ emission ($F_{\text{obs}}(H\alpha) > 2.87 \times 10^{-17} \text{ erg/s}$ and S/N higher than ~ 3), hence with lower levels of $H\alpha$ attenuation. The two selection criteria partially conflict with each other and combined favor sources with $E_{\text{neb}}(B - V) \sim E_{\text{star}}(B - V)$. To understand how the selection criterion influences the results we can compare our analysis with the work of Kashino et al. (2013). Our analysis was performed following the same approach of Kashino et al. (2013) but our sample has different selection criterion and size (168 sBzK galaxies for Kashino, 79 far-IR sources in this work) and we obtained an $f=0.93$, that is 35% larger than the Kashino result. In the case of rest-frame UV-selected galaxies, such as in Erb et al. (2006), this bias favors galaxies with low extinction which may result in a different f value compared to the case of samples including also highly reddened galaxies.

All of these considerations imply that different indicators lead to different estimates of the f -factor. For example, if we consider the ratio $SFR_{H\alpha}^{\text{unc}}/SFR_{\text{IR+UV}}$, we get (see e.g. eq. 2.7)

$$\frac{SFR_{H\alpha, \text{uncorr}}}{SFR_{\text{IR+UV}}} = 10^{-0.4A_{H\alpha}} = 10^{-0.4 \frac{E_{\text{star}}(B-V)}{f} k(H\alpha)}. \quad (2.13)$$

Our data would imply in this case $f \simeq 0.85$, however not very significantly different from our best-guess of $f \simeq 0.93$.

Also the estimate of $E_{\text{star}}(B - V)$ and its errors influences the estimate of the f -factor, leading to results that can vary from $f \sim 0.4$ to a value larger than 1.

The last point to consider is again the reddening law $k(\lambda)$ assumed in the analysis. In the literature one finds very different trends for $k(\lambda)$, such as the presence of a bump at $\sim 2200\text{\AA}$ (Fitzpatrick, 1999, for the LMC) or a smoother trend (Calzetti et al., 2000, for a starburst galaxy), and also very different values for its normalization $R_V \equiv A_V/E_{\text{star}}(B - V)$, that vary from 3.1 (Cardelli et al., 1989) to 4.05 (Calzetti et al., 2000). At redshift ~ 2 both galaxies with and without the $2200\text{\AA}$ bump appear to coexist (Noll et al., 2009). The shape and the normalization of the assumed $k(\lambda)$ strongly influences the value of f , both for direct or indirect measurements. As an exercise we derived the f -factor using different $k(\lambda)$ expressions in eq. 2.12. Table 2.2 summarizes the results, showing that the value of the f -factors ranges from ~ 0.7 to ~ 1.2 .

In summary, the f -factor may offer a fair measure of the relative extinction of emission lines and the stellar continuum, still however relying on not-completely well defined and understood ingredients.

Table 2.2: Summary of the values obtained for the f -factor as a function of the assumed reddening curve $k(\lambda)$: the first column is the $k(\lambda)$ assumed to compute the UV attenuation at 1600 Å, the second column is the $k(\lambda)$ used to compute the H α attenuation while the last column is the f -factor, obtained from eq. 2.12.

$k(UV)$	$k(H\alpha)$	f -factor
Calzetti et al. (2000)	Calzetti et al. (2000)	0.93
Calzetti et al. (2000)	Fitzpatrick (1999)	0.66
Reddy et al. (2015)	Reddy et al. (2015)	0.96
Reddy et al. (2015)	Fitzpatrick (1999)	1.19

2.7 Summary and conclusions

In this work we analyzed the near-IR spectra of 79 star forming galaxies at $z \in [0.7 - 1.5]$, acquired from the 3D-HST survey. The sources were selected in the far-IR from the *Herschel*/PACS observations: the PACS catalogs were associated with the 3D-HST observations using the IRAC positions of the PACS sources. From the near-IR spectra we measured the H α fluxes and the spectroscopic redshifts of the whole sample.

We computed the SEDs with the MAGPHYS software, using data from near-UV to far-IR including the GALEX-NUV, the GOODS-MUSIC optical to mid-IR catalog, the IRS-16 μm and the far-IR photometry from *Herschel* PACS and SPIRE (i.e. at 70, 100, 160, 250, 350 and 500 μm). From the SEDs we derived the stellar masses, $M_\star$, the bolometric infrared luminosities, L_{IR} , the UV luminosities, L_{UV} , and the UV slope, β .

We then evaluated the color excess $E_{\text{star}}(B - V)$ from the $\text{IRX} = L_{\text{IR}}/L_{\text{UV}}$ ratio and from the UV slope β and found that these two quantities are in good agreement. In our sample the color excess on the stellar continuum ranges from $E_{\text{star}}(B - V) \sim 0.1 \text{ mag}$ to $E_{\text{star}}(B - V) \sim 1.1 \text{ mag}$.

We computed the dust attenuation on the H α emission $E_{\text{neb}}(B - V)$ as a function of $E_{\text{star}}(B - V)$ by comparing the $SFR_{\text{H}\alpha}$ and the SFR_{UV} , both uncorrected for extinction. We obtained that the f -factor, which parametrizes the differential extinction on the nebular lines, is $f = E_{\text{star}}(B - V)/E_{\text{neb}}(B - V) = 0.93 \pm 0.06$. This result is consistent within the errorbars with the analysis of Kashino et al. (2013) from the Balmer Decrement and of Pannella et al. (2014), performed in a similar redshift range. Our analysis is also consistent with the results of Erb et al. (2006) and Reddy et al. (2010) performed at higher z , as summarized in Table 2.3, which collect a list of results from others works. The good agreement found in our sample between the $SFR_{\text{IR+UV}}$ and the $SFR_{\text{H}\alpha}$ corrected for extinction using our recipe further confirm our results.

From our dust correction we then computed the attenuation $A_{\text{H}\alpha}$ as a function of $M_\star$. We found that $A_{\text{H}\alpha}$ is increasing with $M_\star$ and this trend seems to diverge from the local relationship: our sources shows an excess of $A_{\text{H}\alpha}$ with respect to the relationship of Garn & Best (2010) for $M_\star \gtrsim 10^{11} M_\odot$, suggesting an evolution in the dust properties of star-forming galaxies with z .

2.7. SUMMARY AND CONCLUSIONS

In conclusion we found that the level of differential extinction required to match the $SFR_{H\alpha}$ with the SFR_{IR+UV} is lower than in the local Universe, thus $A_{H\alpha} \sim A_{UV}$ for the sources in our sample. The value of the f -factor seems to be related to the physical properties of the sample rather than be dependent on z . The trends of Figures 2.12 and 2.13 suggest that the $H\alpha$ extinction (thus the f -factor) is a function of SFR and M_* . In particular we notice that in Figure 2.12 our dust correction underestimate $SFR_{H\alpha}$ with respect to SFR_{IR+UV} for sources with $SFR \lesssim 20 M_{\odot}/yr$: these sources require a lower value of f , similar to the local $f=0.58$. This trend could be explained by the two components model of dust sketched in Figure 5 of Price et al. (2014). A galaxy with high sSFR is supposed to have an high number of OB stars, which are located inside the optically thick birth cloud: in this case these massive stars dominate both the UV-continuum and the $H\alpha$ emissions, so the level of attenuation for the continuum and the nebular emission will be similar ($A_{UV} \sim A_{H\alpha}$). On the other and, for a galaxy with low sSFR the number of OB stars will be lower, so in this case the optical-UV continuum is mainly produced by the less massive stars that are located both in the birth cloud and in the diffuse ISM: in this case $A_{H\alpha} > A_{UV}$ since the $H\alpha$ emission is produced in a different and more dust-dense region with respect to the continuum.

In this paper we do not examine in depth the consequences of this modellistic approach for the reasons discussed in the previous section. We defer to a future paper a more detailed analysis of the extinction properties of star-forming galaxies based on the “Intensive Program” (S12B-045, PI J. Silverman) with the FMOS spectrograph at the Subaru Telescope in the COSMOS field (Silverman et al., 2015b).

Table 2.3: Different values of f obtained from literature. In the table are also specified the redshift ranges (third column of Tab. 2.3), the types of sample and the methods implied to measure the differential extinction on nebular lines (fourth and fifth columns of Tab. 2.3, respectively).

<i>Author</i>	<i>f</i>	<i>z range</i>	<i>Sample</i>	<i>Method</i>
Calzetti et al. (2000)	0.44 (0.58)	0.003-0.05	starburst galaxies	Balmer decrement
Kashino et al. (2013)	0.83 ± 0.10	1.4-1.7	sBzk galaxies	Balmer decrement (stacked spectra)
"	0.69 ± 0.02	"	"	$H\alpha$ to UV SFRs
Wuyts et al. (2011)	0.44	0-3	K_s selected galaxies	SFR indicators
Price et al. (2014)	0.55 ± 0.16	1.36-1.5	MS star forming galaxies	Balmer decrement (stacked spectra)
Pannella et al. (2014)	0.58	< 1	UVJ selected galaxies	comparison between $A_{UV}-M_*/A_{H\alpha}-M_*$
"	0.77	1	"	"
"	1	> 1	"	"
Valentino et al. (2015)	0.74 ± 0.05	2	CL J1449+0856	Balmer decrement (stacked spectra)
Erb et al. (2006)	1	2	rest-frame UV selected galaxies	matching UV and $H\alpha$ SFRs
Reddy et al. (2010)	1	1.5-2.6	Lyman Break Galaxies	matching X-ray, UV and $H\alpha$ SFRs
This work	0.93 ± 0.06	0.7-1.5	far-IR selected galaxies	$H\alpha$ to UV SFRs

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2.8 Appendix A: Computation of the UV spectral slope

2.8.1 β from the best-fit SED

The UV slope is derived from a linear fit to the model best-fit SED in the wavelength range $\lambda \in [1250 - 2600]$ Å, lacking observations in this rest-frame range for the majority of the sample. An example of the fit is shown in figure 2.15. The errors related to the β_{model} , i.e. the UV slope derived from the MAGPHYS SED, are computed

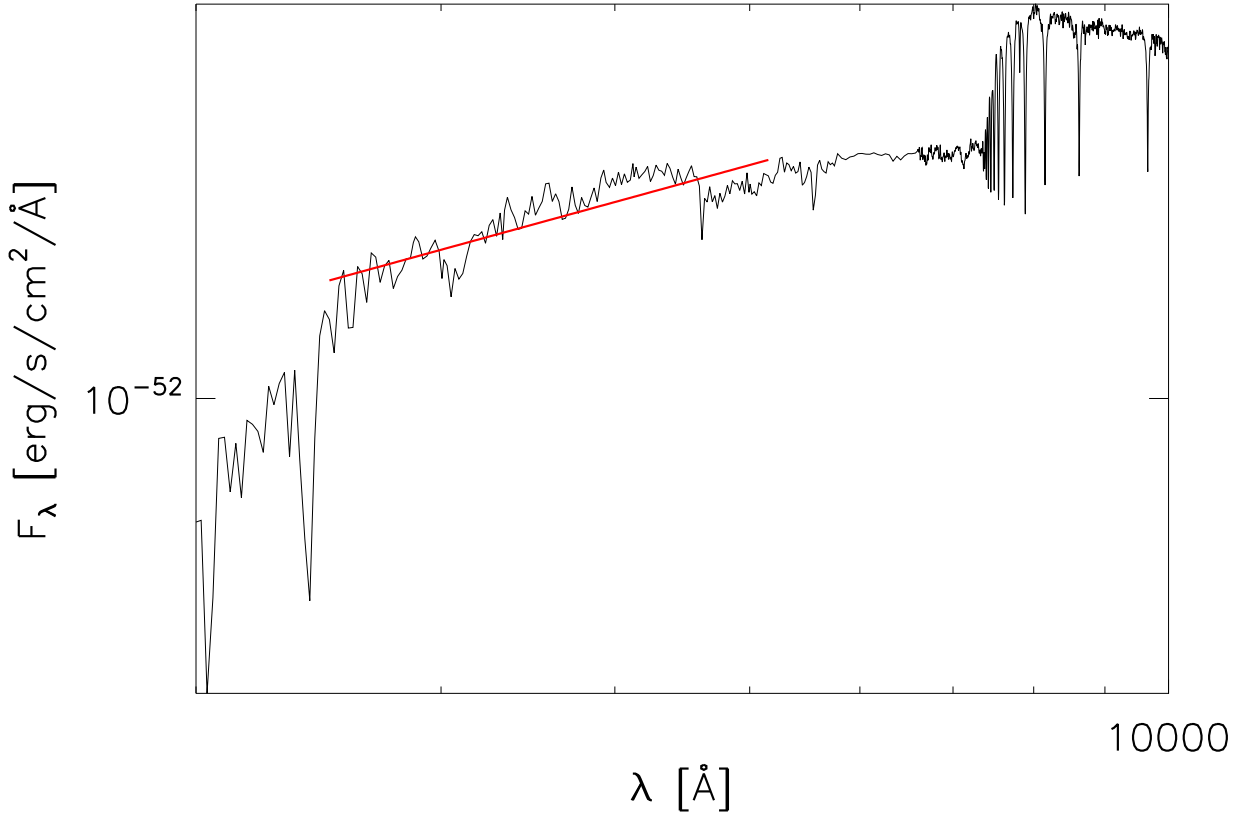


Figure 2.15: Linear fit (red line) to the best-fit SED in the plane $\log(\lambda), \log(F_\lambda)$.

from the linear fit.

2.8.2 β from the observed photometry

In order to test the validity of the estimate of β_{model} we computed the UV-slope also from the observed data, when is available the photometric coverage in the rest-frame range of interest. We interpolated the observed photometry in the rest-frame range $\lambda \in [1200 - 3500]$ Å, following the method described in Nordon et al. (2013). The photometric UV-spectral slope is defined as:

$$\beta_{\text{phot}} = \frac{-0.4(M_1 - M_2)}{\log(\lambda_1/\lambda_2)} - 2 \quad (2.14)$$

where M_1 and M_2 are the AB magnitudes at wavelengths $\lambda_1=1600$ Å and $\lambda_2=2800$ Å.

2.8. APPENDIX A: COMPUTATION OF THE UV SPECTRAL SLOPE

The rest-frame 1600 Å and 2800 Å magnitudes (M_{1600} and M_{2800}) were estimated by interpolating between the available photometric bands. To derive M_{1600} we used the filters between rest-frame $\lambda \in [1200 - 2800]$ Å and interpolated the flux at 1600Å (converted to AB magnitudes) by fitting a linear function between the observed photometric bands. To derive M_{2800} we selected the filters that observe the rest-frame $\lambda \in [1500 - 3500]$ Å. Figure 2.16 shows an example for the computation of M_{1600} and M_{2800} for a source that have the required photometric coverage. Figure 2.17 shows the case in which we haven't the coverage in the rest-frame. The β_{phot} was computed for **13** sources. We computed the errors for β_{phot} by using a set of MC simulations: we randomly varied the observed photometry within the errorbars and we then computed the interpolation for each set of simulated values of the observed photometry. The 1σ uncertainty on β_{phot} was then estimated from the width of the probability distribution function of the simulated values, assuming that this distribution has a Gaussian shape. The median error on β_{phot} was added in quadrature to the error of β_{model} thus the error for the UV-slope is $\sigma_{\beta,i}^2 = \sigma_{\beta_{\text{model},i}}^2 + \text{median}(\sigma_{\beta_{\text{phot},i}}^2)$.

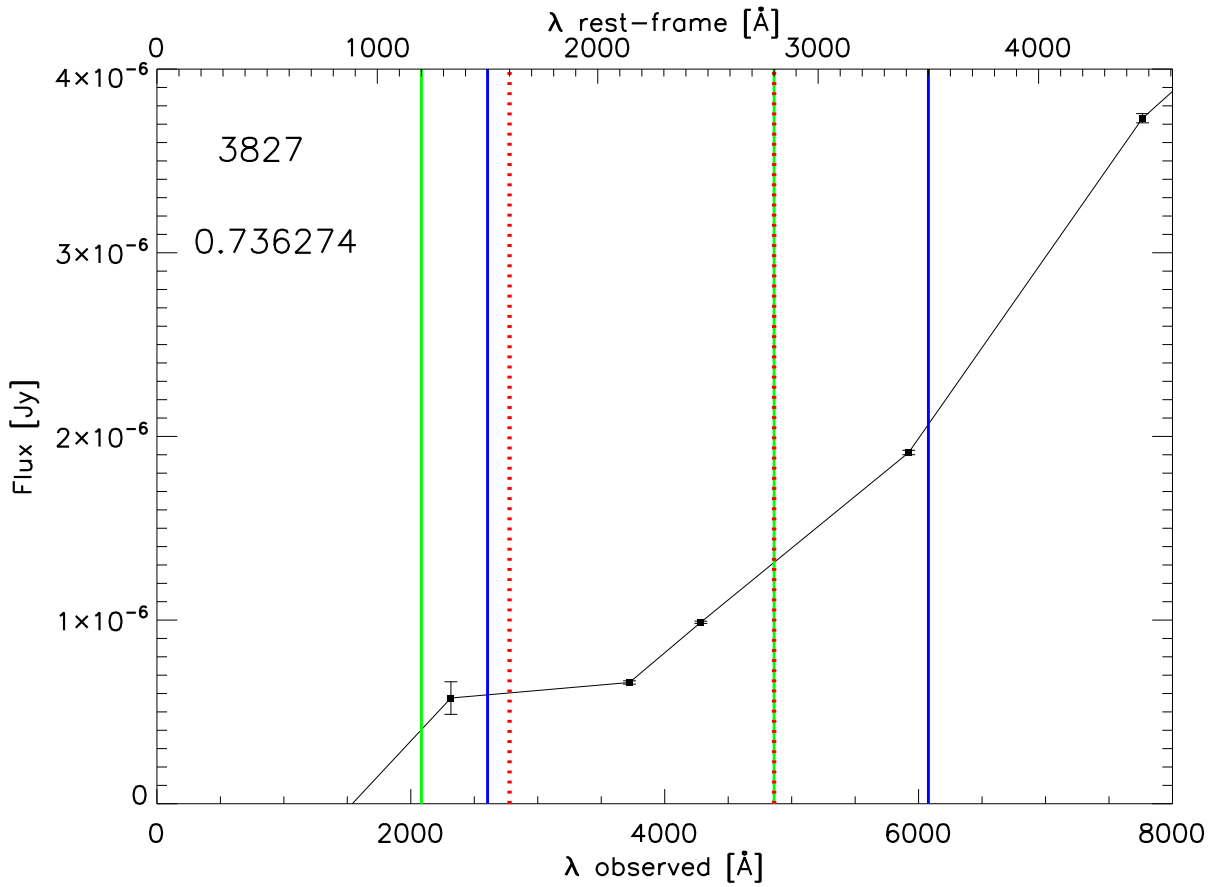


Figure 2.16: The plot displays the method for the computation of β_{phot} for the source 3213 (ID MUSIC). In the figure it is specified also the redshift of the source. The black open diamonds are the observed photometry, connected with a linear interpolation (black solid line). The green vertical lines highlight the rest-frame spectral range considered to compute M_1 while the blue vertical lines mark the range for the computation of M_2 . The two dash-dot red lines mark respectively the positions of 1600 Å and 2800 Å rest-frame.

2.8.3 β_{phot} vs β_{model}

The UV spectral slope is model-dependent, since it is obtained from a fit to the SED: in order to verify the validity of our measurements we compared β_{model} to β_{phot} for the 13 sources that have the required photometric coverage in the UV spectrum.

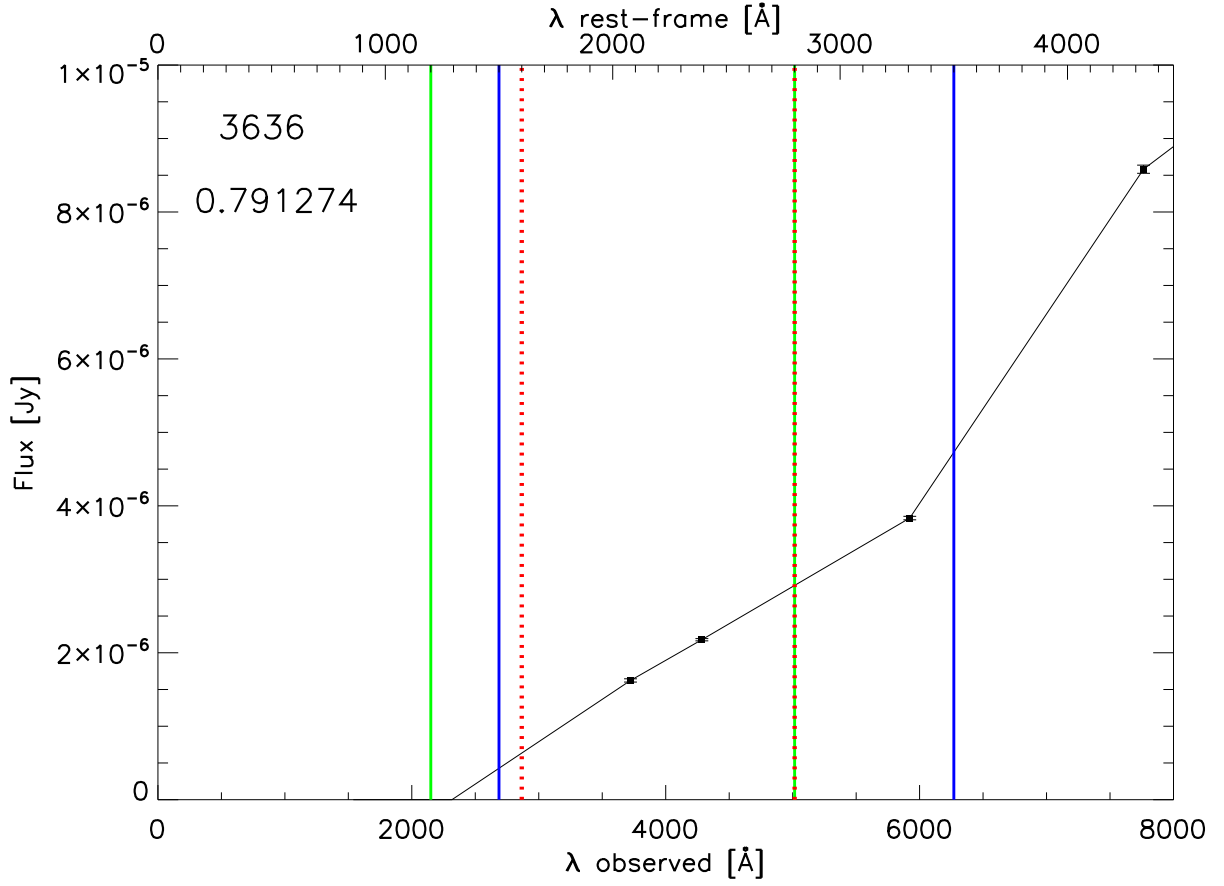


Figure 2.17: The plot is analogous to the previous. In this case we do not have the photometric coverage to derive β_{phot} .

The Spectral Energy Distributions were re-computed in this case excluding the photometric bands in the UV rest-frame spectral range, as we want to compare a value strongly dependent on the model to those constrained by the observed data. The correlation between β_{model} and β_{phot} is shown in Figure 2.18: the agreement between the two estimates is quite good, considering also the poor statistic, and confirms the reliability of β_{model} derived by fitting the modeled SEDs.

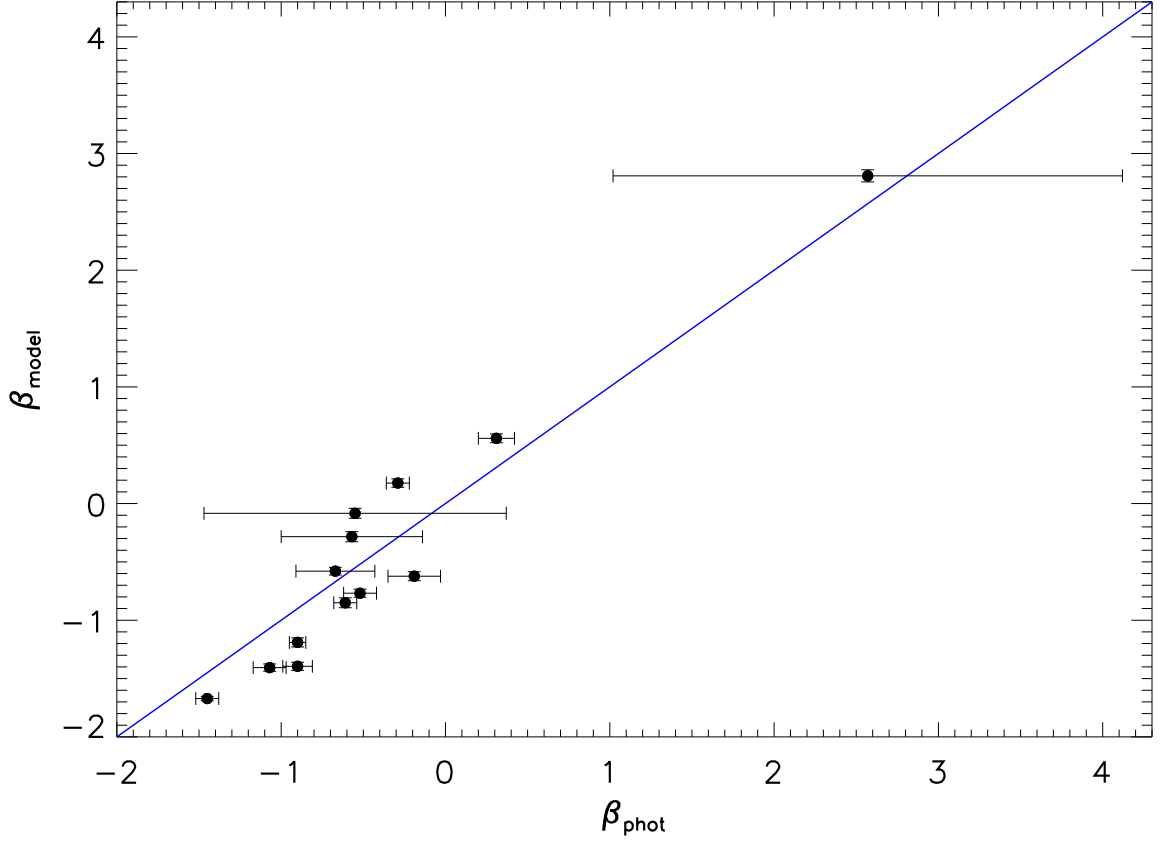


Figure 2.18: Comparison between β_{model} , derived from the SED fitting, and β_{phot} , computed by fitting the observed photometry, for the 15 sources with photometric coverage in the rest-frame range $\lambda \in [1200 - 3500]\text{\AA}$. The blue line is the 1:1 line. The linear Pearson correlation coefficient is $r=0.96$

2.9 Appendix B: main parameters of the sample

Table 2.4 summarizes the MUSIC ID, the coordinates, the redshift measured from the 3D-HST near-IR spectra, the observed $H\alpha$ luminosity $L_{H\alpha,obs}$ corrected for the aperture as explained in section 2.3.2, the infrared luminosity L_{IR} , the observed UV luminosity L_{UV} and the stellar masses $M_{\star}$ of the sample.

Table 2.4: List of the main parameter measured for the galaxies in the sample. The first column indicates the MUSIC-ID of the sources, the second and third columns are the coordinates, the 4th column reports the redshift derived from the 3D-HST near-IR spectrum, the 5th column is the observed H α luminosity (i.e. not corrected for dust attenuation), the 6th column reports the infrared luminosity, the 7th column is the bolometric rest-frame UV luminosity (derived from L_{1600} , as explained in Section 2.4.2) and the last column is the stellar mass. For each of the quantities listed here it is also indicated the 1σ uncertainty. The quantities L_{IR} , L_{UV} and $M_{\star}$ are derived from the SED fitting with the MAGPHYS code (see Section 2.4.1). The H α luminosity is corrected for the contamination by [NII] (cfr. Section 2.4.2) and for the aperture (see Section 2.3.2)

MUSIC ID	RA [decimal deg.]	Dec [decimal deg.]	$z_{\text{3D-HST}}$	$\log(L_{\text{H}\alpha,\text{obs}}) \pm 1\sigma$ [erg/s]	$\log(L_{\text{IR}}) \pm 1\sigma$ [$L_{\odot}$]	$\log(L_{1600}) \pm 1\sigma$ [$L_{\odot}$]	$\log(M_{\star}) \pm 1\sigma$ [$M_{\odot}$]
3213	53.0714684	-27.8809948	0.99	41.95 $\pm$ 0.03	11.46 $\pm$ 0.07	9.71 $\pm$ 0.97	10.06 $\pm$ 0.10
3636	53.0941353	-27.8755627	0.79	41.37 $\pm$ 0.06	10.97 $\pm$ 0.06	9.81 $\pm$ 0.98	10.21 $\pm$ 0.07
3698	53.0734024	-27.8745785	1.10	42.34 $\pm$ 0.05	11.82 $\pm$ 0.03	9.72 $\pm$ 0.97	11.30 $\pm$ 0.06
3827	53.0760498	-27.8736115	0.74	41.98 $\pm$ 0.01	11.20 $\pm$ 0.01	9.34 $\pm$ 0.93	10.32 $\pm$ 0.01
4491	53.0893517	-27.8644161	0.83	42.27 $\pm$ 0.01	10.89 $\pm$ 0.09	9.99 $\pm$ 1.00	9.90 $\pm$ 0.25
4738	53.2219315	-27.8594131	0.74	42.05 $\pm$ 0.02	10.82 $\pm$ 0.05	9.90 $\pm$ 0.99	10.46 $\pm$ 0.09
5142	53.2202797	-27.8540936	1.00	41.85 $\pm$ 0.04	11.72 $\pm$ 0.02	9.66 $\pm$ 0.97	11.10 $\pm$ 0.07
5302	53.2209053	-27.8513260	0.74	42.25 $\pm$ 0.01	11.14 $\pm$ 0.04	8.13 $\pm$ 0.81	10.76 $\pm$ 0.09
5334	53.1965446	-27.8516655	1.22	42.00 $\pm$ 0.04	11.74 $\pm$ 0.01	9.17 $\pm$ 0.92	11.16 $\pm$ 0.08
5429	53.0707664	-27.8506660	0.99	41.57 $\pm$ 0.42	11.36 $\pm$ 0.02	8.62 $\pm$ 0.86	9.84 $\pm$ 0.06
5812	53.1155014	-27.8446636	1.09	42.00 $\pm$ 0.07	11.82 $\pm$ 0.02	9.62 $\pm$ 0.96	11.08 $\pm$ 0.06
6272	53.1077652	-27.8388157	1.11	41.74 $\pm$ 0.14	11.40 $\pm$ 0.01	9.96 $\pm$ 1.00	10.33 $\pm$ 0.01
6344	53.2149391	-27.8382416	0.85	42.38 $\pm$ 0.01	11.24 $\pm$ 0.01	10.24 $\pm$ 1.02	10.02 $\pm$ 0.08
6722	53.2181320	-27.8336830	0.85	42.15 $\pm$ 0.03	11.24 $\pm$ 0.01	9.57 $\pm$ 0.96	10.31 $\pm$ 0.10
6983	53.2155266	-27.8308353	0.74	42.16 $\pm$ 0.02	11.33 $\pm$ 0.01	9.66 $\pm$ 0.97	10.23 $\pm$ 0.08
7224	53.0898857	-27.8282318	1.10	42.09 $\pm$ 0.02	11.17 $\pm$ 0.04	9.32 $\pm$ 0.93	10.11 $\pm$ 0.17
7335	53.0936508	-27.8263798	0.88	42.30 $\pm$ 0.01	11.93 $\pm$ 0.01	8.84 $\pm$ 0.88	11.32 $\pm$ 0.09
7400	53.2023735	-27.8262043	1.11	41.48 $\pm$ 0.10	12.03 $\pm$ 0.01	7.81 $\pm$ 0.78	11.05 $\pm$ 0.01
8003	53.0892830	-27.8171749	0.75	42.60 $\pm$ 0.01	10.82 $\pm$ 0.04	9.83 $\pm$ 0.98	9.84 $\pm$ 0.06
8090	53.0667534	-27.8166199	1.41	41.84 $\pm$ 0.11	12.11 $\pm$ 0.01	8.14 $\pm$ 0.81	11.31 $\pm$ 0.02
8231	53.1498871	-27.8140030	1.31	41.69 $\pm$ 0.12	11.09 $\pm$ 0.04	10.52 $\pm$ 1.05	10.34 $\pm$ 0.20
8737	53.0681343	-27.8066711	1.30	41.93 $\pm$ 0.17	11.41 $\pm$ 0.01	9.60 $\pm$ 0.96	10.01 $\pm$ 0.01
9269	53.1198807	-27.7987385	1.38	42.45 $\pm$ 0.02	11.59 $\pm$ 0.01	9.35 $\pm$ 0.93	10.85 $\pm$ 0.08
9302	53.0341835	-27.7977962	0.84	42.24 $\pm$ 0.01	11.45 $\pm$ 0.02	9.46 $\pm$ 0.95	10.58 $\pm$ 0.12
9310	53.0292320	-27.7981472	0.84	41.91 $\pm$ 0.01	10.92 $\pm$ 0.05	8.69 $\pm$ 0.87	10.45 $\pm$ 0.09
9452	53.1567535	-27.7956085	1.11	42.10 $\pm$ 0.04	11.22 $\pm$ 0.03	9.73 $\pm$ 0.97	10.31 $\pm$ 0.07
9687	53.1841621	-27.7926331	0.73	41.14 $\pm$ 0.19	11.16 $\pm$ 0.02	9.79 $\pm$ 0.98	9.80 $\pm$ 0.05
9779	53.0268173	-27.7913227	1.02	42.18 $\pm$ 0.03	11.71 $\pm$ 0.02	9.61 $\pm$ 0.96	11.18 $\pm$ 0.09
9903	53.0906639	-27.7901840	0.99	41.82 $\pm$ 0.04	11.15 $\pm$ 0.05	9.33 $\pm$ 0.93	10.29 $\pm$ 0.13
10015	53.1095657	-27.7882004	0.99	42.29 $\pm$ 0.01	10.92 $\pm$ 0.09	9.99 $\pm$ 1.00	9.89 $\pm$ 0.05
10263	53.1765938	-27.7854614	1.31	42.03 $\pm$ 0.02	11.45 $\pm$ 0.01	8.84 $\pm$ 0.88	11.15 $\pm$ 0.04
10295	53.0440521	-27.7850533	1.04	41.78 $\pm$ 0.03	11.40 $\pm$ 0.03	9.81 $\pm$ 0.98	10.17 $\pm$ 0.16
10617	53.1352501	-27.7816753	1.43	41.91 $\pm$ 0.05	10.54 $\pm$ 0.10	9.26 $\pm$ 0.93	10.32 $\pm$ 0.06
10669	53.0406151	-27.7803345	0.96	41.91 $\pm$ 0.02	10.98 $\pm$ 0.08	9.31 $\pm$ 0.93	10.04 $\pm$ 0.10
10674	53.1790581	-27.7805214	1.03	42.21 $\pm$ 0.01	11.73 $\pm$ 0.04	7.55 $\pm$ 0.75	11.04 $\pm$ 0.10
10681	53.1288300	-27.7804184	1.17	42.58 $\pm$ 0.01	11.29 $\pm$ 0.02	9.03 $\pm$ 0.90	10.67 $\pm$ 0.08
10730	53.0497627	-27.7790527	1.22	41.45 $\pm$ 0.11	11.44 $\pm$ 0.02	9.24 $\pm$ 0.92	10.91 $\pm$ 0.05
10859	53.1452293	-27.7779026	1.09	42.01 $\pm$ 0.02	11.56 $\pm$ 0.02	9.11 $\pm$ 0.91	10.44 $\pm$ 0.07
10972	53.0584106	-27.7761879	0.83	42.01 $\pm$ 0.01	11.44 $\pm$ 0.02	8.54 $\pm$ 0.85	10.26 $\pm$ 0.06
11121	53.0370216	-27.7747364	1.03	42.17 $\pm$ 0.01	10.07 $\pm$ 0.07	8.94 $\pm$ 0.89	10.37 $\pm$ 0.10
11346	53.1279831	-27.7714329	1.31	41.59 $\pm$ 0.06	11.21 $\pm$ 0.04	9.90 $\pm$ 0.99	10.71 $\pm$ 0.06
11381	53.1059380	-27.7714195	0.89	41.92 $\pm$ 0.02	11.46 $\pm$ 0.02	9.39 $\pm$ 0.94	10.60 $\pm$ 0.10
11658	53.1169853	-27.7683487	1.11	41.77 $\pm$ 0.04	11.37 $\pm$ 0.03	8.44 $\pm$ 0.84	10.69 $\pm$ 0.07
11708	53.0656624	-27.7678661	1.53	42.06 $\pm$ 0.04	11.59 $\pm$ 0.04	9.61 $\pm$ 0.96	10.30 $\pm$ 0.10
11794	53.1513672	-27.7666893	0.89	42.20 $\pm$ 0.01	11.08 $\pm$ 0.01	8.94 $\pm$ 0.89	10.23 $\pm$ 0.01
11814	53.1812057	-27.7656651	1.22	41.60 $\pm$ 0.12	11.37 $\pm$ 0.06	9.80 $\pm$ 0.98	10.44 $\pm$ 0.06

2.9. APPENDIX B: MAIN PARAMETERS OF THE SAMPLE

Table 2.5: List of the main parameter computed for the galaxies in the sample (continuation).

MUSIC ID	RA [deg]	Dec [deg]	z_{3D-HST}	$\log(L_{H\alpha,obs}) \pm 1\sigma$ [erg/s]	$\log(L_{IR}) \pm 1\sigma$ [$L_{\odot}$]	$\log(L_{1600}) \pm 1\sigma$ [$L_{\odot}$]	$\log(M_{\star}) \pm 1\sigma$ [$M_{\odot}$]
11958	53.0285225	-27.7639732	0.84	42.40 $\pm$ 0.01	10.95 $\pm$ 0.04	9.83 $\pm$ 0.98	9.96 $\pm$ 0.07
12297	53.1636009	-27.7589455	1.09	41.71 $\pm$ 0.04	11.29 $\pm$ 0.02	9.35 $\pm$ 0.93	11.11 $\pm$ 0.06
12349	53.1119385	-27.7578316	0.83	42.33 $\pm$ 0.01	11.15 $\pm$ 0.02	9.00 $\pm$ 0.90	10.87 $\pm$ 0.07
12401	53.0729218	-27.7578526	1.04	42.15 $\pm$ 0.01	11.04 $\pm$ 0.01	9.56 $\pm$ 0.96	10.30 $\pm$ 0.01
12468	53.0228424	-27.7570210	1.19	42.07 $\pm$ 0.02	11.63 $\pm$ 0.02	8.64 $\pm$ 0.86	10.95 $\pm$ 0.07
12660	53.0804939	-27.7538910	0.73	41.79 $\pm$ 0.03	10.78 $\pm$ 0.07	9.32 $\pm$ 0.93	9.75 $\pm$ 0.06
12667	53.1952438	-27.7537766	0.84	41.94 $\pm$ 0.01	11.26 $\pm$ 0.08	9.34 $\pm$ 0.93	10.56 $\pm$ 0.05
12781	53.0962143	-27.7525444	1.01	42.91 $\pm$ 0.01	10.39 $\pm$ 0.06	8.92 $\pm$ 0.89	10.36 $\pm$ 0.07
12815	53.0361824	-27.7522297	1.29	42.15 $\pm$ 0.04	11.92 $\pm$ 0.01	8.95 $\pm$ 0.89	11.22 $\pm$ 0.04
12967	53.1073837	-27.7498131	0.83	42.06 $\pm$ 0.01	10.99 $\pm$ 0.02	9.36 $\pm$ 0.94	9.64 $\pm$ 0.06
13192	53.1616096	-27.7469234	0.73	41.59 $\pm$ 0.02	11.72 $\pm$ 0.01	8.38 $\pm$ 0.84	10.91 $\pm$ 0.01
13194	53.0687332	-27.7469501	0.97	41.38 $\pm$ 0.12	11.44 $\pm$ 0.02	9.66 $\pm$ 0.97	10.54 $\pm$ 0.16
13382	53.1463699	-27.7443180	1.03	41.66 $\pm$ 0.03	11.29 $\pm$ 0.02	9.70 $\pm$ 0.97	10.18 $\pm$ 0.03
13505	53.0615921	-27.7425251	0.73	42.37 $\pm$ 0.01	11.03 $\pm$ 0.13	7.84 $\pm$ 0.78	10.37 $\pm$ 0.05
13540	53.1073494	-27.7419224	0.89	41.47 $\pm$ 0.06	11.48 $\pm$ 0.02	7.93 $\pm$ 0.79	11.03 $\pm$ 0.18
13552	53.0940933	-27.7405052	0.73	41.45 $\pm$ 0.06	11.49 $\pm$ 0.01	9.86 $\pm$ 0.99	11.11 $\pm$ 0.03
13617	53.1501236	-27.7399464	1.05	42.11 $\pm$ 0.03	11.30 $\pm$ 0.04	10.02 $\pm$ 1.00	10.12 $\pm$ 0.09
13664	53.0837898	-27.7395668	1.22	42.08 $\pm$ 0.03	11.51 $\pm$ 0.02	9.48 $\pm$ 0.95	10.93 $\pm$ 0.09
13694	53.1752434	-27.7392445	1.15	41.29 $\pm$ 0.23	11.10 $\pm$ 0.07	9.50 $\pm$ 0.95	10.31 $\pm$ 0.09
13844	53.0494080	-27.7370377	1.28	41.87 $\pm$ 0.09	11.43 $\pm$ 0.06	9.86 $\pm$ 0.99	10.51 $\pm$ 0.06
13915	53.1443443	-27.7355614	1.26	41.90 $\pm$ 0.04	11.11 $\pm$ 0.02	8.94 $\pm$ 0.89	10.80 $\pm$ 0.08
14519	53.0166168	-27.7270679	0.96	42.52 $\pm$ 0.01	11.57 $\pm$ 0.02	8.80 $\pm$ 0.88	11.23 $\pm$ 0.08
14585	53.0393867	-27.7266464	1.02	42.41 $\pm$ 0.01	10.91 $\pm$ 0.01	8.74 $\pm$ 0.87	10.65 $\pm$ 0.01
15143	53.1693153	-27.7189751	1.22	41.86 $\pm$ 0.07	11.39 $\pm$ 0.01	9.94 $\pm$ 0.99	10.65 $\pm$ 0.01
15279	53.1508827	-27.7161102	0.96	42.37 $\pm$ 0.02	11.37 $\pm$ 0.02	10.53 $\pm$ 1.05	10.13 $\pm$ 0.08
15568	53.1889420	-27.7137222	1.19	41.89 $\pm$ 0.13	11.49 $\pm$ 0.07	9.16 $\pm$ 0.92	10.83 $\pm$ 0.09
15711	53.1235085	-27.7118225	0.65	42.16 $\pm$ 0.01	11.38 $\pm$ 0.02	9.79 $\pm$ 0.98	10.27 $\pm$ 0.11
16046	53.0786095	-27.7074299	1.08	41.48 $\pm$ 0.08	11.13 $\pm$ 0.05	9.56 $\pm$ 0.96	10.09 $\pm$ 0.07
16930	53.1391869	-27.6941433	1.04	42.47 $\pm$ 0.01	11.45 $\pm$ 0.02	9.37 $\pm$ 0.94	10.96 $\pm$ 0.05
17069	53.1626816	-27.6923409	0.73	42.52 $\pm$ 0.01	10.39 $\pm$ 0.09	9.76 $\pm$ 0.98	9.55 $\pm$ 0.05
17450	53.0881500	-27.6851749	1.12	42.75 $\pm$ 0.01	11.04 $\pm$ 0.04	9.52 $\pm$ 0.95	11.01 $\pm$ 0.07
17593	53.1090813	-27.6835785	1.04	42.53 $\pm$ 0.01	11.04 $\pm$ 0.08	9.49 $\pm$ 0.95	9.18 $\pm$ 0.09
30257	53.1665344	-27.7037868	0.82	41.44 $\pm$ 0.06	10.93 $\pm$ 0.07	9.42 $\pm$ 0.94	9.69 $\pm$ 0.04

Chapter 3

The Bright and Dark Sides of High-Redshift starburst galaxies from *Herschel* and *Subaru* observations

Abstract

We present rest-frame optical spectra from the FMOS-COSMOS survey of twelve $z \sim 1.6$ *Herschel* starburst galaxies, with Star Formation Rate (SFR) elevated by $\times 8$, on average, above the star-forming Main Sequence (MS). Comparing the $H\alpha$ to IR luminosity ratio and the Balmer Decrement we find that the optically-thin regions of the sources contain on average only ~ 10 percent of the total SFR whereas ~ 90 percent comes from an extremely obscured component which is revealed only by far-IR observations and is optically-thick even in $H\alpha$. We measure the $[\text{NII}]_{6583}/H\alpha$ ratio, suggesting that the less obscured regions have a metal content similar to that of the MS population at the same stellar masses and redshifts. However, our objects appear to be metal-rich outliers from the metallicity-SFR anticorrelation observed at fixed stellar mass for the MS population. The $[\text{SII}]_{6732}/[\text{SII}]_{6717}$ ratio from the average spectrum indicates an electron density $n_e \sim 1,100 \text{ cm}^{-3}$, larger than what estimated for MS galaxies but only at the 1.5σ level. Our results provide supporting evidence that high- z MS outliers are the analogous of local ULIRGs, and are consistent with a major merger origin for the starburst event.¹

3.1 Introduction

The majority of Star Forming (SF) galaxies at all redshifts form stars in a quasi-steady state along the Main Sequence (MS), a correlation between their stellar mass ($M_\star$) and the Star Formation Rate (SFR, Noeske et al., 2007; Elbaz et al., 2007; Renzini & Peng, 2015). MS galaxies also form a tight sequence in the $M_\star$ -metallicity (Z) plane (the Mass-Metallicity Relation MZR, see e.g., Tremonti et al., 2004; Maiolino et al., 2008), with metallicity increasing with $M_\star$. The scatter in the MZR is reduced when considering the anti-correlation of Z with the SFR at fixed $M_\star$ (e.g. Ellison et al., 2008). Mannucci et al. (2010) found such relation to be invariant up to $z \sim 2.5$ and called it the Fundamental Metallicity Relation (FMR). The interpretation of this relation is that the SFR is enhanced by upward fluctuations in the gas inflow rate from the cosmic web, while such inflow dilutes the metal content of the system (e.g., Lilly et al., 2013).

¹The present Chapter is an extended version of the work presented in Puglisi et al. (2017)

A fourth key parameter of SF galaxies is their dust content, which correlates with their M_* , SFR and Z so that more massive objects, as well as most SF or metal-rich galaxies tend to host larger dust reservoirs, thus suffering higher extinction (Garn & Best, 2010; Pannella et al., 2014; Tan et al., 2014).

Besides the MS galaxy population, a population of outliers has been observed at all redshifts, supporting extreme SFRs for their M_* . While such MS-outliers contribute only $\sim 10\%$ to the cosmic Star Formation History (SFH) (Rodighiero et al., 2011), they may represent a key phase in galaxy evolution, having been considered among the progenitors of passively evolving ellipticals (e.g. Cimatti et al., 2008). Local outliers appear to be mainly Ultra-Luminous InfraRed Galaxies (ULIRGs) undergoing a major merger that funnels gas into the nucleus, enhances the Star Formation Efficiency (SFE) and triggers a StarBurst (SB, Sanders & Mirabel, 1996). These systems have strong dust extinction (Monreal-Ibero et al., 2010) and complex kinematic and gas properties (Rich et al., 2015), with strong nuclear outflows and shock dominated regions (Westmoquette et al., 2009b). The nature of the high- z counterparts to these SB galaxies is however still debated, as it is not clear yet to which extent their high SFR is uniquely due to a higher SFE, as if experiencing a different mode of SF (e.g. Daddi et al., 2010b; Tacconi et al., 2013, 2017; Sargent et al., 2014; Silverman et al., 2015a), or to a higher gas content, or a combination thereof (Genzel et al., 2015; Scoville et al., 2016). Studies of the metal content of high- z SBs may shed light on their nature as the gas-phase metallicity reflects their recent SF activity and is a crucial input when estimating their gas content via either the CO luminosity or the dust continuum emission (e.g. Genzel et al., 2015; Tacconi et al., 2017).

In this work we present an analysis of the Inter Stellar Medium (ISM) properties of 12 *Herschel*-selected SB galaxies at $1.4 \leq z_{\text{spec}} \leq 1.7$ with $H\alpha$ detection via near-IR spectroscopy from the FMOS-COSMOS survey (Silverman et al., 2015b). These galaxies have SFRs from 4 to over $10 \times \text{SFR}_{\text{MS}}$ and are analyzed in comparison to the MS population, taking advantages of our complementary studies on MS galaxies at the same redshift (Zahid et al., 2014; Kashino et al., 2013, 2017a). Throughout this Letter we adopt a Chabrier (2003) IMF, standard cosmology ($H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$), AB magnitudes and a Calzetti et al. (2000) extinction law.

3.2 The FMOS-COSMOS survey

The FMOS-COSMOS survey (Silverman et al., 2015b) is a large survey in the central area of the COSMOS field (see Fig. 1 in Silverman et al. 2015b), designed to acquire near-IR spectra of a statistical sample of star-forming galaxies at $1.4 \leq z \leq 1.7$. Observations of this survey are carried out with the Fiber Multi-Object Spectrograph (FMOS, Kimura et al., 2010) at the *Subaru* telescope, which provides fiber spectra in the near-IR regime. With its multi-object capabilities, it allows to collect ~ 200 galaxy spectra in a single exposure within a $30'$ circular field of view, when it is used in Cross-Beam Switching mode (CBS). This technique dithers target between fiber pairs allowing to measure the sky background in the vicinity of the science target and through the same fiber. The size of these fibers is $1.2''$. The strong atmospheric emission affecting near-IR observations is masked out by an OH-airglow suppressor (Iwamuro et al., 2011) which causes a $\sim 25\%$ loss on the wavelength coverage. Out of the four available, the FMOS-COSMOS survey uses the *H-long* ($\lambda \in [1.6-1.8] \mu\text{m}$) and *J-long* ($\lambda \in [1.1-1.35] \mu\text{m}$) gratings in high-resolution mode ($R = \lambda/\Delta\lambda \sim 2600$) to observe the $H\alpha + [\text{NII}]_{6549,6583}$ and $H\beta + [\text{OIII}]_{4959,5007}$ emission lines respectively.

Since the first aim of the project is to detect the $H\alpha$ emission to obtain a reliable estimate of the spectroscopic redshift, the primary observations have been conducted with the *H-long* grating. The single exposure for each pointing is 900 sec and the total exposure time is around 5 hours in the original program (see Table 2 in Silverman et al. 2015b). However the exposure times on the final data-set may vary across the field of view as some individual pointings were re-observed during the 25 additional nights our team was awarded to complete the program. More details about the final sample are given in Kashino et al. (2017b). The work presented in this chapter is based on observations carried out within the initial program, fully described in Silverman et al. (2015b).

In addition to the *H-long* observations, a shorter wavelength followup with the *J-long* grating was performed to detect the $H\beta + [\text{OIII}]_{4959,5007}$ lines: this leads to substantial improvements in the assessment of the spectroscopic redshifts and enables a more complete characterization of the sources. The detection of emission lines at shorter rest-frame wavelength is however very challenging, due to the strong attenuation in the galaxy at this regime. To overcome contamination from the sky and improve the SN, the majority of our scientific results rely on stacking techniques (see Sect. 3.4.2 for more details about the stacking).

Samples selection

The main targets of FMOS-COSMOS observations are K_s selected star-forming galaxies with $K_s \leq 23$ (Silverman et al., 2015b). This selection corresponds to a selection in $M_\star$ (Ilbert et al., 2010; Rodighiero et al., 2014) and allows to sample the MS down to a limit of $M_\star \sim 10^9 M_\odot$ (see Sect. 3.3 for more details). The sources were selected having $1.43 \leq z_{\text{phot}} \leq 1.69$ to ensure that the expected position of the emission lines falls in the wavelength range sampled by the *H* and *J-long* gratings. The photometric redshifts were estimated using the *hyperzspec* code (Bolzonella et al., 2000) taking advantage of the excellent photometric coverage of the COSMOS field (Ilbert et al., 2009). To maximise the emission lines detection rate, an additional cut on the expected $H\alpha$ flux was applied and only galaxies with $F_{\text{pred}}(H\alpha) \geq 6.8 \times 10^{-17} \text{ ergs}^{-1} \text{ cm}^{-2}$ were observed (Silverman et al., 2015b). This predicted $H\alpha$ flux was computed from the SFR of each galaxy, derived by fitting the optical to near-IR photometry (up to the IRAC 3.4 μm band, Ilbert et al., 2009) with the *hyperzmass* code (Bolzonella et al., 2000). To convert the SFR into an observed $H\alpha$ flux, a dust attenuation factor was applied with this attenuation being estimated from the $(B_J - z)$ color (Daddi et al., 2004). A scaling factor $f \sim 0.7$ was also applied in this conversion, to account for differential attenuation effects between continuum and line emission (see Puglisi et al., 2016, and discussion in previous chapters). As a result of this cut, FMOS observations sample the upper envelope of the $z \sim 1.6$ MS (see Fig. 2 in Silverman et al. 2015b and Fig. 1 in Kashino et al. 2017a).

In addition to the main MS sample, some fibers were assigned to additional samples as far-IR detected galaxies, X-ray detected AGN and low-mass galaxies. The *Herschel* far-IR sample will be discussed in the following of this chapter while for the description of the other samples we refer the reader to Silverman et al. (2015a).

Data reduction ²

All the data were processed using the IRAF-based FIBER package (Iwamuro et al., 2011). This routine uses the dome-flat images to compute a function that corrects the frames for spatial and spectral distortions. The distortion-corrected Th-Ar lamp images are then used to determine the pixel-to-wavelength function. Since the observations are performed in CBS mode, the thermal background is removed by subtracting the $A - B$ image, where A and B are the two positions of the field center (separated by $60''$). The frames are subtracted with an optimized weight to minimize residual sky errors. Corrections are applied to account for the detector cross talk and the bias difference between quadrants. Pixel-to-pixel variations across the two FMOS detectors (IRS1 and IRS2) are minimized using the flat field image of a uniform light source taken at the beginning of each observing night. After rejecting bad pixels, the science frame is corrected for distortions by using the function estimated from the dome-flat exposure. The residual OH airglow emission lines are then subtracted. The individual science frames are combined into a single averaged image with an additional subtraction of the residual background and bad pixels correction. Due to the CBS observing mode, each target is observed in two fibers and the corresponding spectra in position A and B are combined. During this process, the relative throughput between fibers is measured using the dome-flat image taken with the fibers in the same position as arranged for the science exposure.

²I took part in the data-reduction process of the FMOS-COSMOS survey data described in this section. In particular, I reduced the *J-long* data of the last observing runs (April 2016) and the *H-long* data for additional pointings in the GOODS-Southern field.

3.3. DATA SET AND SAMPLE SELECTION

Finally, broad atmospheric absorption features are corrected by using a flux calibration star of known spectral type. The image is then wavelength calibrated using the wavelength solution computed on the Th-Ar lamp image. The typical uncertainty of the wavelength calibration is less than 1 pixel, corresponding to 1.2 Å in high-resolution mode.

Measurements of spectroscopic redshifts ³

Spectroscopic redshifts are measured from the H α and [NII] emission lines by a visual inspection of the 1D and 2D spectra, taking advantage of the graphical interface *SPECPRO* (Masters & Capak, 2014). This tool has been updated for the FMOS spectra to overlay the OH emission on the spectrum: this is essential to determine the likelihood of line identification. In addition, *SPECPRO* displays the full broad-band photometry of the object together with a best-fit spectral template: the presence of key features as the 4000 Å break allows to improve the confidence in the redshift determination from the solely FMOS spectrum. To improve the accuracy of the final measurement, the z_{spec} is then computed from the line-fitting routine (see Sect. 3.4.1 for details) using as a “first guess” the by-eye determination.

The average success rate of the redshift measurements is $\sim 40\%$, with almost no variations among different FMOS-COSMOS subsamples (e.g. MS galaxies versus far-IR sources). A quality flag was assigned to these redshifts, according to the SN of the emission-line detections (see Sect. 9.1 in Silverman et al. 2015b).

Kashino et al. (2013, 2017a) and Silverman et al. (2015b) contain further details about the spectroscopic observations and the data analysis.

3.3 Data set and sample selection

SB galaxies are identified for lying above the MS, hence a careful definition of the MS at the redshift of interest is required. We defined the MS equation ($\log(\text{SFR}/[M_{\odot}/\text{yr}]) = 0.906 \times \log(M_{\star}/[M_{\odot}]) - 7.798$, blue solid line in Fig. 3.1) from a sample of ~ 3000 star-forming BzK galaxies (Daddi et al., 2004) at $1.4 \leq z_{\text{phot}} \leq 1.7$ in the COSMOS field, for which we computed $M_{\star}$ and SFR by fitting their Spectral Energy Distribution (SED), using broad-band photometry from the Laigle et al. (2016) catalog and the *hyperzmass* code (Bolzonella et al., 2000) with Bruzual & Charlot (2003) stellar populations synthesis models and constant SFH. More details about the $M_{\star}$ and SFR computation for these star-forming BzK galaxies will be provided in Appendix 3.8.

Our SBs are drawn from a *Herschel* sample (see Rodighiero et al. 2011 for details about the PACS photometry) at $1.4 \leq z_{\text{phot}} \leq 1.7$ having near-IR spectroscopy from the FMOS-COSMOS survey. FMOS observations with the *H*-long and *J*-long gratings allows us to detect H α , [NII]_{6549,6583} and H β , [OIII]_{4959,5007} emission lines, respectively. We refer the reader to Section 3.4.1 for the description of emission line fitting and flux measurements, while the stacking technique adopted to construct the average spectra shown in Fig. 3.2 is explained in Section 3.4.2.

SB sources analyzed in this work are selected as outliers from the MS defined above, with $\text{SFR} \geq 4 \times \text{SFR}_{\text{MS}}$ (see Fig. 3.1), following Rodighiero et al. (2011). Our selection may overlap with samples of Sub-mm selected Galaxies (SMGs). However, SMGs galaxies represent a mixed population (Rodighiero et al., 2011; Roseboom et al., 2013; Miettinen et al., 2017) that include both massive MS galaxies as well as objects qualified as of SBs according to our criterion. Instead, our criterion selects a pure sample of SB galaxies by construction.

For each *Herschel*-FMOS source, we compute $M_{\star}$ using homogeneous photometry and methodology as applied for MS galaxies, while fixing the redshift to the FMOS z_{spec} . SFRs are measured from the bolometric IR luminosity (L_{FIR}), using the calibration of Kennicutt (1998b), rescaled to a Chabrier IMF by dividing by a factor of 1.7.

³I personally contributed to the measurements of spectroscopic redshifts and quality assessment (i.e. flag assignment) for a thousand number of targets during 2016.

The L_{FIR} are computed by integrating the far-IR SED over the range $\lambda \in [8 - 1000]\mu\text{m}$, with the SEDs being derived by fitting the Magdis et al. (2012) templates to the *Herschel* photometry (PACS 100 and 160 μm , SPIRE 250, 350 and 500 μm).

AGN candidates among the SBs are identified and discarded using the BPT diagram and the Kewley et al. (2013) dividing line at $z \sim 1.6$ (when $\text{H}\alpha$, $\text{H}\beta$, $[\text{OIII}]_{5007}$ and $[\text{NII}]_{6583}$ are detected), the $[\text{NII}]_{6583}/\text{H}\alpha$ ratio (if only $[\text{NII}]_{6583}$ and $\text{H}\alpha$ are available), X-ray detections and inspection of the mid-IR SED (Marcella Brusa, private communication). With these criteria we identify 8 AGN, resulting in an AGN fraction among the off-MS sample of $\sim 40\%$, substantially higher than the $\sim 8\%$ identified on the MS by Kashino et al. (2017a). The average spectrum of these AGN candidates differs from the one of the “purely SF” population, showing broader $\text{H}\alpha$ and $[\text{NII}]_{6549,6583}$ emissions and an additional broad component on the $\text{H}\alpha$ emission. The properties of these AGN will be further discussed in Chapter 4.

The sample analyzed here includes 12 $\text{H}\alpha$ -detected SBs (red filled circles in Figure 3.1, upper panel of Fig. 3.2). Table 3.1 summarizes the main physical properties of these sources. Among them, 8 objects have a *J*-long follow-up (blue circles in Fig. 3.1, lower panel of Fig. 3.2). Seven of these objects have molecular gas measurements through ALMA CO 2-1 observations, indicating an average gas fraction $f_{\text{gas}} \sim 50\%$, which implies very high SFE and short depletion timescale (Silverman et al., 2015a, ~ 40 Myrs).

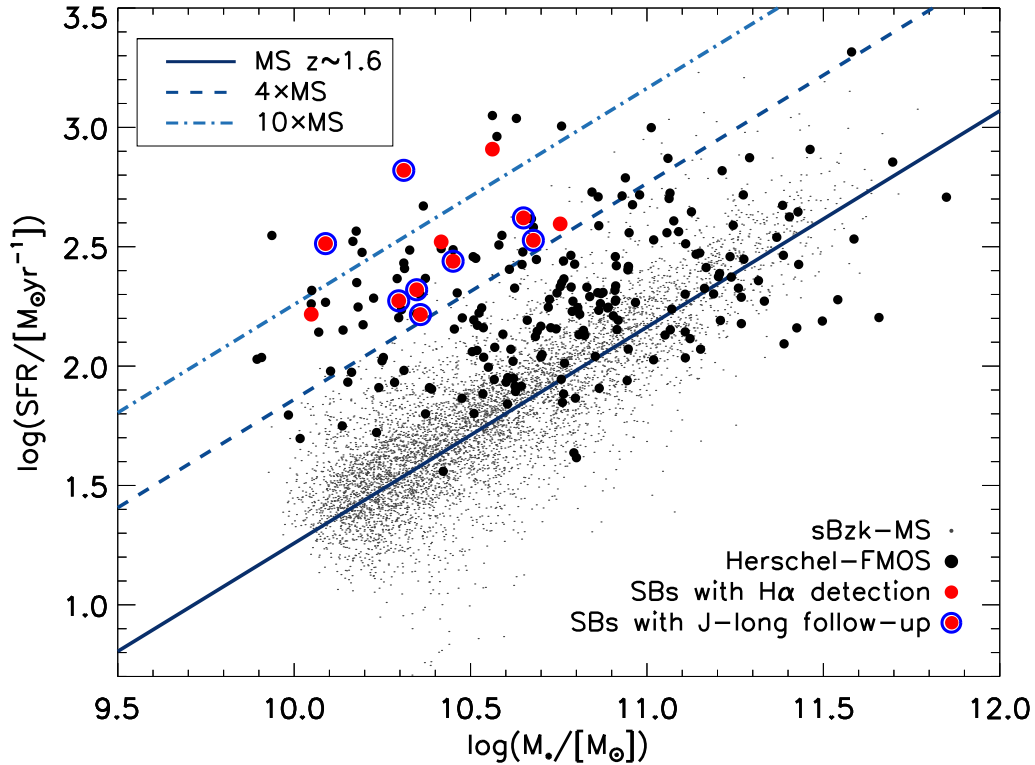


Figure 3.1: SFR as a function of M_* for the *Herschel*-FMOS sources. Small grey dots are the sBzk sources used to define the MS. Red filled circles indicate the *Herschel* SBs with $\text{H}\alpha$ detection. Those with a *J*-long follow-up are highlighted with blue circles.

3.4. SPECTRAL ANALYSIS

Table 3.1: Physical properties of the $z \sim 1.6$ SB sample. The 1σ error on M_* is 0.1 dex . Emission line fluxes are aperture corrected, as described in Silverman et al. (2015b). Absolute line flux values are also affected by the error on the aperture correction (0.17 dex , Silverman et al., 2015b)

PACS-ID	RA hours	Dec Deg	z_{spec}	$\log(M_*)$ $M_\odot$	$\text{SFR}_{\text{FIR}} \pm 1\sigma$ $M_\odot/\text{yr}$	$F(\text{H}\alpha) \pm 1\sigma$ $[10^{-16} \text{erg/s/cm}^2]$	$F([\text{NII}]_{6583}) \pm 1\sigma$ $[10^{-16} \text{erg/s/cm}^2]$
300	09:58:24.32	2:15:15.10	1.6706	10.4	332 ± 8	1.88 ± 0.04	0.38 ± 0.03
299	09:59:41.31	2:14:42.80	1.6467	10.1	326 ± 14	1.24 ± 0.32	0.43 ± 0.26
455	09:59:43.88	2:38:08.20	1.6696	10.4	275 ± 11	1.45 ± 0.12	0.39 ± 0.06
491	10:00:05.19	2:42:04.70	1.6366	10.4	209 ± 21	1.15 ± 0.08	0.35 ± 0.06
830	10:00:08.73	2:19:02.50	1.4610	10.7	336 ± 34	1.53 ± 0.09	0.41 ± 0.05
472	10:00:08.95	2:40:10.50	1.5988	10.3	661 ± 66	0.78 ± 0.04	0.24 ± 0.04
135	10:00:15.72	1:49:48.00	1.6508	10.3	188 ± 6	0.46 ± 0.19	0.15 ± 0.16
175	10:00:34.62	1:55:25.40	1.6664	10.4	164 ± 9	1.32 ± 0.07	0.30 ± 0.03
682	10:01:23.96	1:52:28.60	1.4681	10.6	418 ± 8	1.21 ± 0.19	0.58 ± 0.15
197	10:01:34.46	1:58:47.70	1.6005	10.7	394 ± 11	0.82 ± 0.07	0.32 ± 0.08
787	10:02:27.95	2:10:04.70	1.5234	10.6	811 ± 81	1.42 ± 0.05	0.75 ± 0.03
251	10:02:39.64	2:08:47.10	1.5847	10.0	165 ± 16	2.71 ± 0.07	0.59 ± 0.04

3.4 Spectral analysis

3.4.1 Emission line fitting on individual spectra

The emission line fluxes and the associated errors are measured on each individual spectrum by applying an ML procedure that takes advantage of the MPFITFUN routine (Markwardt, 2009).

This procedure fits a set of Gaussian functions to the continuum-subtracted spectrum, using a weighting scheme that takes into account the noise spectrum produced by the data-reduction pipeline. The routine uses this noise spectrum also to mitigate the impact of residual OH features not masked by the OH suppressor by excluding from the fit the pixels impacted by the OH airglow (see caption of Figure 3.3 for more details). All the spectra are further inspected by eye in comparison with the Rousselot et al. (2000) sky spectrum, to ensure that the fitted emission lines are not contaminated by residual OH airglow features.

When non-zero, the continuum level is determined by fitting a linear function in two wavelength ranges free of emission lines. For the *H-long* spectra, five Gaussian functions are fitted simultaneously to the $[\text{NII}]_{6549}$, $\text{H}\alpha$, $[\text{NII}]_{6585}$ ⁴ emission lines by fixing the centroids to the position expected from the spectroscopic redshift. To improve the quality of the fit, the width of the $[\text{NII}]$ and $[\text{SII}]$ lines are fixed to be equal to the measured $\text{H}\alpha$ width while the ratio $F([\text{NII}]_{6585}/[\text{NII}]_{6549})$ is fixed to the theoretical value of 2.96. The formal errors to the emission line fluxes are derived from the MPFITFUN output.

A similar procedure is applied to fit the $\text{H}\beta$ and $[\text{OIII}]_{4959,5007}$ features on the *J-long* spectra. In this case, the width of the $\text{H}\beta$ emission is tied to the $\text{H}\alpha$ width, assuming that both features are emitted by the same gas component. The width of the $[\text{OIII}]_{5007}$ is kept as a free parameter. The width of the $[\text{OIII}]_{4959}$ line is fixed to the value measured on the $[\text{OIII}]_{5007}$ and the flux ratio of these two lines is fixed to the theoretical value of 2.89.

To account for the flux loss outside the $1.2''$ diameter fiber and estimate *total* emission line fluxes, aperture corrections were estimated from HST photometry as detailed in Sect. 7.2 of Silverman et al. (2015b) and in Sect. 3.1 of Kashino et al. (2013). In this procedure The HST F814W image, sampling the rest-UV emission of the galaxy, is smoothed with point spread functions with sizes ranging from 0.8 to $1.2''$ to simulate the effective seeing.

⁴and $[\text{SII}]_{6717}$ and $[\text{SII}]_{6732}$ in the integrated spectrum

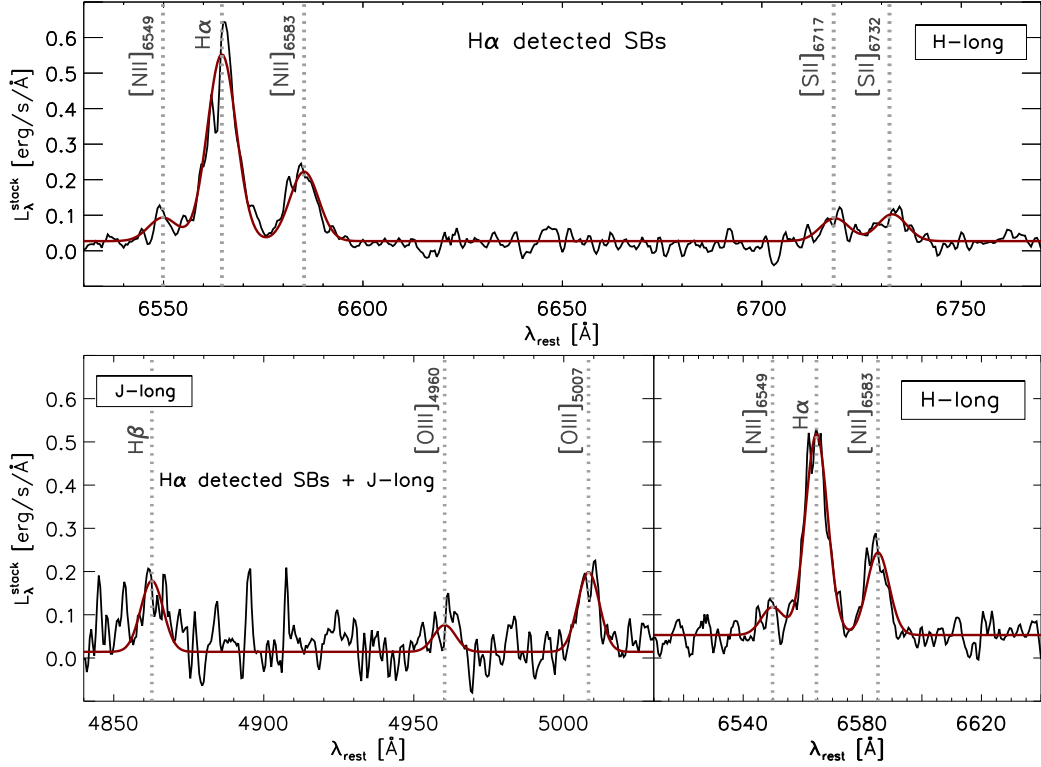


Figure 3.2: *Upper panel:* average *H-long* spectrum of the 12 $H\alpha$ -detected SB sources. *Lower panel:* average *J-long* (left) and *H-long* (right) spectra for the 8 $H\alpha$ -detected SBs with *J-long* follow-up. The red curve is the emission lines + continuum fit.

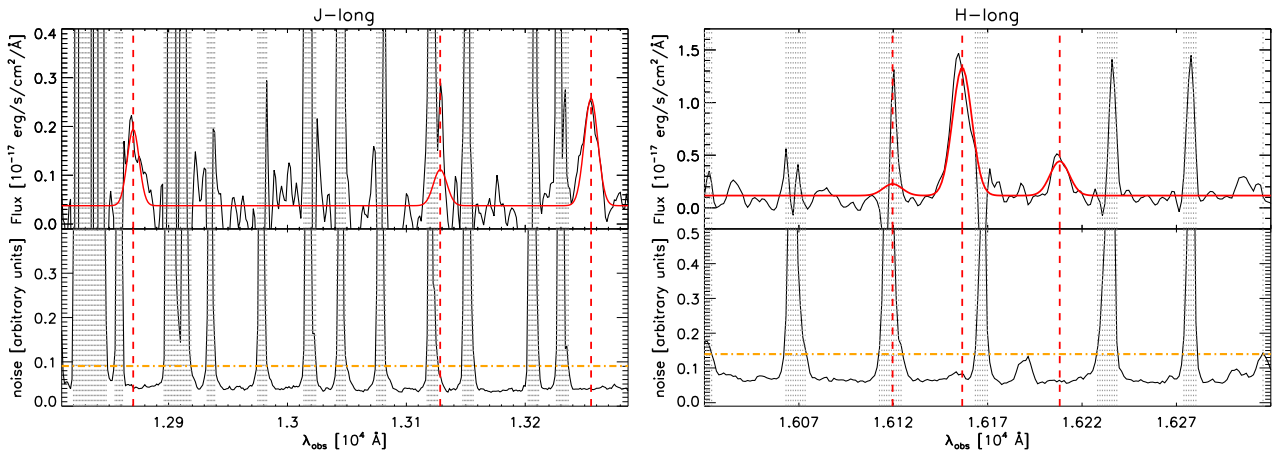


Figure 3.3: Individual *J-long* (left) and *H-long* (right) spectrum with emission line fits (red curve) for one of the sources in our starburst sample. The upper panel shows the FMOS spectra, while the bottom panel displays the noise in output from the data-reduction pipeline. In all the panels, the position of the emission lines is highlighted with red dashed lines. The dotted vertical regions highlight the position of flagged pixels, i.e. pixels heavily affected by residual sky emission. Bad pixels are identified as pixels with a noise larger than 2σ the average noise spectrum: the threshold is highlighted with a horizontal dashed line in orange.

3.4. SPECTRAL ANALYSIS

This effective seeing used to smooth the HST/ACS images of each galaxy observed within the corresponding FMOS configuration is determined as the scaling factor required to match ground-based magnitudes from UltraVISTA (either J or H) to that derived from the FMOS spectra of bright targets (i.e. galaxies for which the continuum is detected with FMOS at a SN greater than 5 and $mag_{H,UVISTA} \leq 23$). Then, aperture photometry is performed with *SExtractor* (Bertin & Arnouts, 1996) on the smoothed HST image both within the FMOS fiber and including the whole object. The aperture correction is finally derived as the ratio between the aperture-to-total flux. The resulting aperture correction factors have a typical value of ~ 2 (Kashino et al., 2013). This procedure assumes that $H\alpha$ and UV emission follow the same spatial distribution, an assumption justified by the tight correlation observed in IFU observations (Mancini et al. 2011, see also Kashino et al. 2013).

3.4.2 Stacking analysis

To improve the SN, minimize the residual OH contamination and derive trends for the average population, we apply a stacking technique to construct an average spectrum of our SB sample. We stack the FMOS H -long spectra in a wavelength range $6500 \leq \lambda_{\text{rest}} \leq 6800 \text{ \AA}$, to cover the spectral range of the $[\text{NII}]_{6549}$, $H\alpha$, $[\text{NII}]_{6585}$, $[\text{SII}]_{6717}$ and $[\text{SII}]_{6732}$ emission lines. To stack the J -long spectra we use instead the range $4850 \leq \lambda_{\text{rest}} \leq 5050$ covering the $H\beta$, $[\text{OIII}]_{4959}$ and $[\text{OIII}]_{5007}$ lines. We average the de-redshifted spectra using a 5σ clipping technique, with these spectra being resampled to a common resolution of $0.5 \text{ \AA/px}$ (i.e. the mean rest-frame resolution of FMOS). We tested however that changing the co-adding method (for example considering the median rather than the average) does not affect our final conclusions. We account for the flux falling outside the slit by multiplying each spectrum by the aperture corrections, derived from the H and J band photometry, as described in the previous section. We include in the average only pixels not affected by atmospheric emission, masking regions with a high noise level (see caption of Fig. 3.3). The noise on the average spectrum is derived by adding in quadrature the noise of the individual spectra at each pixel, normalized to the number of spectra per pixel. As a result of the masking, not all the pixels in the stacked spectrum are uniformly covered by all the spectra. To account for this effect, we multiply the noise of the stacked spectrum at each pixel by the number of spectra at each pixel, normalized by the total number of spectra.

This procedure is fully consistent with those adopted in Kashino et al. (2013), Zahid et al. (2014) and Kashino et al. (2017a) for deriving average spectra. However, as a sanity check, we re-apply this procedure to the Kashino et al. (2013) sample fully reproducing the Kashino et al. (2017a) results. This test confirms that the various stacking methods are fully consistent.

Fig. 3.2 shows the average spectrum of our $H\alpha$ -detected SBs (*upper panel* in Fig. 3.2) and for the subsample with J-long follow-up (*lower panel* in Fig. 3.2). Emission line fitting on stacked spectra are performed as described in Sect. 3.4.1 for individual spectra.

Testing the robustness of the stacking procedure

The size of the SB sample is small and the final average spectrum could be potentially affected by poor statistics effects. For example, it can be strongly dominated by a single bright object. To test the dependence of the average spectrum on the sample size, we apply a resampling technique to the sample presented in Kashino et al. (2013), which consists in 168 MS galaxies. We draw randomly a subsample of MS sources with the same size of the starburst sample (i.e. 8 sources) and we apply to this subset our stacking and emission line fitting tools. We repeat the procedure 1000 times to construct a distribution of the emission line ($H\alpha$, $H\beta$, $[\text{OIII}]_{5007}$, $[\text{NII}]_{6585}$) luminosities measured on the stacked spectrum. The shape of this distribution is shown in Fig. 3.4: its mean value results in good agreement with the flux measured from the average spectrum of the complete sample. The main effect of reducing the sample size is a decrease in the SN of the average spectrum. We therefore conclude that our results are not driven by a single bright object but likely reflect the average population.

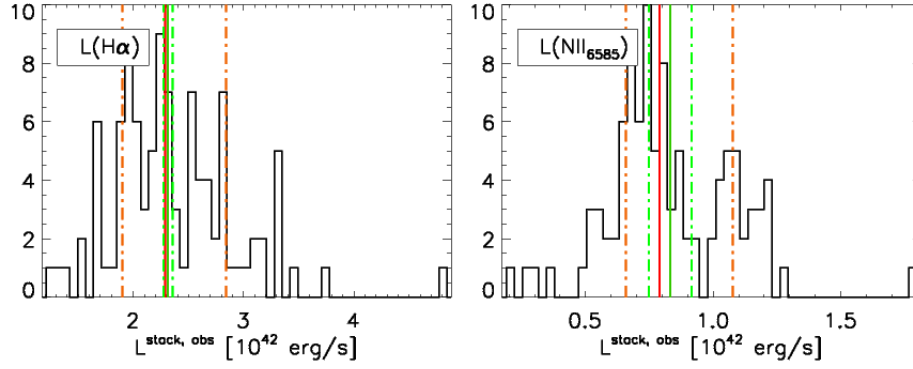


Figure 3.4: Distribution of emission line fluxes from the average spectra resulting from the resampling technique described in the main text. The red lines highlight the median value and the confidence intervals of the distribution (continuous and dashed, respectively). The green lines indicate the line flux and error measured from the average spectrum of the full sample, i.e. 168 sources.

As an additional check for the accuracy of our procedure and for testing the how the emission line fluxes from the stacked spectrum are representative of the overall population, we compare the distribution of individual line fluxes with the values from the average spectrum. This test is shown in Figure 3.5 for the MS sample of Kashino et al. (2013). The average fluxes of the distributions are fully consistent with the fluxes derived from the stack. Stacked spectra seems to give a very good estimate of the average trend for the analyzed population. We do not show in this comparison the measurements from the [SII] doublet as it is undetected in all the individual spectra.

3.5 Results

The key physical quantities examined in the following are measured from different portions of the rest-frame spectrum: $M_\star$ is primarily sampled by the near-IR photometry, the SFR by the far-IR luminosity, while the gas-phase metallicity and the electron density from the optical spectrum. Given the complex morphology and the high extinction of SB galaxies, each indicator may not trace the same component in each system and we carefully assess which possible galaxy component the various measurements likely refer to.

3.5.1 Dust attenuation above the MS

We use two methods for estimating the nebular attenuation $A_{H\alpha}$ in our sample: the $H\alpha/H\beta$ emission line ratio (the Balmer Decrement, BD), assuming Case B recombination, a gas temperature $T = 10^4\text{K}$ and assuming a Calzetti et al. (2000) dust attenuation curve:

$$A_{H\alpha, \text{BD}} = \frac{2.5}{k_{H\beta} - k_{H\alpha}} \log \left[\frac{H\alpha/H\beta}{2.86} \right] \times k_{H\alpha} \quad (3.1)$$

and the $\text{SFR}_{\text{FIR}}/\text{SFR}_{H\alpha, \text{obs}}$ ratio (the *IRX* ratio):

$$A_{H\alpha, \text{IRX}} = 2.5 \log \left(1 + \frac{\text{SFR}_{\text{FIR}}}{\text{SFR}_{H\alpha, \text{obs}}} \right). \quad (3.2)$$

From our average spectrum we obtain $A_{H\alpha, \text{BD}} \simeq 0.89 \pm 0.69$ mag, while the IRX method gives $A_{H\alpha, \text{IRX}} \sim 3.3 \pm 0.51$ mag, much larger than the former and than the typical MS value, as seen in Fig. 3.6. This means that the optical light (from which $A_{H\alpha, \text{BD}}$ is measured) comes from relatively unobscured lines of sight, whereas the bulk of the SF is almost completely obscured at optical wavelengths.

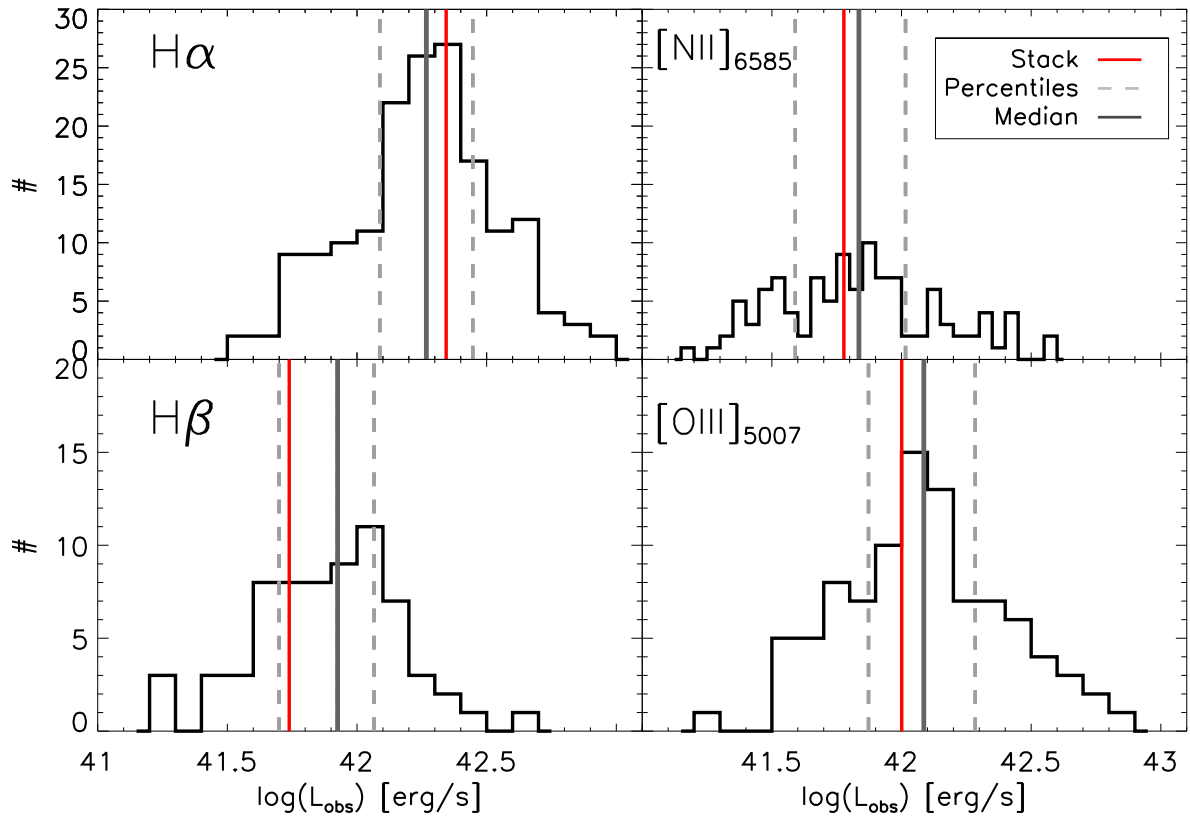


Figure 3.5: Individual emission lines distributions and median emission line fluxes (grey vertical line) for the sample of Kashino et al. (2013), compared with the average flux derived from the average spectrum (red vertical line). Dashed grey vertical lines highlight the 50th percentile of each distribution.

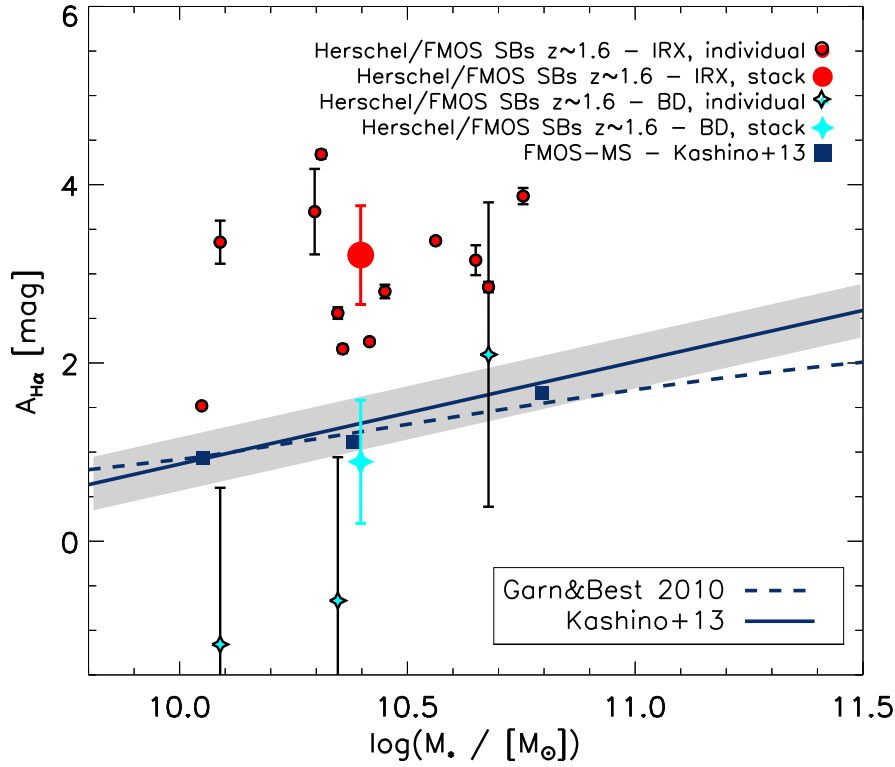


Figure 3.6: $H\alpha$ attenuation as a function of M_* for $z \sim 1.6$ SBs, derived from the BD and the IRX. Our measurements are compared with the MS-trend at $z \sim 1.6$ and in the local Universe (solid and dashed lines respectively).

This is commonly observed in local ULIRGs where the starburst usually takes place in a region not coincident with optical bright regions or dark dust lanes observed in the optical (e.g., Poggianti et al., 2001) and does not contribute to the optical emission, while it dominates the bolometric energy output of the system with the FIR emission.

Quantifying how much the heavily obscured and optically bright components contribute to our spatially unresolved measurements (both the optical spectrum and the FIR emission is key for interpreting our results. To asses the amount of nebular emission arising from the obscured core, we model our average galaxy with two components: an optically thin part (with intrinsic nebular emission $L_{H\alpha,thin}$ and attenuation $A_{H\alpha,thin}$) and an optically thick region (characterized by $L_{H\alpha,thick}$ and $A_{H\alpha,thick}$) corresponding to the starburst core. The integrated line emission $L_{H\alpha,tot}$ measured from the FMOS fiber is:

$$L_{H\alpha,tot} = L_{H\alpha,thin} \times 10^{-0.4A_{H\alpha,thin}} + L_{H\alpha,thick} \times 10^{-0.4A_{H\alpha,thick}} \quad (3.3)$$

The total SFR of the system is given by the sum of SFR_{FIR} , obtained from the average L_{FIR} of our sample, and $SFR_{H\alpha,stack}$, measured from the stacked spectrum and uncorrected for dust attenuation, thus:

$$SFR_{tot} = SFR_{FIR} + SFR_{H\alpha,stack} = (322 + 16.2) = 338.2 M_{\odot}yr^{-1}. \quad (3.4)$$

Both the thick and thin component will contribute to SFR_{tot} and to our integrated measurements, with their relative contribution depending on their attenuation. We cannot constrain the value of $A_{H\alpha,thin}$ and $A_{H\alpha,thick}$ with our data, but we can solve the problem in two extreme cases, bracketing a range of possible configurations. For the first limiting case (lower panel of Fig. 3.7), we assume that the core is fully obscured. In this case, the core will not contribute to the optical emission:

$$\begin{cases} A_{H\alpha,thick} = \infty \rightarrow L_{H\alpha,thick} \sim 0 \\ L_{H\alpha,tot} = L_{H\alpha,thin} \times 10^{-0.4A_{H\alpha,thin}}. \end{cases} \quad (3.5)$$

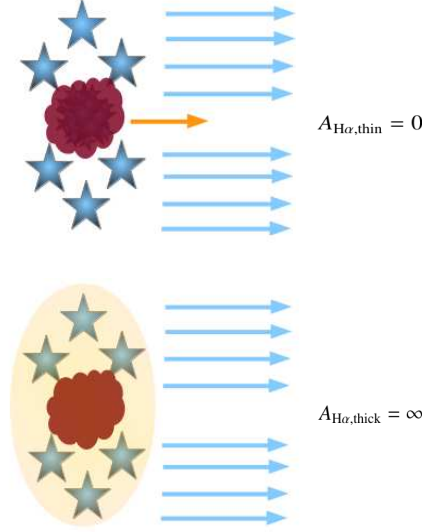


Figure 3.7: Cartoon sketching our two-component dust model in the two limiting solution discussed in the main text. *Left panel:* In this case the extended component is dust-free and the starburst has $A_{\text{H}\alpha,\text{thick}} \geq 4.5 \text{ mag}$. *Right panel:* the starbursting core is fully obscured ($A_{\text{H}\alpha,\text{thick}} \sim \infty$) and the diffuse component has $A_{\text{H}\alpha,\text{thin}} \sim 0.9 \text{ mag}$. In both cases, the optical emission is dominated by the less obscured regions while the starbursting core is bright in the far-IR.

Therefore, the BD gives the extinction of the thin component only

$$A_{\text{H}\alpha,\text{tot}} \equiv A_{\text{H}\alpha,\text{thin}} \equiv A_{\text{H}\alpha,\text{meas}} = 0.89 \text{ mag} \quad (3.6)$$

and this thin component has a dust-corrected $SFR_{\text{H}\alpha,\text{thin}} = 36.8 M_{\odot} \text{yr}^{-1}$ which will partially contribute to the FIR emission. As such, the contribution of the thick component to SFR_{FIR} will be:

$$SFR_{\text{FIR},\text{thick}} = SFR_{\text{FIR}} - SFR_{\text{FIR},\text{thin}} = 301.4 M_{\odot} \text{yr}^{-1} \quad (3.7)$$

or $\sim 89 \%$ of SFR_{tot} . The other extreme situation is the one in which the thin component is dust free (upper panel in Fig. 3.7) thus it will not contribute to the FIR emission, which samples the thick core only:

$$\begin{cases} A_{\text{H}\alpha,\text{thin}} = 0 \\ L_{\text{H}\alpha,\text{tot}} = L_{\text{H}\alpha,\text{thin}} + L_{\text{H}\alpha,\text{thick}} \times 10^{-0.4 A_{\text{H}\alpha,\text{thick}}} \\ SFR_{\text{FIR}} \equiv SFR_{\text{FIR},\text{thick}}. \end{cases} \quad (3.8)$$

In this case the intrinsic $\text{H}\alpha$ emission from the thick core can be inferred from SFR_{FIR} while its attenuation $A_{\text{H}\alpha,\text{thick}}$ can be derived as the minimum attenuation required on $L_{\text{H}\alpha,\text{thick}}$ to obtain an attenuation-free thin component. With this computation, we estimate a lower limit for the attenuation of the thick core $A_{\text{H}\alpha,\text{thick}} = 4.5 \text{ mag}$, which would imply that the $\text{H}\alpha$ emission from the core is attenuated by a factor of at least ~ 70 , being still optically thick. In this limiting situation the thick component has its maximum possible contribution to the optical emission lines of $\sim 33\%$, while contributing $\sim 94\%$ of the SFR_{tot} .

The two-component model discussed above and sketched in Fig. 3.7 offers an idealized representation of our objects. Nevertheless, high resolution data strongly support this model. We report in Figure 3.8 the rest-frame UV image of one of our sources, PACS-787, for which we have recently obtained high resolution ALMA imaging of the CO $J = 5-4$ emission tracing the obscured star-formation (indicated with contours in the plot). From this figure it is clear that the star-formation of PACS-787 mainly arises by a fully obscured region barely detected at UV/optical wavelengths.

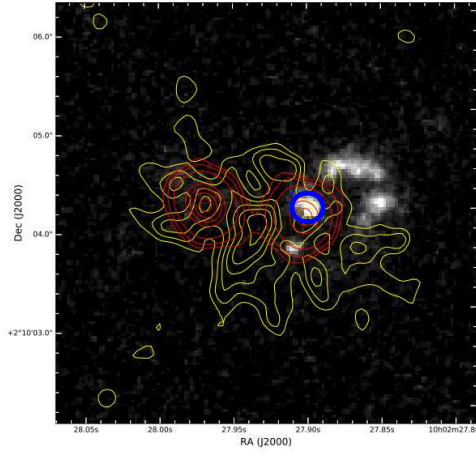


Figure 3.8: HST/ACS F814W image of source PACS-787 with CO J = 5-4 overlaying contours (at 3, 5, 10, 20, 30, 40, $50\sigma_{\text{rms}}$, in red). The beam size of $0.33'' \times 0.3''$ is indicated in the lower left. The majority of the CO and mm emission are essentially unresolved with two well-separated components, illustrative of very compact starbursts. The HST/ACS image has diffuse emission possibly indicating tidal features from the interaction. In yellow we show the ALMA map of the emission with the two individual source removed. Extended low surface brightness emission is seen that extends between the positions of the two nuclei as indicative of an interaction. The blue circle indicates the position of the FMOS fiber (diameter $1.2''$). Courtesy of John Silverman.

3.5.2 Gas-phase metallicity above the MS: MZR and FMR

Having in mind the caveat that the emission-line ratios may not be representative of the optically thick core, we measure the metallicity (O/H) from the $[\text{NII}]_{6583}/\text{H}\alpha$ ratio, adopting the Maiolino et al. (2008) calibration for both the SB and MS samples. In the left panel of Figure 3.9 we show the MZR for our SBs, compared with the trend from Kashino et al. (2017a) and Zahid et al. (2014). Most of our individual estimates are consistent with the MS trend, although with some scatter. We note in particular two high-metallicity outliers, possibly late-stage mergers enriched by the SB itself, or sources with a low-level AGN emission, as their position in the BPT diagram is relatively close to the dividing line. However, the estimate from the stacked spectrum indicates that (on average) the metallicity of SBs is consistent with that of MS galaxies.

We explore the correlation between O/H, $M_\star$ and SFR in the right panel of Fig. 3.9: SBs appear as outliers in this plot, showing a metal content significantly higher than expected from the FMR, which comes directly from them having near-MS metallicities but much higher SFR.

We note that the $[\text{NII}]_{6583}/\text{H}\alpha$ ratio can be contaminated by shocks and this contribution may be important in SB galaxies (see, e.g., Westmoquette et al., 2009b). Still, the location of our sample in the $[\text{SII}]$ -BPT diagram (constructed from their average spectrum, shown in Fig. 3.2) confirms that their line ratios are dominated by SF. Moreover, our conclusion regarding the average metallicity based on the calibration of Dopita et al. (2016) (independent of the ISM pressure and ionization parameter) remain unaltered.

A toy model for the metallicity evolution in the starburst

We present in this subsection a simple computation to derive the enrichment time-scale of a typical galaxy at $z \sim 1.6$ experiencing a burst of star-formation. This enrichment time-scale t_{enrich} can be derived from the Oxygen production rate $\dot{M}_{\text{oxy}}$, assuming that it is entirely produced by star-formation:

$$\dot{M}_{\text{oxy}} = \text{yield} \times \text{SFR} \sim \frac{\Delta M_{\text{oxy}}}{\Delta t_{\text{enrich}}} \quad (3.9)$$

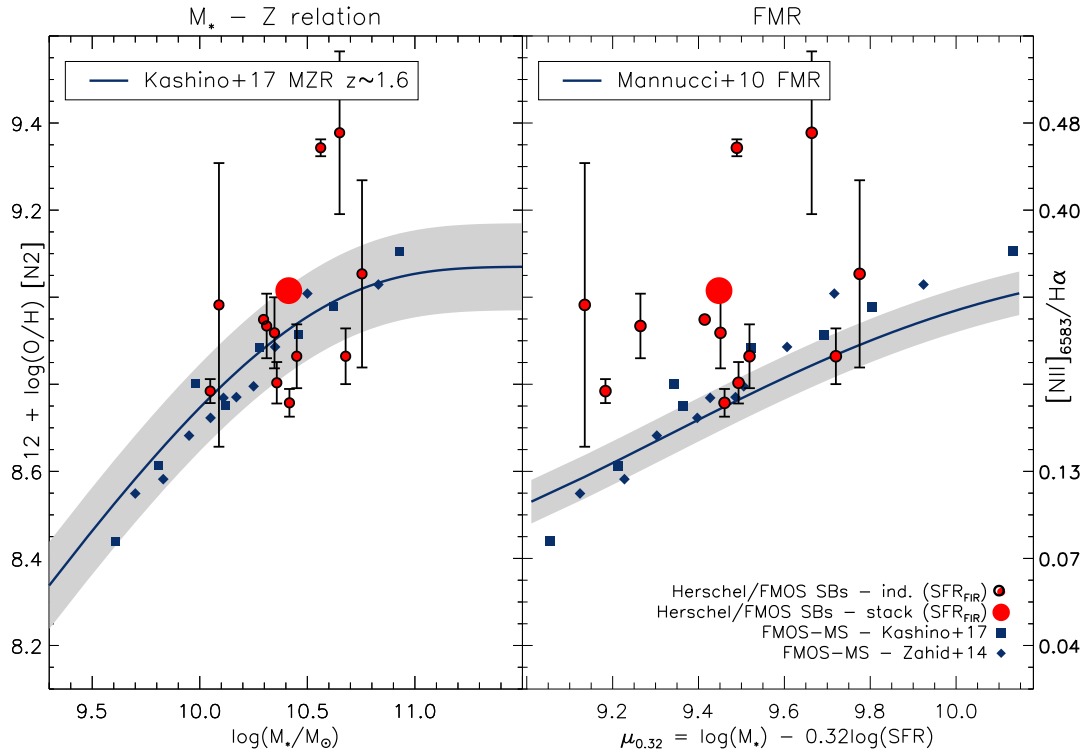


Figure 3.9: *Left:* Metallicity as a function of M_* for the SB sample based on individual and stacked spectra, compared with the MZR and data points at $z \sim 1.6$ from the FMOS-MS sample of Kashino et al. (2017a) and Zahid et al. (2014). The shaded area marks a range of ~ 0.1 dex, roughly the scatter of this relation. *Right:* FMR for SB galaxies compared with the Mannucci et al. (2010) equation and its scatter of ~ 0.05 dex. The color code is as in the left panel. The right axis indicates the $[\text{NII}]_{6583}/\text{H}\alpha$ ratio.

where the *yield* express the fraction of heavy elements returning to the ISM from a stellar population. We assume $yield \sim 2.5 \times 10^{-3}$ (Greggio & Renzini, 2011). Using Equation 3.9, knowing the variation of Oxygen mass $\Delta M_{\text{oxy}} \sim M_{\text{oxi,f}} - M_{\text{oxi,i}}$ we can derive t_{enrich} . The oxygen mass can be derived from the oxygen abundance:

$$M_{\text{oxi}} = M_{\text{gas}} \times X \times A_{\text{oxi}} \times 10^{12+\log(O/H)-12} \quad (3.10)$$

where X is the hydrogen abundance and A_{oxi} is the oxygen molecular weight. Eqn. 3.10 assumes that the main heavy element in our gas is Oxygen, which might be a fair assumption given that is the most abundant element in the ISM (e.g. Tremonti et al., 2004). Now, assuming that M_{gas} does not change dramatically during the burst, we can write

$$\Delta M_{\text{oxy}} \sim M_{\text{gas}} \times X \times A_{\text{oxi}} \times [(O/H)^f - (O/H)^i] \quad (3.11)$$

And finally:

$$t_{\text{enrich}} = \frac{M_{\text{gas}} \times 0.75 \times 16 \times [(O/H)^f - (O/H)^i]}{yield \times SFR} \quad (3.12)$$

Adopting the solar value $X \sim 0.7$ (Asplund et al., 2009).

Equation 3.12 allows to derive the metallicity evolution of the starbursting system. In Figure 3.10 we report the metallicity evolution of a typical starburst with $M_{\star} \sim 1.2 \times 10^{10} M_{\odot}$, $SFR \sim 120 M_{\odot} \text{yr}^{-1}$ and a corresponding $f_{\text{gas}} \sim 0.35$ (see Table 1 in Silverman et al., 2015a). The time required to enrich the ISM of $\Delta 12 + \log(O/H) \sim 0.15 \text{ dex}$ is **15 Myr**, consistent with the typical depletion time for starburst galaxies (Silverman et al., 2015a, , e.g.). However, our crude estimate of t_{enrich} does not consider that the burst consumes hydrogen while producing oxygen. If including the gas consumption, t_{enrich} will be faster as both processes concur to increase the metal budget of the system.

Assuming that the system continues forming stars at the initial rate, it would finish the available gas in $\sim 10 \text{ Myr}$ while assembling a stellar mass $M_{\text{starburst}} \sim 5 \times 10^9 M_{\odot}$ during the burst, which is about 50% of the present mass of the system. With this model we show that the starburst is capable of rapidly enrich the surrounding ISM because of the extreme ongoing star-formation. This enrichment is however not observed in our measurements likely because of the strong obscurations that hide the burst at optical wavelengths.

3.5.3 Constraining the ISM conditions of starbursts: preliminary results

We use the $[\text{SII}]_{6717,6732}$ lines to measure the electron density n_e for our SBs from their average spectrum. We convert the ratio $[\text{SII}]_{6717}/[\text{SII}]_{6732}$ to n_e using the *TEM DEN* package in *IRAF*, assuming an electron temperature $T_e = 10,000 \text{ K}$, which is typical for HII regions. As we show in Fig. 3.11, the average electron density derived for our 12 SBs is $n_e = 1,111_{-587}^{+1143} \text{ cm}^{-3}$ ($[\text{SII}]_{6717}/[\text{SII}]_{6732} = 0.851 \pm 0.167$), higher than the average $n_e \sim 220_{-128}^{+172} \text{ cm}^{-3}$ ($[\text{SII}]_{6717}/[\text{SII}]_{6732} = 1.213 \pm 0.11$) measured in the same way on the MS by Kashino et al. (2017a). This enhancement is significant only at 1.5σ thus further measurements are required to confirm this result.

The diagnostic recently proposed by Dopita et al. (2016) uses the $\text{H}\beta$, $[\text{OIII}]_{5007}$, $\text{H}\alpha$, $[\text{NII}]_{6585}$ and $[\text{SII}]_{6717,6731}$ emission lines to study the ISM conditions separating the dependence on the metallicity from the effects of ionization parameter and gas pressure. Kashino et al. (2017a) used this diagnostic to show that $z \sim 1.6$ MS galaxies have higher values of ionization parameter U and gas pressure $\log(P/k)$ with respect to local star-forming sources. In addition, the author show that low-mass ($M_{\star} \leq 10^{10} M_{\odot}$) MS galaxies at $z \sim 1.6$ have lower metallicity with respect to local galaxies with the same stellar mass, reflecting results from other metallicity diagnostics (see e.g. the MZR in their Fig. 14). The authors explore the effects of variations of the model parameters on the observed line ratios (see their Fig. 12 and corresponding discussion) concluding that the primary responsible for the emission line enhancement in galaxies with stellar masses below $10^{10} M_{\odot}$ is a higher ionization parameter. In high-mass galaxies ($M_{\star} \geq 10^{10} M_{\odot}$) additional effects as an increase in n_e and a harder ionization field may conspire in driving a line ratio enhancement.

Following Kashino et al. (2017a) we measure these line ratio for our sample, to infer the ISM conditions in our starbursts.

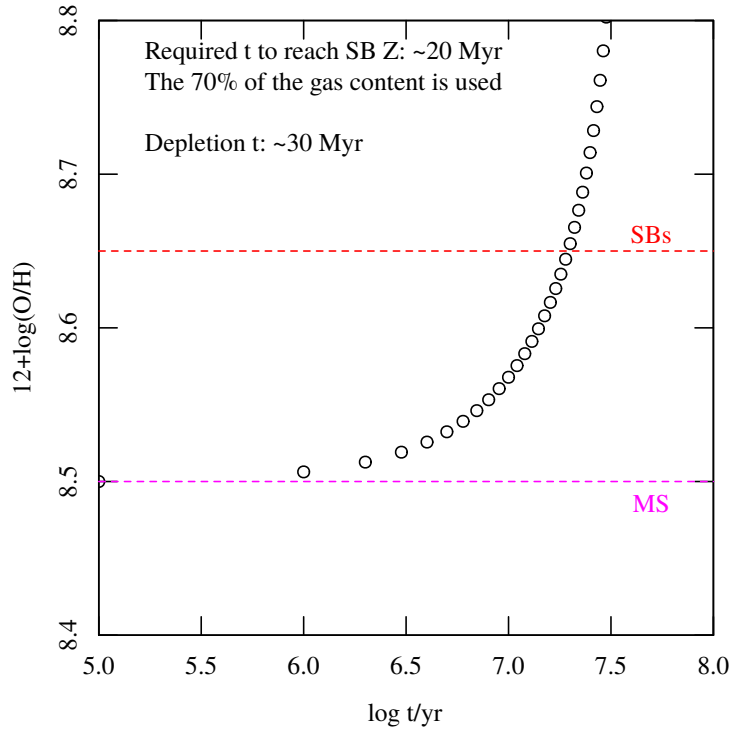


Figure 3.10: Metallicity evolution for a galaxy with $\log(M_{\star}/M_{\odot}) \sim 10.2$ experiencing a burst of star-formation. The horizontal dashed line in magenta highlights the metallicity corresponding to $\log(M_{\star}/M_{\odot}) \sim 10.2$ as derived from the MZR of Zahid et al. (2014). The red dashed line highlights the value of $Z = 8.65$ reached by the system after $\Delta t_{\text{enrich}} \sim 20 \text{ Myr}$. We note here that the metallicity scale of this figure differs from the one used in Fig. 3.9 as different calibrations are considered. In this plot we adopted the Pettini & Pagel (2004) metallicity calibration, to be consistent with the MZR of Zahid et al. (2014) used as a reference in the computation.

In the right panel of Fig. 3.11 we compare the Kashino et al. (2017a) measurements for the MS with the starburst sample: starburst galaxies appear to be characterized by higher metallicity, ionization parameter and ISM pressure than MS galaxies with similar $M_{\star}$ (fourth bin in the Kashino et al. 2017a sample). Following the interpretation of Kashino et al. (2017a), if the shift in emission line ratios is primarily due to a higher ionization parameter, this can be an additional indication that the efficiency of star formation is enhanced in $z \sim 1.6$ starburst galaxies. However, a full modeling including also the effects of optically thick dust attenuation would be required to properly interpret these measurements. Thus, we do not explore any further the comparison with the Dopita et al. (2016) models. This exercise will be implemented in a future work.

3.6 Discussion and conclusions

Different recipes fail to recover the nebular attenuation in our SBs, as the BD gives an attenuation almost $4\times$ smaller than what measured from the far-IR, resulting in an attenuation-corrected $\text{SFR}_{\text{H}\alpha}$ that is $\sim 10\%$ of SFR_{tot} . This is at odds with observations on the MS, where different attenuation diagnostics fairly agree (Kashino et al., 2013; Rodighiero et al., 2014; Puglisi et al., 2016; Shivaee et al., 2016) and leads to describe SBs as composed of two components: a compact, optically thick core, and an optically thin part, that primarily contributes in the optical continuum and line emissions. Measurements of the electron density through the [SII] doublet is fairly high, indicating that even the optically thin part is denser than in normal MS galaxies and perhaps suggests that we might be starting to probe the denser starburst core, similar to local SBs (Juneau et al., 2009).

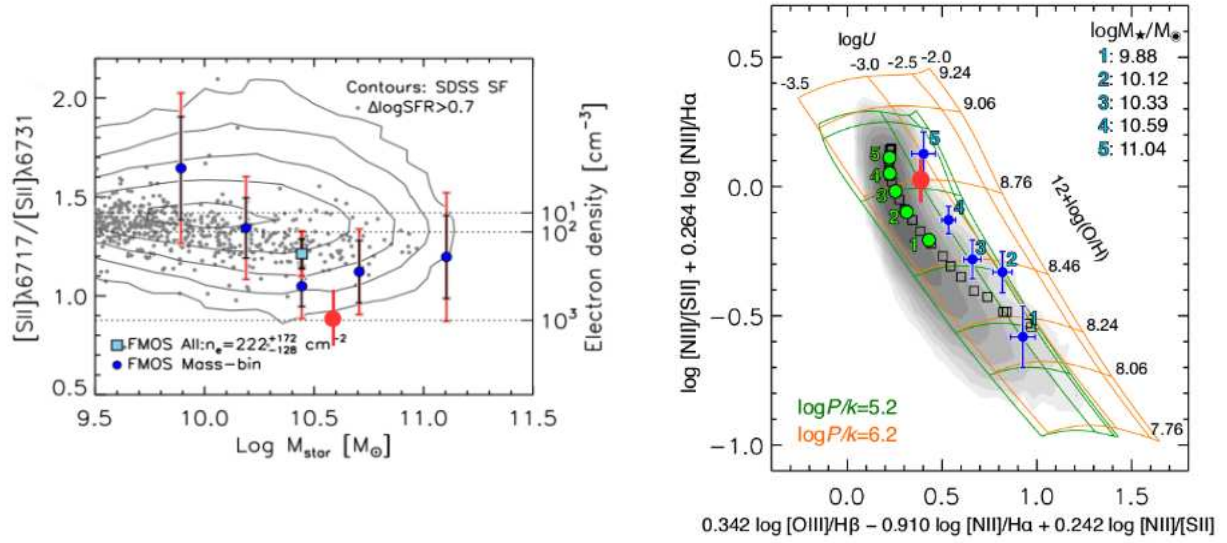


Figure 3.11: *Left:* $[\text{SII}]_{6717}/[\text{SII}]_{6731}$ ratio as a function of $M_{\star}$, from Kashino et al. (2017a), with our measurement from the average spectrum of the starburst population (red dot) overlaid. Blue filled squares are the Kashino et al. (2017a) measurements in $M_{\star}$ bins while the cyan square corresponds to measurement on their entire sample. The small black dots show measurements for local galaxies from the SDSS. For more details, see Kashino et al. (2017a).

Right: Comparison of optical line ratios, as presented in Figure 2 of Dopita et al. (2016), with theoretical model grids from MAPPINGS V. The models are computed as a function of the metallicity ($Z = 12 + \log(O/H)$), ionization parameter ($U = q_{\text{ion}}/c$), and gas pressure (P). Average measurements of the FMOS sample are based on stacked spectra in five stellar mass bins (Sample-2; blue circles, labeled). The median $M_{\star}$ are given in the upper right corner. Shaded contours show local star-forming galaxies, with their stacked points in equally-spaced 24 mass bins ($10^{8.9} \leq M_{\star}/M_{\odot} \leq 10^{11.3}$; squares) and in the same five mass bins as the FMOS sample (green circles, labeled). We add in this plot the measurement from the average spectrum of starbursts (red dot). From Kashino et al. (2017a).

In both panels, a Salpeter (1955) IMF is adopted to compute the $M_{\star}$ for the MS sample. The $M_{\star}$ of the starburst sample are thus converted to a Salpeter (1955) IMF for consistency, by dividing by a factor 1.7.

3.6. DISCUSSION AND CONCLUSIONS

This result will require further confirmation at higher S/N. A visual inspection of the ALMA CO vs optical morphology independently supports our interpretation as, at least in few cases, the peak of the CO emission tracing the molecular gas corresponds to a region undetected at optical wavelengths while IRAC re-aligns with the ALMA emission (see Fig. 2 in Silverman et al., 2015a), in a similar way to what is observed for some high- z SMGs (Simpson et al., 2016). However, comparisons between the BD and IRX in high- z SMGs show that these two diagnostics are in agreement (Takata et al., 2006), at odds with our results. This is expected, as the SMGs population includes both massive MS galaxies and off-MS sources.

The complex structure of our sources is revealed also from their average $\text{FWHM}(\text{H}\alpha) \sim 390 \text{ km/s}$, higher than the MS estimate at similar $M_\star$ (313 km/s at $\log(M_\star) \sim 10.48$, see Fig. 2 in Kashino et al. 2017a): this enhancement might indicate the presence of tidal fields, merger signatures and/or outflows in the optically-thin regions of our SBs.

Our results disfavor the possibility that SBs are simply isolated extremely gas-rich galaxies, while supporting a merger-driven scenario for their origin, as the latter scenario can lead to the formation of a heavily obscured compact core in the center. A caveat here is that the estimate of $A_{\text{H}\alpha}$ involves using aperture corrections computed from I_{F814W} -band photometry to account for the flux falling outside the fiber (see Sect. 7.2 in Silverman et al., 2015b). One might wonder that for such peculiar objects the continuum and emission line morphologies may strongly differ, unlike for the MS. Nevertheless, the attenuation at $\text{H}\alpha$ and observed I-band continuum (hence about $2800 \text{ \AA}$ at $z \sim 1.6$) are expected to be nearly identical (when accounting for the extra attenuation of the line, e.g. Kashino et al., 2013). Also, the tension between different attenuation diagnostics persists even when aperture corrections are not applied, thus not altering our conclusions. Future integral field observations can help to overcome these uncertainties and also to recover the effective nebular extinction pattern, that may be patchy.

Finally, we note that the BD-IRX mismatch could also arise by the fact that FIR samples the SFR on a longer timescale than $\text{H}\alpha$. Such an effect would be detectable only on short (several tens of Myr) timescales and only in case of strong SFR variations. Any such trend would be averaged out in our average measurements.

We also add another important piece to our understanding of the high- z SB physics. While “normal” galaxies follow a correlation in the $M_\star$ -Z-SFR plane, our SBs are outliers from the FMR, due to a metal-content substantially higher than one would predict from their $M_\star$ and SFR. This is somewhat expected if the core is thick at $\lambda_{\text{H}\alpha}$, but it further supports the idea that the starburst would not be triggered by a *major* accretion event of metal-poor gas, because such event would have caused a ISM dilution, reducing its metal content also presumably in its surroundings. However, we must note that the contribution of the core to the optical spectrum might reach at most 30% (likely, it is much lower) and our measurement mainly refers to the thin component. Still, this metallicity may be a lower limit to the metal-content of the heavily obscured core, if the ongoing SF has already significantly enriched the bulk of the ISM even if there are evidences in local ULIRG that the metallicity is uniform because of rapid mixing (Väisänen et al., 2017). These local studies, however, make use of optical emission lines indicators thus not probing still the metal content of the heavily obscured core. Given that the starburst region is optically thick, near-IR rest-frame or sub-mm observations would be needed to measure its metal content.

In conclusion, our work demonstrates for the first time that high- z SB galaxies behave like local ULIRGs, with a heavily obscured, probably metal-rich core that hosts $\gtrsim 90 \%$ of their vigorous SF, and supports the scenario in which high- z SBs are experiencing a violent and rapid SF episode because of their high density gas concentrations, probably driven by a major merger as in the local Universe.

3.7 Acknowledgements

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3.8 Appendix: Different methods for measuring $M_\star$ and their impact on starburst statistics

As extensively discussed in Rodighiero et al. (2014), selecting star-forming galaxies from *Herschel* observations corresponds to select galaxies in SFR . Consequently, *Herschel*-selected galaxies sample only the high- $M_\star$ end of the MS while at the lowest $M_\star$ this selection picks mostly galaxies with high SFR , i.e. starbursts. Thus, to properly define the MS locus, one has to consider a $M_\star$ -selected sample which allows to probe the full $sSFR$ range of the MS. Rodighiero et al. (2014) used a sample of star-forming galaxies selected through the Bzk technique (sBzk galaxies hereafter, Daddi et al., 2004) to define the MS at $1.4 \leq z \leq 2.5$. Following the prescription of Daddi et al. (2004), $M_\star$ for these sBzk galaxies were derived from the solely K_s -band photometry (from the catalog of McCracken et al., 2010). This simple empirical calibration is in good agreement with the method from the full SED, computed using photometry from UV to IRAC3, from the catalog of Ilbert et al. (2009). This excellent correlation is shown in Fig. 3.12, where we compare the SED and K_s -band $M_\star$ for *Herschel*-detected galaxies with a Bzk counterpart in the redshift range $1.4 \leq z \leq 2.5$ in COSMOS (~ 500 objects, see also Fig. 1 in Rodighiero et al., 2014). From this plot, we see that all the galaxies are located around the 1:1 line and the average dispersion of the correlation is ~ 0.3 dex. Using as a reference this MS derived from sBzk galaxies at $z \sim 2$, Rodighiero et al. showed that the UV indicators of star-formation systematically underestimate the SFR with respect to the FIR indicators for sources lying above the MS (i.e. with high $sSFR$). The authors interpret these objects as heavily obscured starbursts where SFR_{UV} and $E(B - V)$ are underestimated because of the exceptional dust attenuation. Because of this extreme dust obscuration, starburst galaxies are objects in which dust attenuation recipes fail catastrophically and as such, their ratio SFR_{FIR}/SFR_{UV} is expected to be much larger than unity (see their Fig. 3).

In the original version of Puglisi et al. (2017) we were using the MS equation from Rodighiero et al. (2014) to select off-MS galaxies, re-scaling its normalization at $z \sim 1.6$ by a factor $(1 + z)^{2.8}$ to account for the redshift evolution in $sSFR$ (Sargent et al., 2012). Since in our sample we were using the SED-fitting technique for computing $M_\star$, we compared this quantity with the same derived from the K_s -band. We performed this exercise discovering the existence of a systematic: for a consistent IMF, K_s -band measurements of $M_\star$ are larger than SED-based ones by a factor of ~ 2 on average, as shown in Figure 3.13

We thus split the sample shown in Fig. 3.12 in three redshift bins ($1.4 \leq z \leq 1.7$, $1.7 \leq z \leq 2$, $2 \leq z \leq 2.5$) and compare the two methods for measuring $M_\star$ in the full redshift range probed by Rodighiero et al. (2014). The result of this exercise is shown in Figure 3.14. From Fig. 3.14 it appears clear that the scatter observed in Fig. 3.12 is due to a redshift-dependent systematic. In particular, the K_s -band method overestimates $M_\star$ by a factor of ~ 2 with respect to the SED-fitting method in the lowest redshift bin ($1.4 \leq z \leq 1.7$, red circles in Fig. 3.14). Vice-versa, K_s -band $M_\star$ appear to be a factor ~ 2 lower than SED-fitting $M_\star$ at $2 \leq z \leq 2.5$ (blue circles in Fig. 3.14). Only sources at $1.7 \leq z \leq 2$ (green circles in Fig. 3.14) are located around the 1:1 relation. This effect can have a major impact in the starburst selection, as starburst galaxies are identified from their MS offset at a given $M_\star$. This mis-classification can have important consequences in the statistics of off-MS outliers and also on the physical properties of a sample selected in this way due to the inclusion of several interlopers.

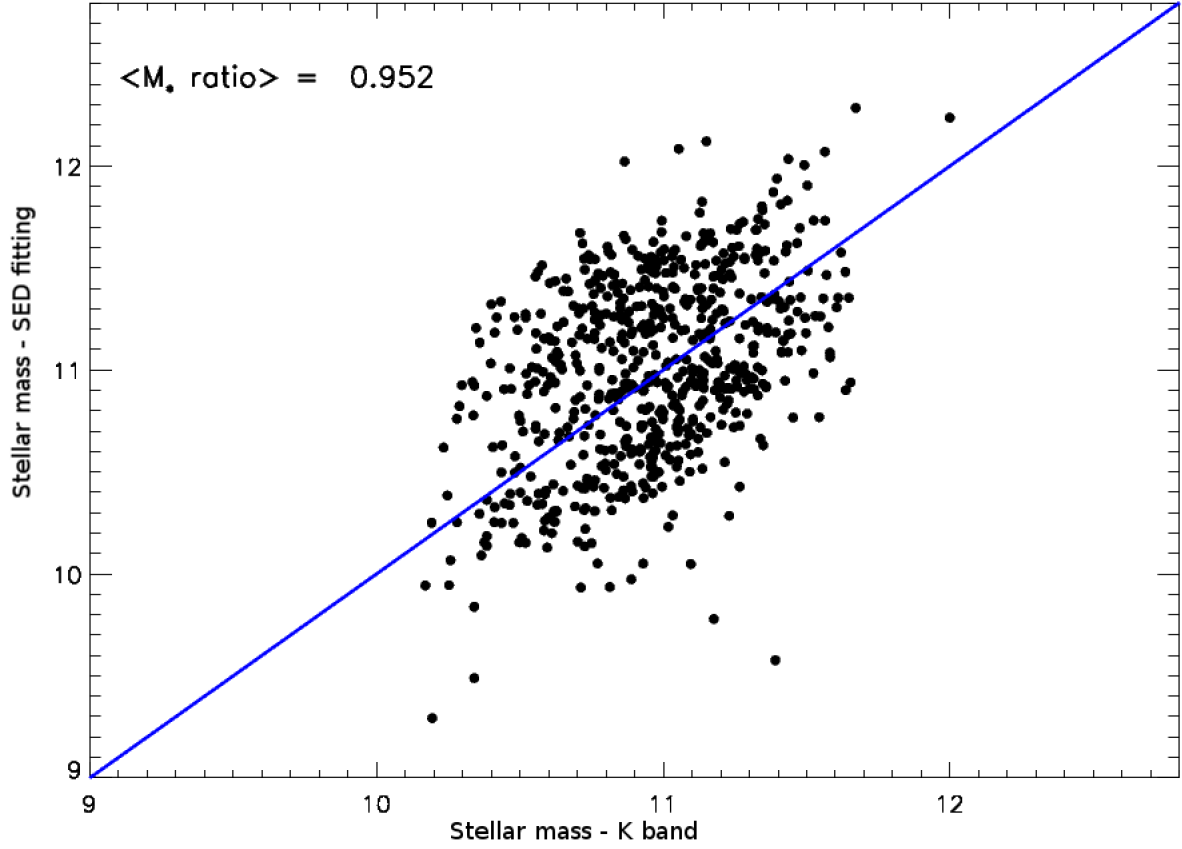


Figure 3.12: Correlation between $M_\star$ derived from the SED-fitting to the optical/near-IR photometry from Ilbert et al. (2009) and from the K_s -band photometry for the *Herschel*-detected sBzk sources in COSMOS at $1.4 \leq z \leq 2.5$.

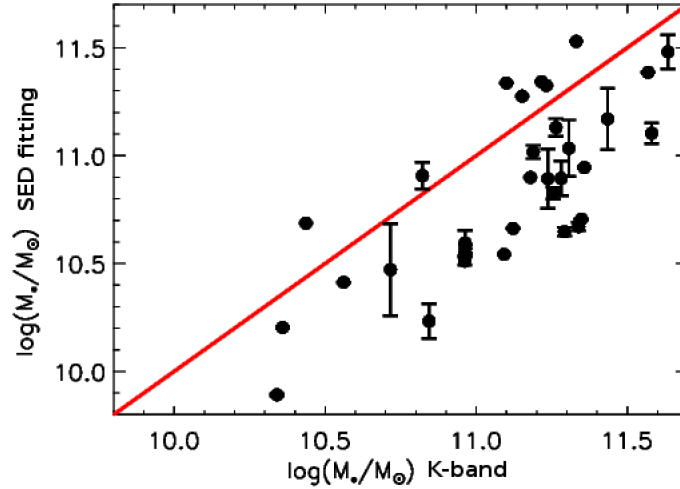


Figure 3.13: Comparison between $M_\star$ derived from the K_s -band and from the SED fitting to the optical/near-IR rest-frame photometry for the *Herschel*-FMOS sources at $z \sim 1.6$ with a sBzk counterpart. Red line is the 1:1 relation.

To explore the effect of this systematic, we split galaxies in the three redshift bins defined above and we compute the number of MS outliers, using for the selection their masses as obtained with both methods. We show the result in Fig. 3.15. The statistic of starburst sources selected when varying the $M_\star$ as a function of redshift is also summarized in Table 3.2.

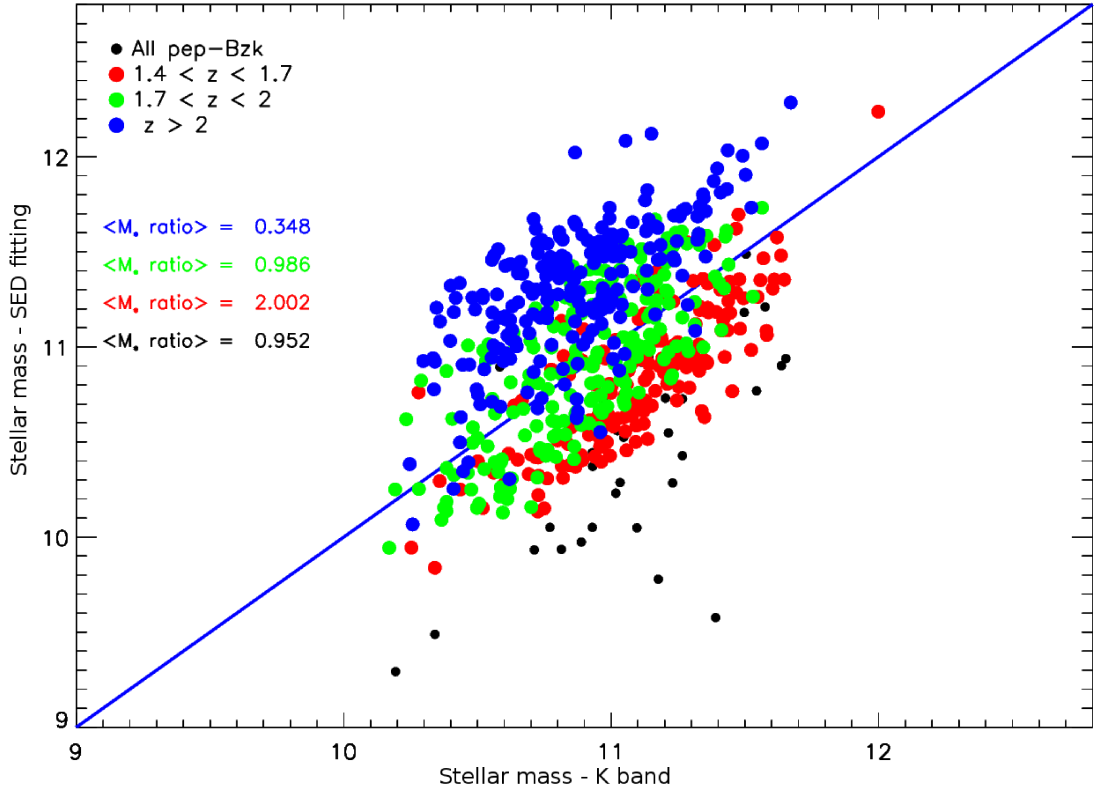


Figure 3.14: Same as Figure 3.12 with sources splitted in three redshift bins, as indicated in the legend.

Table 3.2: Statistic of starburst (off-MS) galaxies at $1.4 \leq z \leq 2.5$ and splitted in the three redshift bins defined in Figure 3.14 when varying M_* . The first column reports the starbursts statistics when galaxies are selected using M_* from the K_s -band while the second column report the same quantity but for starbursts selected with M_* from the SED fitting.

Redshift range	off-MS (M_* K_s -band)	off-MS (M_* SED fitting)
$1.4 \leq z \leq 2.5$	140	177
$1.4 \leq z \leq 1.7$	19	72
$1.7 \leq z \leq 2.0$	74	80
$2.0 \leq z \leq 2.5$	47	25

The impact of the use of different methods to estimate M_* is minor on the starburst statistics in the whole redshift range $1.4 \leq z \leq 2.5$, as expected given the overall agreement of the two estimates: only the scatter of the MS is mildly affected. However, the number of off-MS sources in the lowest and the highest redshift bins depends on the method considered for computing M_* , reflecting the systematic in M_* . In particular, at $z \sim 1.6$ we derive a much larger number of starbursts when using SED-fitting based M_* . At $z \sim 2.3$ the number of starbursts is underestimated by a factor of ~ 2 when using SED-based M_* . Only at $z \sim 2$ the use of different methods for deriving M_* does not affect the statistics, as in this redshift range the two methods are well correlated.

In Fig. 3.15 we also report the ratio $SFR_{\text{FIR}}/SFR_{\text{UV,corr}}$ for starburst galaxies in each redshift bin, which quantifies the fraction of fully obscured star-formation. The use of the two different M_* impacts also on the ratio $SFR_{\text{FIR}}/SFR_{\text{UV,corr}}$ of the selected starburst sample due to the presence of interlopers in the sample. To better visualize this effect, we show the distribution of $\langle SFR_{\text{FIR}}/SFR_{\text{UV,corr}} \rangle$ in redshift bins when varying the M_* method in Fig. 3.16. The dust-corrected $SFR_{\text{UV,corr}}$ is underestimated by only a factor of ~ 2.8 with respect to SFR_{FIR} in starburst galaxies at $1.4 \leq z \leq 1.7$, while we would expect this mismatch to be much larger. In particular, since starburst galaxies lie on the MS if one uses their $SFR_{\text{UV,corr}}$ (see green open circles in Fig. 3.15) we expect $SFR_{\text{FIR}}/SFR_{\text{UV,corr}} \sim SFR_{\text{FIR}}/SFR_{\text{MS}}$.

3.8. APPENDIX: DIFFERENT METHODS FOR MEASURING $M_\star$ AND THEIR IMPACT ON STARBURST STATISTICS

This is clearly an artifact induced by the systematic of the $M_\star$ measurements which causes to classify as off-MS starburst many “normal” MS galaxies due to an underestimate of their $M_\star$. Despite the dependence of $SFR_{\text{FIR}}/SFR_{\text{UV,corr}}$ on the $M_\star$ measurement, we notice in both panels of 3.16 that this ratio seem to be an increasing function of redshift. This could suggest that the amount of fully obscured star-formation in starburst galaxies increases at higher redshift. However, we cannot exclude at this stage that this effect is induced by residual systematic effects, either in the $M_\star$ or in the measurement of $SFR_{\text{UV,corr}}$. Investigating this trend is out of the scope of this work and we refer to future analysis to explore in details such possibility.

The main conclusion from this test is that one has to obtain accurate estimates of $M_\star$ and SFR s to properly define the position of galaxies in the MS plane and properly interpret the properties of galaxies as a function of their position with respect to the MS.

To minimize the impact of these systematics in our analysis of the dust attenuation and metallicity properties of MS outliers at $z \sim 1.6$ we thus re-compute consistently the $M_\star$ for sBzk galaxies (identifying the MS) and *Herschel*-FMOS galaxies (from which starbursts are selected). We decide to apply the SED-fitting method to exploit the high-quality and broad photometric coverage of the COSMOS field, using the up to date photometry from Laigle et al. (2016). For the SED-fitting we used the *hyperzmass* code (Bolzonella et al., 2000), adopting SSP models from Bruzual & Charlot (2003), a Calzetti et al. (2000) dust attenuation curve and a Chabrier (2003) IMF. In our SED fitting we consider photometry up to $8 \mu\text{m}$, to sample the rest-frame near-IR at $z \sim 1.6$, a wavelength range crucial to properly recover the stellar mass (e.g. Pforr et al., 2012, see also the introduction of this Thesis). We fix the redshift to the spectroscopic measurement from FMOS when available and we use the z_{phot} from Laigle et al. (2016) elsewhere.

We explore the effects of several parameters on the derivation of $M_\star$ by running *hyperzmass* in different configurations and we adopt the combination of parameters which yields the best agreement with the original $M_\star$ estimate from the K_s -band (used in Kashino et al. 2013) and a MS in agreement with pre-existent equations published in literature.

We test the effect of varying the amount of dust attenuation allowed in the fit. We run the code by allowing the attenuation to vary between $0 \leq A_V \leq 3$ and $0 \leq A_V \leq 4$ and we compare the measurements of $M_\star$. Varying the maximum dust attenuation allowed in the fit has a minor impact on the $M_\star$ measurement and it produces only a small scatter around the 1:1 relation (see left panel in Fig. 3.17). This is expected because the stellar mass is mainly constrained by intermediate/low-mass stars emitting in the rest-frame near-IR, less affected by dust attenuation. The photometry seems to have a major impact in the estimate of $M_\star$: the use of photometry from Ilbert et al. (2009) rather than Laigle et al. (2016) induces a substantial scatter in the estimate of $M_\star$ for the same galaxies (see right panel of Fig. 3.17). We thus argue that part of the effects discovered can be ascribed to differences in the two photometric catalogs.

For computing $M_\star$ for our $z \sim 1.6$ galaxies we finally adopt $A_V \in [0 - 3] \text{ mag}$, a constant SFH and photometry and photo- z from Laigle et al. (2016) up to $8 \mu\text{m}$ observed frame. Then, the MS equation is derived on sBzk galaxies by a linear fit to their $M_\star$ and SFR using the IDL routine *MPFITEXY* (Markwardt, 2009). The derived MS, shown with blue solid line in Fig. 3.18, is in good agreement with the Rodighiero et al. (2011) equation after re-scaling it to $z \sim 1.6$, with the relation reported in Silverman et al. (2015a) and the parametrization of Speagle et al. (2014) at $z \sim 1.6$. In addition, our measurements of $M_\star$ are in excellent agreement with the K_s -band estimates used in Kashino et al. (2013) and the SED-fitting $M_\star$ computed in Kashino et al. (2017a), used as a comparison sample in Puglisi et al. (2017).

We stress however that, if the $M_\star$ is computed using the single color technique from Daddi et al. (2004) with K_s -band photometry from Laigle et al. (2016), a redshift trend with respect to the SED fitting based $M_\star$ is still observed. Therefore we conclude that the effect cannot be simply related to the photometry and it must be related to some additional effect. To further confirm that the effect is not only related to issues in the photometry, we repeat the checks on the sample of *Herschel* galaxies with a sBzk counterpart in the GOODS-S field. Also in this case we observe the same redshift-dependent trend for the two $M_\star$ methods.

We consider two possible alternative artificial effects that could be responsible for this trend. On one hand, the K_s band samples the rest-frame near-IR only in a restricted range of redshift around $z \sim 2$. If we extend the usage of this technique outside this redshift window, we probe different parts of the galaxy SED from which the M/L ratio of intermediate-low mass stars dominating the stellar mass of the system is poorly constrained. On the other hand, the formula of Daddi et al. (2004) contains an additive term of correction to account for the dust attenuation. The observed trend could thus be induced by some problems in the estimate of the dust attenuation correction. Exploring the reasons for this redshift trend is beyond the scope of the work presented in Puglisi et al. (2017) and we will refer to a dedicated analysis to properly understand the origin of this systematic.

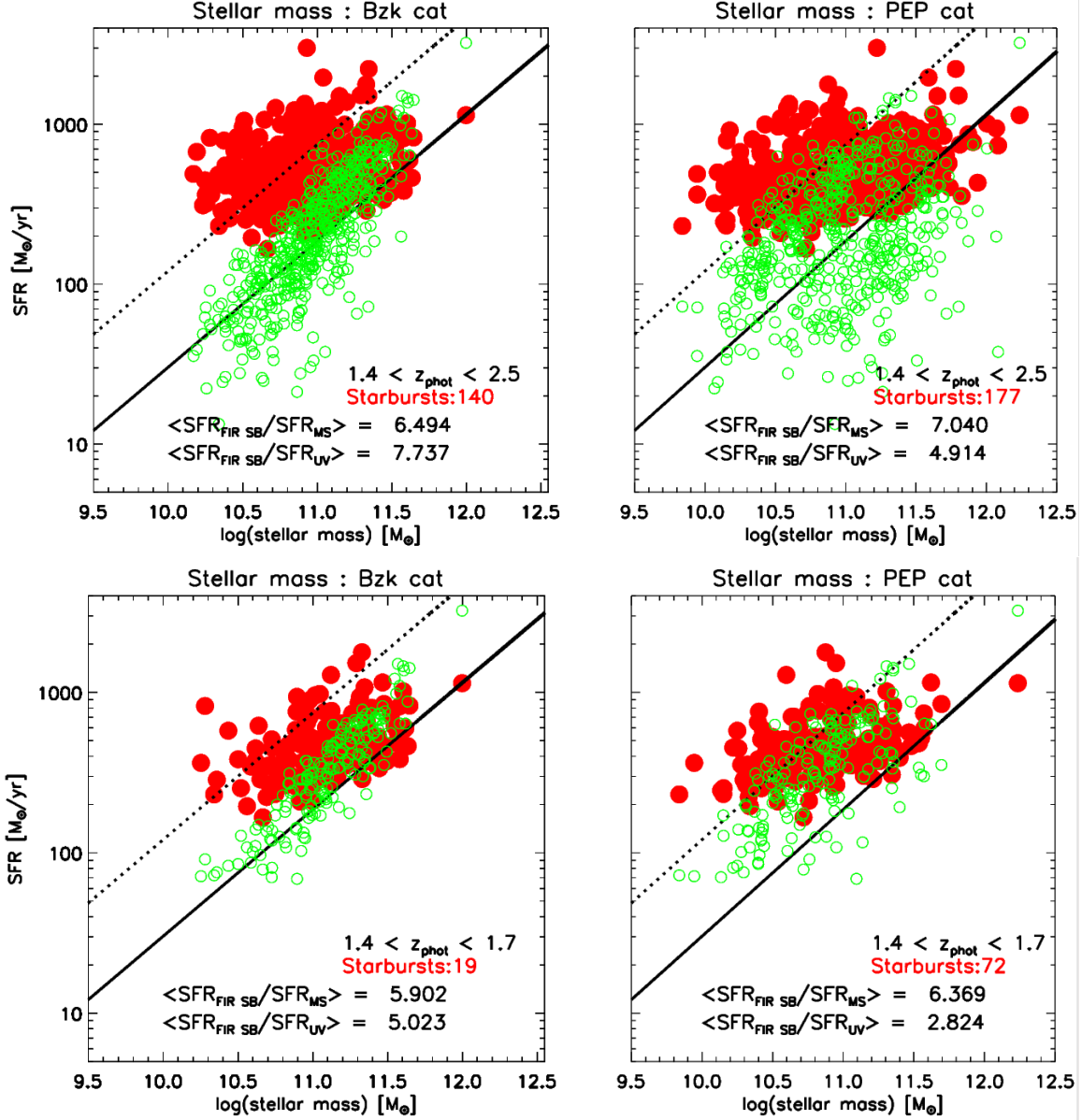


Figure 3.15: SFR versus M_* for *Herschel*-detected galaxies with a sBzK counterpart in the COSMOS field. We report their SFR from the dust-corrected UV emission with green open circles, while their measurement from the FIR with red filled circles. The black solid line is the MS equation from Rodighiero et al. (2011) derived at $z \sim 2$. The dotted line corresponds to the $4 \times \text{MS}$: sources above this line are selected as starbursts. Plots on the left use M_* from the K_s -band while plots on the right use M_* from the SED-fitting. The same plot is produced for the full redshift range considered in Rodighiero et al. (2014) and splitting the sample in three different redshift bins, as indicated in each panel. The SFR of each source is renormalized to $z \sim 2$, i.e. the average redshift at which the MS is computed, to account for the redshift evolution of the MS normalization. In each plot we report also the starburst statistics, their average distance from the MS (i.e. the starburstiness, $\text{SFR}_{\text{FIR,SB}}/\text{SFR}_{\text{MS}}$) and the average ratio between the SFR as derived from the FIR and the dust corrected UV emission ($\text{SFR}_{\text{FIR,SB}}/\text{SFR}_{\text{UV}}$). Continues in the next page.

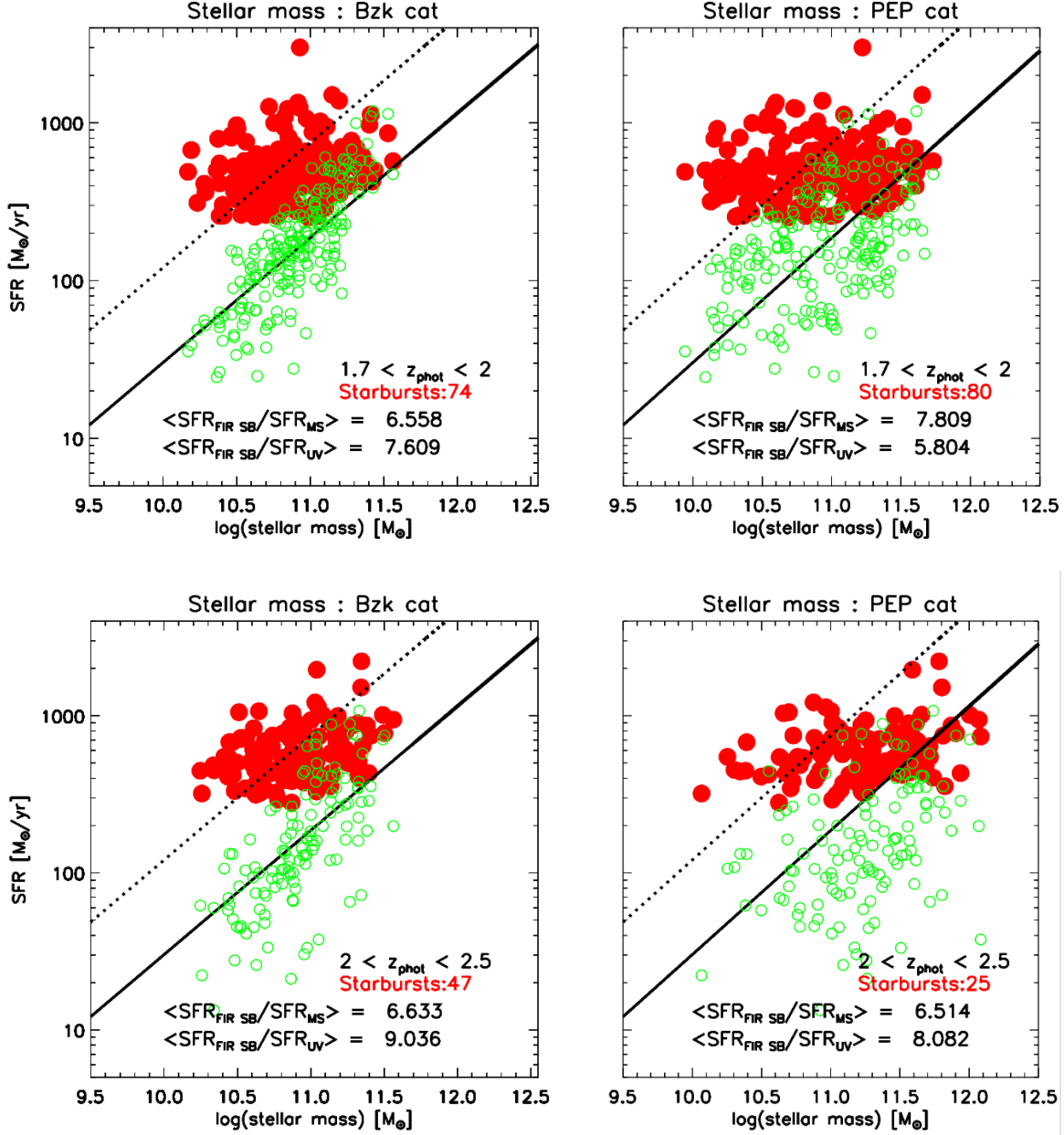


Figure 3.15: SFR versus M_* for *Herschel*-detected galaxies with a sBzK counterpart in the COSMOS field (continued).

3.8. APPENDIX: DIFFERENT METHODS FOR MEASURING $M_\star$ AND THEIR IMPACT ON STARBURST STATISTICS

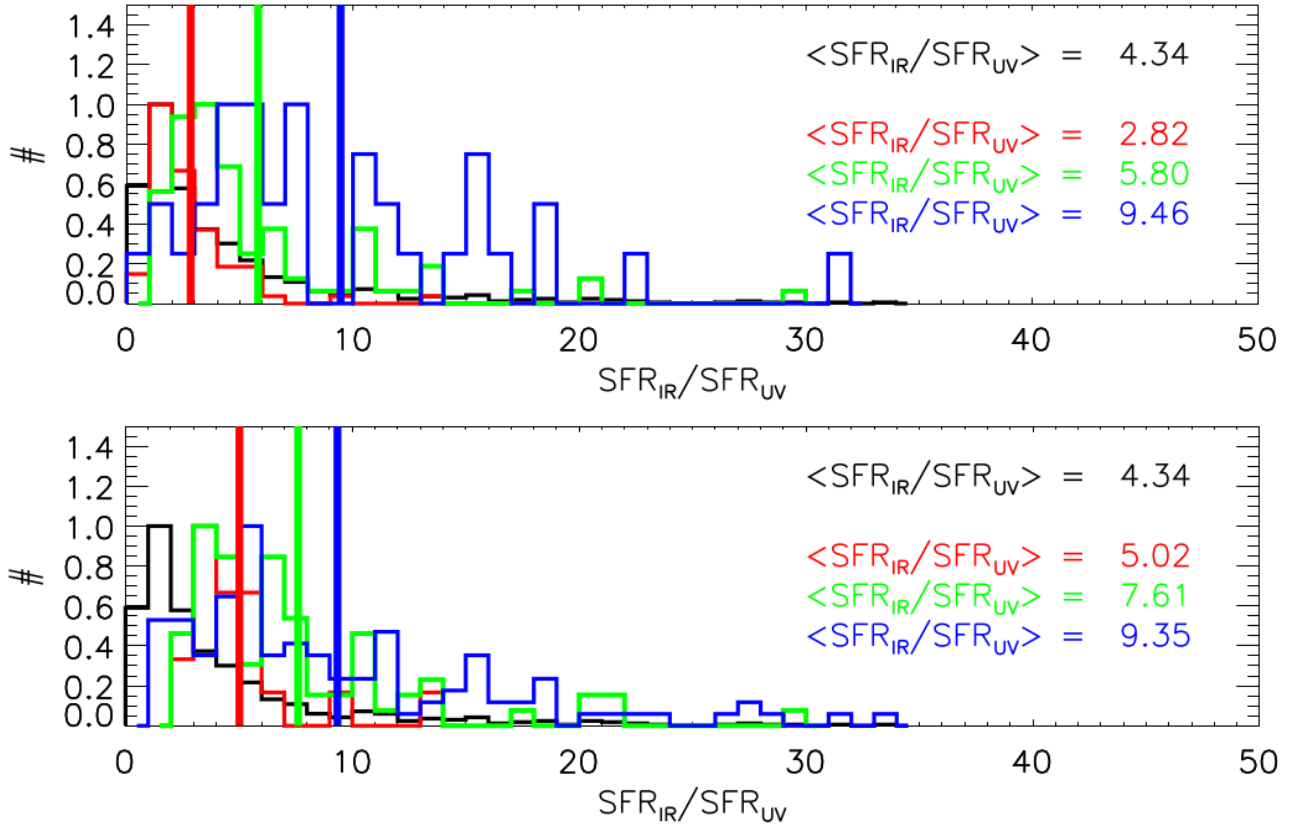


Figure 3.16: $SFR_{FIR}/SFR_{UV,corr}$ distribution for sources above the $4 \times MS$ relation. Different colors highlight sources in three different redshift bins: $1.4 \leq z \leq 1.7$ in red; $1.7 \leq z \leq 2$ in green; $2 \leq z \leq 2.5$ in blue. Solid vertical lines highlight the median value of the distribution in each redshift bin. Off-MS galaxies are selected using $M_\star$ from SED-fitting (up) and from the K_s -band (bottom): note the different median ratios in the lowest redshift bin. In addition, the ratio $\langle SFR_{FIR}/SFR_{UV,corr} \rangle$ increases with redshift.

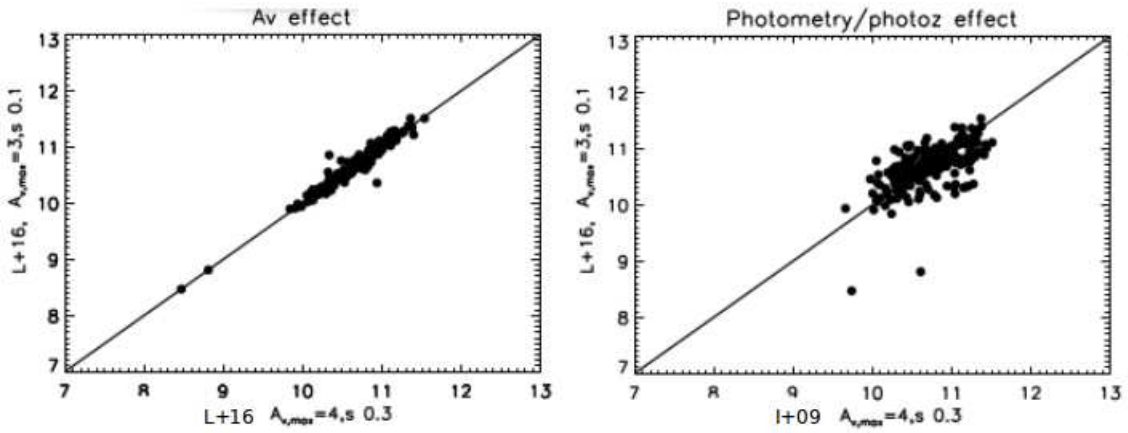


Figure 3.17: Upper panel: comparison between $M_\star$ derived from the SED-fitting when varying the dust attenuation. Lower panel: $M_\star$ computed via the SED fitting using photometry and photo- z from different catalogs. Continuous line is the 1:1 relation.

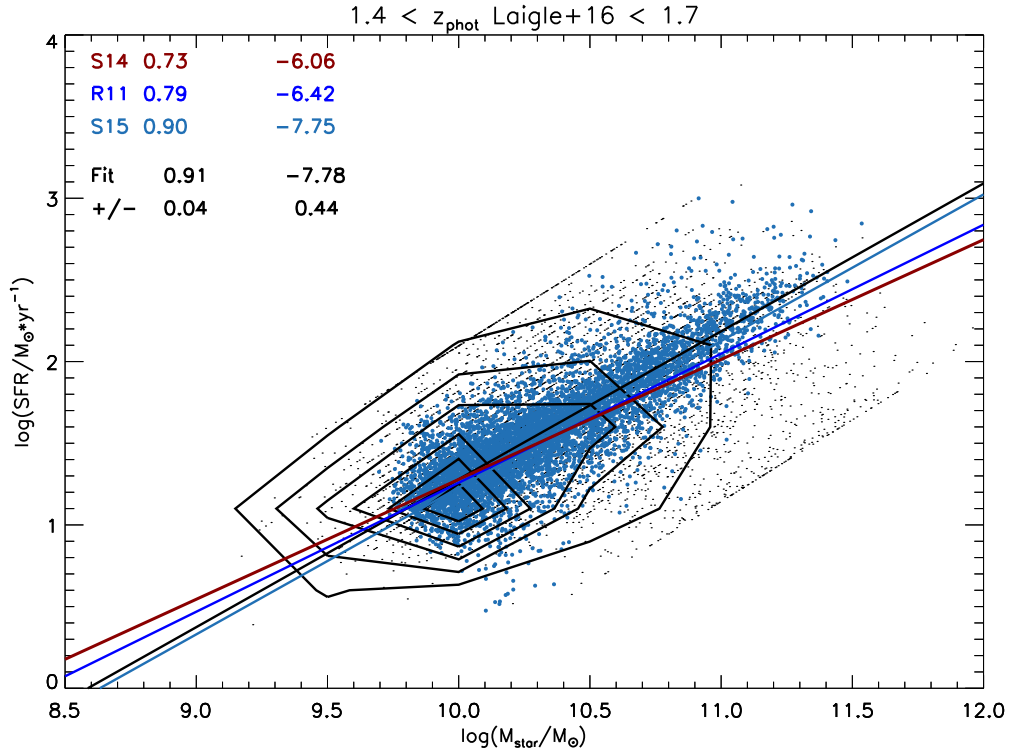


Figure 3.18: $M_{\star}$ vs SFR plane for sBzK galaxies at $z \sim 1.6$. We indicate with black dots and black contours measurements of $M_{\star}$ as derived by fitting their multi- λ SED. We report with light blue dots the pre-existing measurements of $M_{\star}$ from the K_s -band (see text for details). The black solid line is the MS obtained by fitting the black points (i.e. SED-based measurements) while the light blue solid line is the MS equation from Silverman et al. (2015a), derived by fitting the blue points (K_s -band quantities). We also show for comparison the relationship from Rodighiero et al. (2011) and Speagle et al. (2014), re-scaled at $z \sim 1.6$ (blue and dark red lines respectively).

Chapter 4

Testing the Starburst/AGN sequence with AGN outflows

The evolutionary scenario for merger-driven starbursts predicts that after an heavily obscured phase of intense star formation and moderate black hole growth the system expels the obscuring dust cocoon via strong feedback and evolves into an optically bright QSO, before dying as a passively evolving elliptical. The study of starburst galaxies hosting an AGN provides important indications for our understanding of this sequence. In this chapter I will present a preliminary analysis of a sample of 8 AGN-dominated sources above the main sequence at $z \sim 1.6$ identified from optical diagnostics using rest-frame optical spectra from the FMOS-COSMOS survey. These AGN-dominated starbursts are drawn from the sample of starbursts presented in Puglisi et al. (2017) and comprise the $\sim 40\%$ of outliers, indicating a high duty-cycle above the main sequence. I will present the properties of this sample including their distribution in the $M_\star - SFR$ plane, the hosts morphology, the rest-optical average spectrum and measurements of their dust attenuation from the $H\alpha/H\beta$ ratio. These properties will be discussed in comparison with the features of the parent population of Star-Formation dominated starbursts, in the context of the starburst-AGN evolutionary sequence. I will show that AGN-dominated starbursts reside in merging pairs more compact than the parent star-formation dominated starbursts and have marginally lower dust attenuation. In addition, the average spectrum of these AGN reveals the presence of outflowing material from a broad, blue-shifted component in the $[OIII]_{5007}$ emission line. These preliminary results require future confirmations with higher quality data but already suggest that these AGN-dominated starbursts are undergoing a “blow-out” phase subsequent to the heavily obscured starburst phase and are removing the obscuring dust cocoon via efficient feedback.

4.1 Introduction

The majority of stars in the present days Universe is enclosed within massive spheroidal galaxies without traces of ongoing star formation. These systems seem to be present since long time, as they have been observed up to $z \sim 3.7$ (Glazebrook et al., 2017), and their stars must have been formed through rapid star formation episodes, with timescales of ~ 1 Gyr (Thomas et al., 2005). The formation mechanism of these objects remains however still a mystery. One of the possibilities is that they have been originated from major merger of two “normal”, massive and gas rich galaxies (Sanders et al., 1988; Hopkins et al., 2008; Wuyts et al., 2010; Toft et al., 2014). The galaxy-galaxy interaction provokes a heavily obscured nuclear starburst and the system experiences a rapid evolution: the gas content is rapidly consumed in few *Myrs* by the violent star formation and part of this gas is accreted onto the central BH in a moderate growth phase (Alexander & Hickox, 2012), almost invisible because of the large dust concentrations in the nuclear region. This BH has then an important role in the formation of the elliptical galaxy itself (Springel et al. 2005).

In fact, towards the end of the starburst phase, the BH may initiate a phase of intense growth launching powerful winds. These winds can be powerful enough to remove the material (dust and gas) from the system that firstly appears as a bright QSO, after the heavily obscured phase, and then leads the system to its death as a passive spheroid. This scenario was postulated by Sanders et al. (1988) but is still subject of explorations. Proving its validity, in fact, is not easy because it refers to short time-scale phenomena. In addition, for most of the sequence the system is embedded in a large amount of dust so that analysis in the UV/optical are challenging. To probe the evolutionary sequence one can study the properties of objects in different stages of it, i.e. dusty starbursts, red and optically bright QSOs, post-starbursts, and interpret their properties in an evolutionary context. Many works in literature have devoted large efforts to constrain the properties of these systems to probe the aforementioned sequence (see the introduction of this Thesis and references therein). These works have shown for example, that the vast majority of starburst episodes are hosted in interacting/merging systems (Sanders & Mirabel, 1996, Clements et al. 1996) supporting the hypothesis that the merger is the main driver of starburst activity. Moreover starburst galaxies show a high percentage of AGN (Alexander et al. 2003, Iwasawa et al. 2011, Alexander and Hickox 2012 and references therein). The bolometric luminosity (L_{bol}) of these heavily obscured AGN hosts are however dominated by star formation suggesting that these systems are in a phase preceding the quenching (Pope 2008, Coppin 2010). On the other side, the fraction of AGN in merging pairs is high (Iwasawa et al. 2011) and the merger stage correlates with the AGN luminosity (L_{AGN}) so that the merging activity seems to also trigger the BH accretion (Silverman et al., 2011), although the association between AGN and merger systems is not yet clear (Farrah et al., 2017). In agreement with the prediction that the QSO phase corresponds to the blow-out stage in which the system transits from an heavily obscured to an optically bright phase, red quasars often show traces of outflowing material (Page et al. 2011, Banerji et al. 2012, 2015). In this sense, it is expected that feedback processes are efficient in expelling material in these sources, because of the coupling between dust and radiation boosting the outflow power (Ishibashi & Fabian, 2016). Analyzing the occurrence of outflow in starbursting/QSOs, in connection with the host properties such as the merger stage, the star formation activity or the dust attenuation may provide important constraints to the validity of the merging evolutionary sequence.

In this Chapter I will present the characterization of the optical spectra of a sample of AGN-dominated starburst galaxies, identified among the sample of $z \sim 1.6$ high- $sSFR$ MS outliers presented in Puglisi et al. (2017) (see also Chapter 3). The properties of these AGN will be compared with those of the parent sample of star-formation dominated starbursts with the ultimate goal of proving the existence of a causal link between the two samples. The results from this preliminary analysis will be explored in a future work, hopefully with the aid of higher quality data.

4.2 Selecting AGN in the starburst region at $z \sim 1.6$

The sample of AGN described in this Chapter are located in the “starburst region” of the $z \sim 1.6$ $M_{\star} - SFR$ plane and are drawn from the sample of *Herschel*-selected starburst galaxies with optical rest-frame spectra discussed in the previous chapter. These $z \sim 1.6$ starburst galaxies have been selected as sources having $sSFR \geq 4 \times sSFR_{\text{MS}}$ (following the Rodighiero et al., 2011, criterion) and an $H\alpha$ detection in the FMOS spectrum (see Sect. 3.3 and Fig. 3.1). For more details about the selection of the starburst sample as well as for details about the FMOS-COSMOS survey I refer the reader to Chapter 3.

AGN-dominated objects in this sample are identified using different techniques. FMOS spectroscopy covers the wavelength range with the key emission lines required for constructing the BPT diagram ($H\alpha$, $H\beta$, $[\text{NII}]_{6585}$, $[\text{OIII}]_{5007}$, Baldwin et al. 1981). This diagram allows to identify the ionizing source for the emission lines, distinguishing between star-formation and AGN (Kewley et al., 2013). I therefore use the FMOS spectra to construct the classical BPT diagram and differentiate between AGN and starburst as the powering engine for our objects. I define as AGN the sources above the Kewley et al. (2013) dividing line, computed at $z \sim 1.6$, i.e. the mean redshift of the sample. For some sources the $H\beta$ and $[\text{OIII}]_{5007}$ emission lines are strongly contaminated by the atmospheric emission.

In addition, the shorter wavelength follow-up with the *J-long* spectrum is not available for all the objects in this sample. As such, not all the objects have the full emission line coverage required for the BPT diagram: in this case I rely on the ratio $[NII]_{6585}/H\alpha$, selecting as AGN sources with $\log([NII]_{6585}/H\alpha) \geq -0.2$ (Cid Fernandes et al., 2005). I also cross-correlate the catalog with the X-ray catalog of Elvis et al. (2009) classifying as AGN an object with $L_{X-ray} \geq 4 \times 10^{42} \text{ ergs}^{-1}$. I correlate the list of sources also with the up-to-date information contained in Marchesi et al. (2016), which extends the X-ray catalog to the 2.2 deg^2 of the COSMOS field, finding no additional sources with an X-ray counterpart. Finally, I also identify an AGN from the mid-IR colors techniques (e.g. Fadda & Rodighiero, 2014). I note here that all but one of the AGN in the starburst region are identified through the optical spectrum (see Fig. 4.1). This is surprising, giving the strong attenuation expected on the emission lines of off-MS sources (see discussion in Puglisi et al. 2017) and might be an indication that these AGN are caught in the act of removing the obscuring dust cocoon. I will explore this possibility in Sect. 4.6 of this chapter.

Figure 4.1 shows the BPT diagram for the off-MS sources at $z \sim 1.6$: black filled circles represent the starburst population presented in Chapter 3. Red diamonds are the AGN among the starbursts (i.e. the sources that will be discussed in this chapter) with the X-ray and the mid-IR identified AGN are marked with a green circle and a magenta diamond respectively. The big red diamond and big black circle correspond to measurements of the emission line ratios on the stacked spectra of AGN-dominated and SF-dominated starburst sources respectively: as expected, the AGN-dominated sources occupy the locus above the Kewley et al. (2013) dividing line at $z \sim 1.6$ indicating that the emission lines are mostly excited by an AGN.

The position of these sources in the $M_\star - SFR$ plane is shown in Fig. 4.2: AGN-dominated starbursts span a range of $sSFR$ similar to the one observed for the Puglisi et al. (2017) sample. In this figure, the sources with an high-quality FMOS spectrum (i.e. $z_{\text{flag}} = 4$) are highlighted in black. Sources with low SN spectra will not be included in the stacking analysis as the emission lines are heavily contaminated by OH emission from the atmosphere. Additional observations will be required to confirm the spectroscopic redshift and the emission line fluxes of these sources. Including these objects in the stacking however, only degrades the SN of the average spectrum of the AGN population but does not affect the (preliminary) conclusions.

Figure 4.3 shows the SFR_{FIR} distribution for the AGN and the Star-forming SB populations: the two samples span a similar range of SFR s but the AGN-host starbursts have an average SFR_{FIR} marginally lower than the star-forming sample. A Kolmogorov-Smirnov statistical test on the two distributions reveals that there is $\sim 96\%$ probability that they are drawn from the same distribution.

4.3 Average spectra for the AGN-starburst population

In order to increase the SN of our measurements, I construct the average spectrum of the AGN-dominated starbursts adopting the stacking technique that is described in Sect. 3.4.2 of the previous chapter. The stacking technique allows to obtain higher SN spectra that can be used to analyze average trends for the population considered. The emission line in the AGN-dominated spectrum are fitted with a similar procedure used for the non-active sample (see Sect. 3.4.1). In this case I fit an additional broad component to the $H\alpha$, $H\beta$ and $[OIII]$ emissions, to account for the feature observed in the emission lines of the AGN starburst population.

The right panel of Figure 4.4 shows the result of this stacking exercise for the AGN-starburst sample. Sources with a low quality redshift flag ($z_{\text{flag}} \leq 3$) have been discarded in order to maximize the SN on the average spectrum. Figure 4.4 also shows for comparison the average spectrum of star-formation dominated starbursts from Puglisi et al. (2017). The spectra of these two populations show substantial differences from a by-eye comparison: the AGN-dominated spectrum shows enhanced but narrower $[OIII]_{4960,5007}$ emission, a larger $H\beta$ emission and an additional broad component that is not detected in the star-formation dominated starbursts spectrum. This broad component under the $H\alpha$ emission in the AGN composite spectrum is likely tracing the BLR. The $[OIII]_{4960,5007}$ emission lines in the AGN-dominated spectrum clearly show a blue shifted broad component, likely tracing outflowing gas.

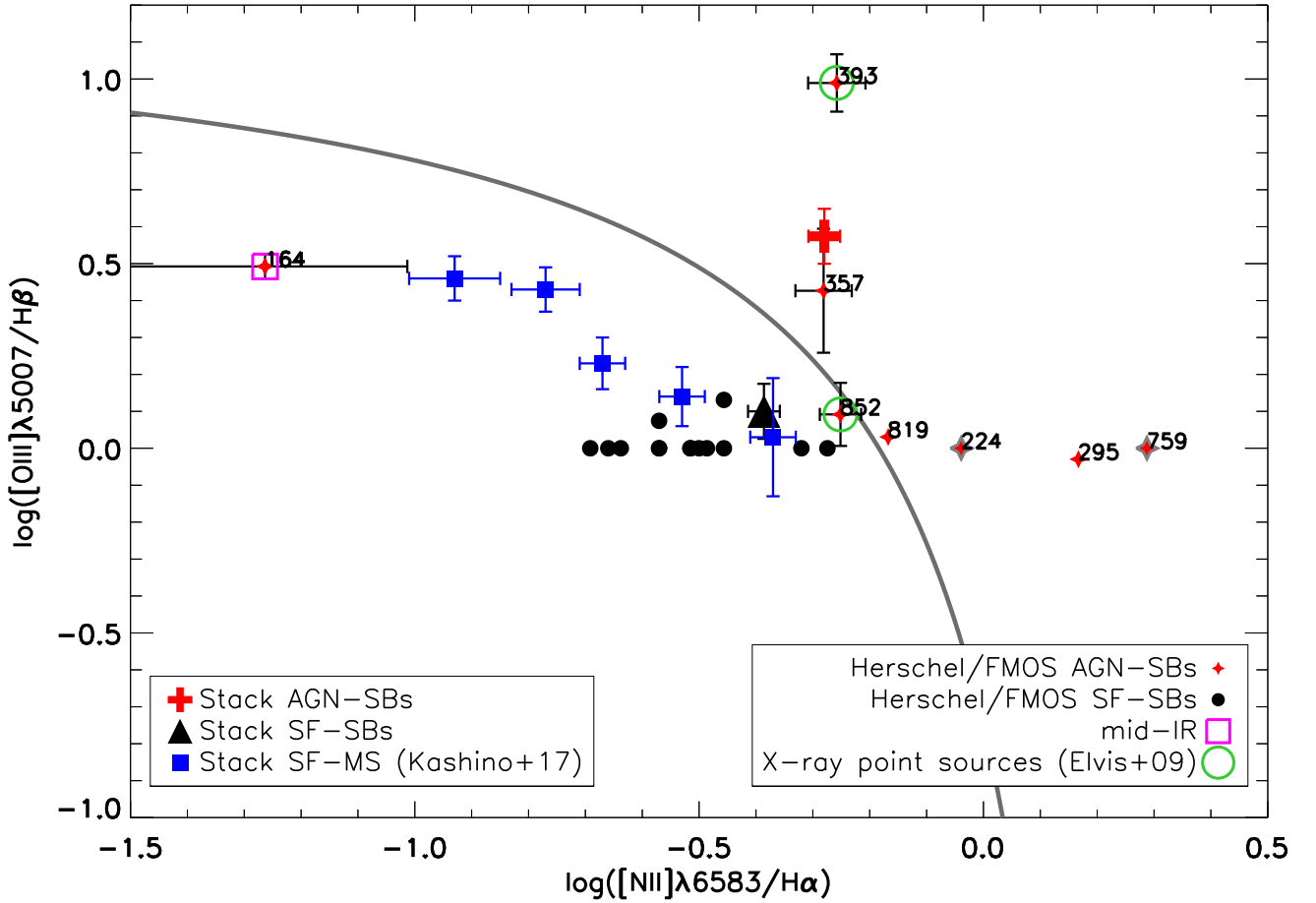


Figure 4.1: BPT diagram for the *Herschel*-FMOS sources above the MS. Red labeled diamonds are the individual measurements for AGN-dominated starbursts. For sources lacking the detection of one or two key emission lines upper limits were considered. Highlighted in grey we show the two galaxies without a *J-long* spectrum, which samples the spectral range around the $H\beta$ and $[OIII]\lambda_{4959,5007}$ emission lines. The big red cross is the average measurement for the AGN-dominated starbursts derived from the stacked spectrum shown in Fig. 4.4 (see text for details about the stacking). Black symbols are the Star-forming dominated starbursts presented in Puglisi et al. (2017): small circles are individual sources, the big triangle corresponds to the stack. We report for comparison average measurements from Kashino et al. (2017a), i.e. the FMOS sources lying on the MS at $z \sim 1.6$ (blue squares).

Unfortunately, the low SN in the individual spectra combined with a limited statistics prevents us to reliably fit this component and thus studying with accuracy the emission line profiles to derive the physical parameters of the outflow (see Sect. 5.2.2 for more details). Still, this qualitative result represent an initial indication of the presence of outflowing material in this population: if confirmed with higher SN observations, this result will provide supporting evidence to the fact that these AGN are undergoing a blowout phase. I further discuss this result in Sect. 4.6.

4.4 Optical morphology for the AGN-starburst population

Figure 4.5 shows the HST-F814W imaging for the $z \sim 1.6$ AGN-dominated starbursts, tracing the rest-frame UV morphology of these objects. Sources with a low-quality FMOS spectrum are highlighted with magenta squares: these objects are not included in the average spectrum. In addition, a blue square highlights the source classified as AGN from the X-ray while the red square identifies the AGN from the mid-IR.

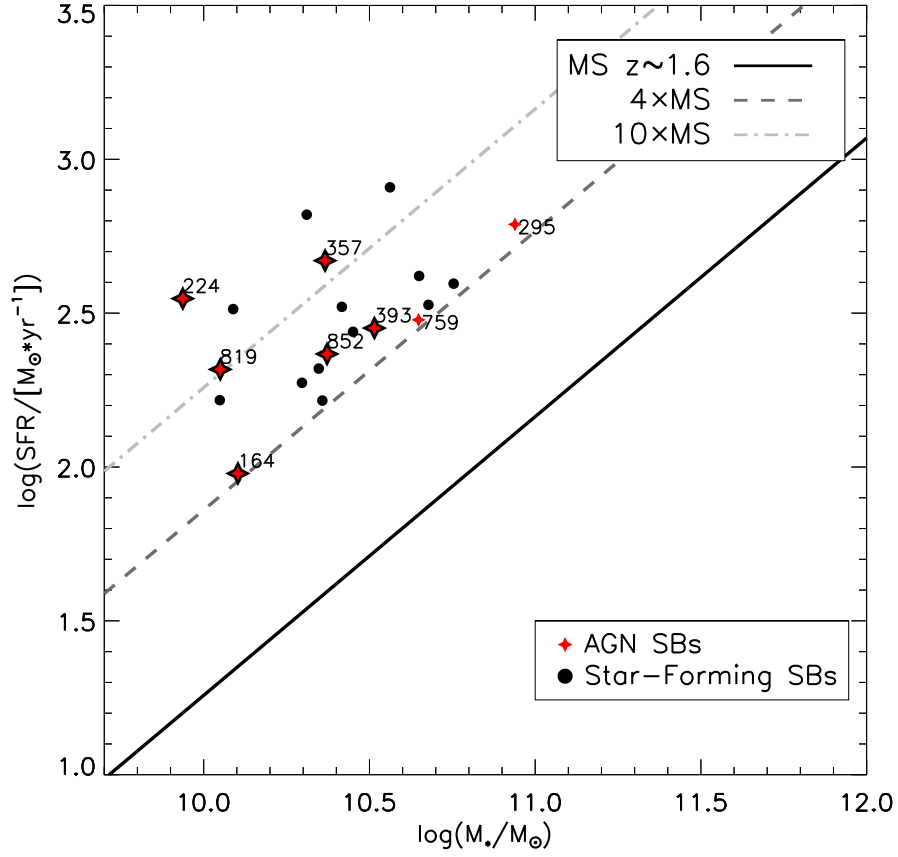


Figure 4.2: SFR vs M_* at $z \sim 1.6$. The red labeled diamonds are the AGN-SBs, while black dots show the star-forming dominated sample discussed in Puglisi et al. (2017). I highlight in black the AGN-dominated SBs with a high-quality spectrum: only these 6 sources are included in the average spectrum shown in Fig. 4.4.

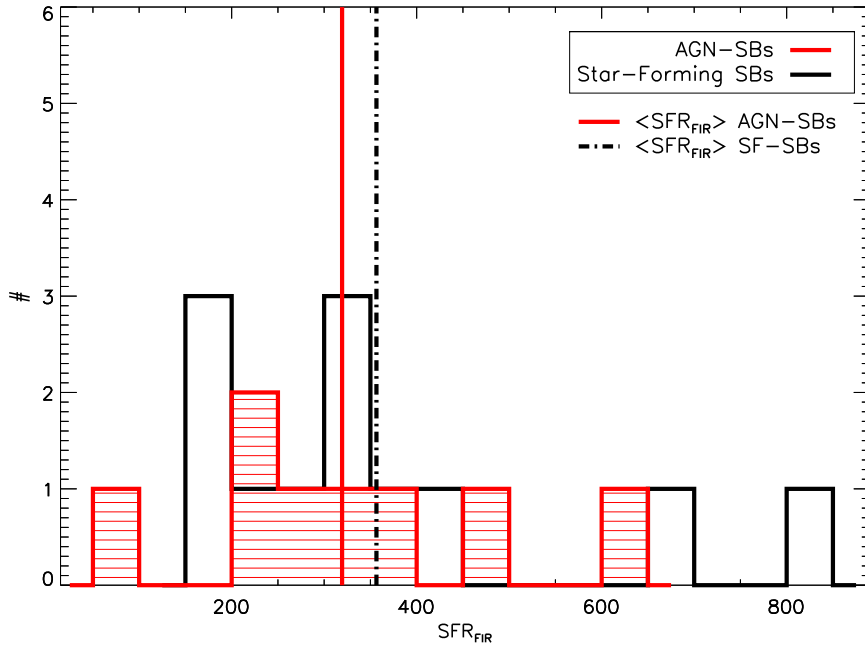


Figure 4.3: Distribution of the SFR inferred from the far-IR emission for the AGN (red hatched histogram) and star-forming starburst (black curve) samples. The average value of each distribution is highlighted with vertical lines.

4.4. OPTICAL MORPHOLOGY FOR THE AGN-STARBURST POPULATION

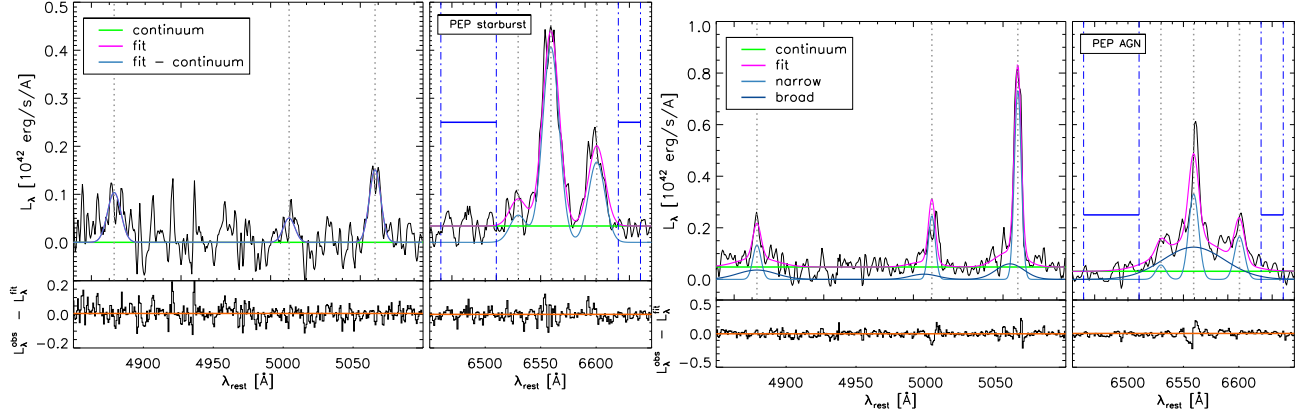


Figure 4.4: Average FMOS spectra of our SB samples at $z \sim 1.6$. *Left:* spectrum of the Star-Forming dominated SBs (Puglisi et al., 2017). *Right:* spectrum of the AGN dominated SBs. Only 6 out of the 8 AGN in the starburst region were included in this spectrum. I highlight the presence of a broad blue shifted component in the AGN spectrum, undetected in the Star-Forming SB one, and a clear outflow signature. I note also the different scales on the y-axis: the AGN-starbursts spectrum extends on a wider dynamic range of L_λ .

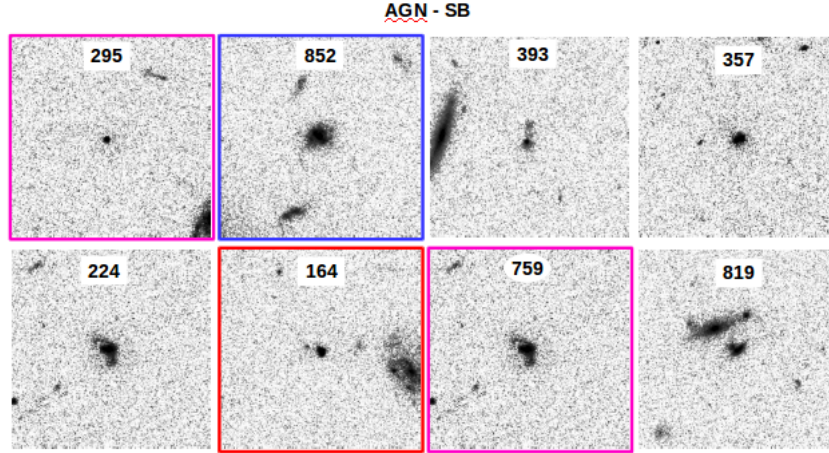


Figure 4.5: HST imaging of the AGN sources in the starburst region at $z \sim 1.6$ observed with FMOS. IDs are reported on top of each cutout.

The HST imaging reveals that nearly all of these AGN are found in interacting/merging systems, as one would expect for starburst sources and in agreement with the idea that galaxy interactions are capable of triggering AGN activity (Silverman et al., 2011). HST-ACS imaging for the star-forming starbursts is shown in Fig. 4.6. By comparing the morphology of the two samples I find that both samples show evidences of interactions but AGN-dominated objects reside in more compact pairs which suggests they are in a more advanced merger stage. This result provides additional hints in support of a causal link between the two samples: I plan to perform a quantitative analysis of the merger stages of both starburst samples, as this quantity provides a tool to probe the starburst-QSO evolutionary sequence (see Veilleux et al., 2009, e.g.).

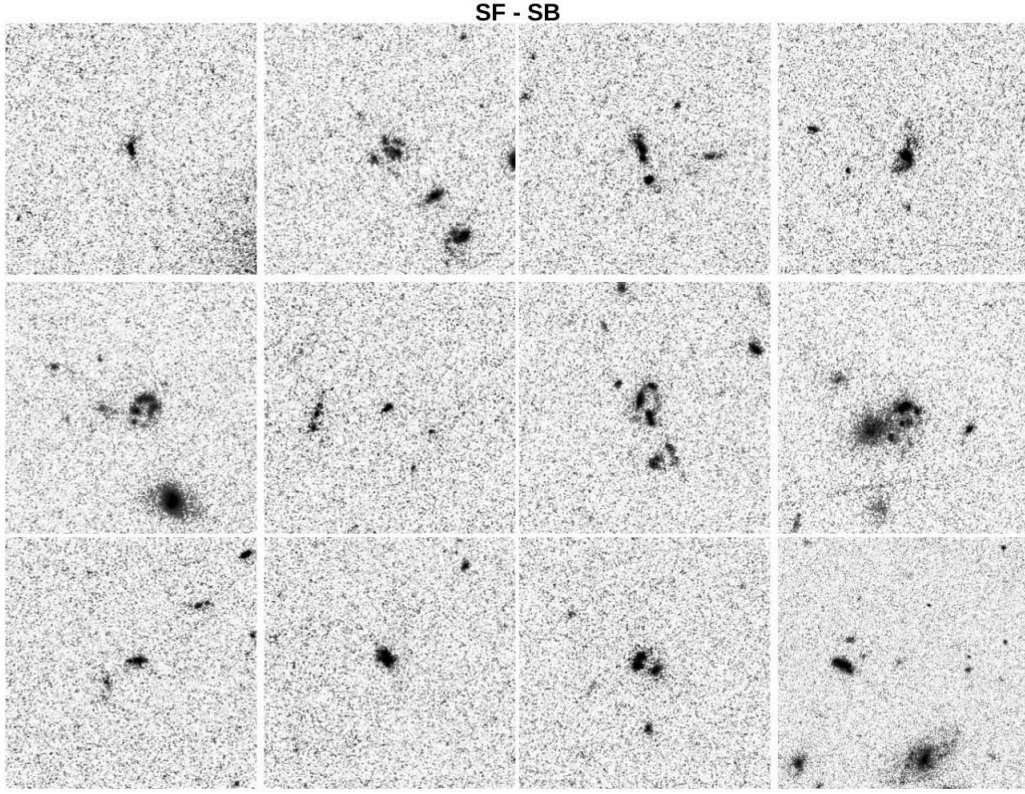


Figure 4.6: HST imaging of the star-forming dominated sources in the starburst region at $z \sim 1.6$ with FMOS- $H\alpha$ detection (Puglisi et al., 2017).

4.4.1 A closer look: zooming on a merger with SINFONI

For source PACS-357, I retrieved SINFONI observations from the ESO archive. These SINFONI observations are performed in Adaptive Optic (AO) mode in the H -band, probing the spectral window around the $H\alpha$ and $[\text{NII}]_{6549,6585}$ emission lines, with a spatial scale of 100 mas/px , corresponding to a spatial scale of $\sim 2 \text{ kpc}$ at the redshift of the source. More details about SINFONI observations and IFU techniques will be given in the next sections. The exposure time of this observation is 40 min thus the SN on the science cube is not suitable to perform a spatially resolved analysis. In addition, this low SN results in a poor sky subtraction and the science cube is heavily contaminated by OH emission lines and cosmic rays. However spatially integrated spectra can still be used for analyzing the system. Fig 4.7 shows (see insets in *upper-left* and *bottom-left* panels) the SINFONI $H\alpha$ line map created with QFitsview selecting manually the wavelength range around the $H\alpha$ emission line on the integrated spectrum. This SINFONI map reveals a compact two system component, with a nuclear separation of the two sub-components $d \sim 0.33''$. The same morphology is observed on the HST imaging (*middle-right* panel). Although this data-cube is not suitable for a proper spatially resolved analysis of the object, the SINFONI observations allow to deblend the two components of this merging system. I obtain in this way two integrated spectra of the two components separately, which are useful for a preliminary study of the system. The *upper-left* and *lower-left* panels show the integrated spectra of these two component (B and A, respectively). These integrated spectra are extracted from the SINFONI cube with QFitsview using pseudo-circular regions with radius of 4 and 2 pixels respectively, highlighted with the green color in the insets. The radius and centroid of these two circular regions was defined by eye using as a reference the HST image of the object.

The emission lines in the integrated spectra of the two merging components were fitted with a procedure analogous to the one described in Sect. 3.4.1 for the FMOS spectra. The redshift of these two components is very similar ($z_A = 1.4848$ and $z_B = 1.4877$) and both redshifts are consistent with the one estimated from the FMOS spectrum ($z_{\text{FMOS}} = 1.48446$).

4.4. OPTICAL MORPHOLOGY FOR THE AGN-STARBURST POPULATION

This confirms that the system is in a merger pair and this is not a by-chance alignment. In addition, the $H\alpha/[NII]_{6585}$ emission line ratio is different with $\log(H\alpha/[NII]_{6585}) = -0.02$ for component A and $\log(H\alpha/[NII]_{6585}) = -0.18$ for component B: component A has an enhanced ratio suggesting an enhanced AGN activity.

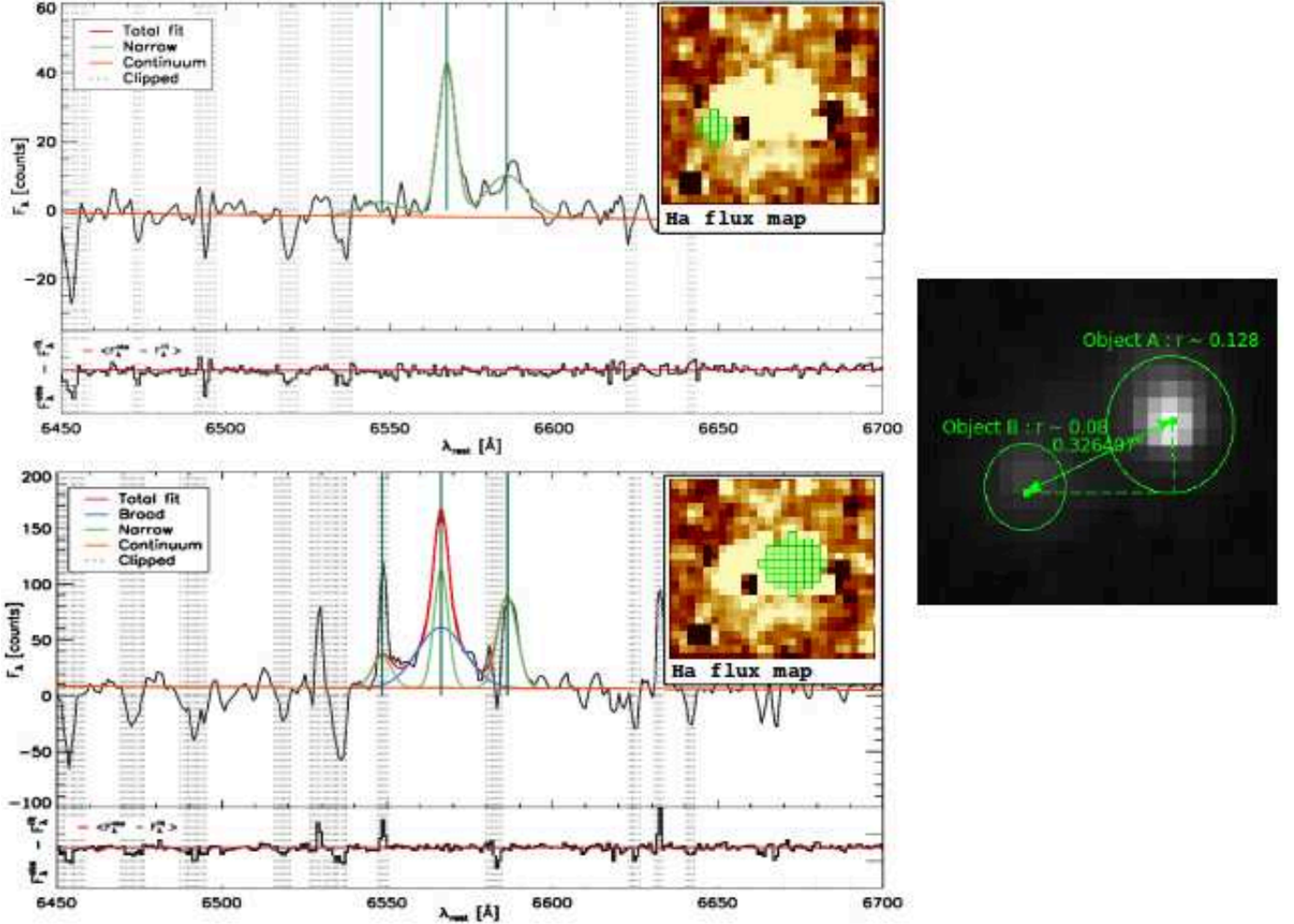


Figure 4.7: The two main panels on the left show the integrated SINFONI spectra for the two components of source PACS-357, one of our AGN in the starburst region undergoing a merger. The integrated spectra are extracted from the SINFONI cube within pseudo-circular apertures having a radius of 4 pixels (component A, *lower-left* panel) and 2 pixels (component B, *upper-left* panels). The insets show the $H\alpha$ map created with QFitsview: light-green pixels indicate the region within which the integrated spectrum was extracted. I report on the right the HST imaging, as a comparison with the SINFONI maps.

These SINFONI archival observations demonstrate the power of IFU techniques in analyzing merging systems. IFU data will enable a more accurate characterization of the merger stage, minimizing the impact of line of sight alignments when classifying interacting pairs. Moreover they allow to overcome aperture effects that may be relevant for fiber-based spectroscopy of extended systems (see discussion in Puglisi et al. 2017). Also, as it will be discussed in the next sections, spatially resolved flux and velocity maps will allow to perform a detailed characterization of the outflowing material, whose presence in this population is revealed from the average spectrum shown in Fig. 4.4.

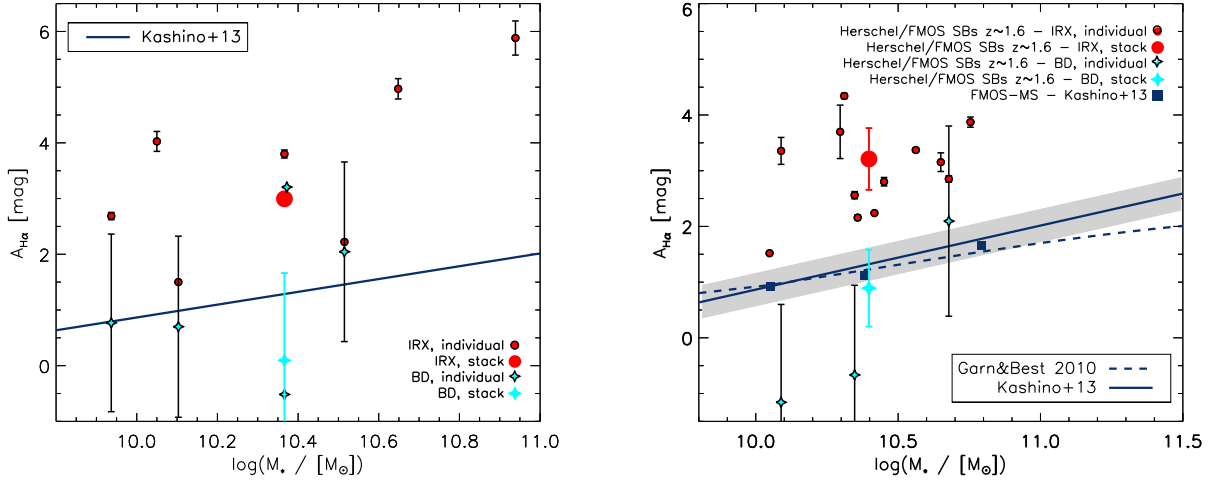


Figure 4.8: *Left:* $H\alpha$ dust attenuation as a function of M_* for $z \sim 1.6$ AGN-dominated starbursts from the BD (cyan) and the IRX (red). The solid line is the $A_{H\alpha}$ versus M_* trend derived by Kashino et al. (2013) for star-forming galaxies on the MS.

Right: Same but for star-forming dominated starbursts (same as Fig. 3.6).

4.5 Dust attenuation properties

If AGN-dominated starbursts are in the phase of removing the dust in the nuclear region through outflows, as their average spectrum of Figure 4.4 seems to suggest, I expect to find differences in their dust attenuation levels with respect to the star-forming starburst population. Measurements of dust attenuation can provide therefore an additional tool for sampling the starburst-QSO sequence. Figure 4.8 shows the dust attenuation at $\lambda_{H\alpha}$ for AGN-dominated starbursts compared with the same quantity computed for the star formation dominated objects. For both samples, measurements from the IRX and the BD are shown. More details about measurements of dust attenuation are given in the introduction of this Thesis, in Sect. 1.1.3 and in Sect. 2.5 of Chap. 2. Estimates of $A_{H\alpha}$ from the IRX are consistent for star-formation and AGN dominated off-MS galaxies, while measurements from the BD are marginally lower in AGN but still consistent within the errorbars. However, the spectrum of the AGN-dominated sample has a lower SN compared to the Star-Formation dominated SB sample and the $H\beta$ emission is marginally detected: additional analysis with higher SN spectra will be required to properly constrain dust attenuation trends. Moreover, the low SN does not enable an accurate decomposition of the broad and narrow components in the emission lines of AGN dominated starbursts, specially for the $H\beta$. A proper line decomposition however, is extremely important to characterize the dust attenuation in the system as the broad and narrow components probe very different spatial scales. The broad $H\alpha$ and $H\beta$ emission lines component probe the BLR, confined within few pc s in the nuclear regions and potentially largely obscured than emission lines arising from wider scales (see Maiolino et al., 2001, for a discussion). Also in this case, higher quality data are needed to properly decompose the emission line components.

Another caveat has to be mentioned here: the calibration of the IRX ratio as a dust attenuation diagnostic assumes that L_{FIR} and $L_{H\alpha}$ both trace the galaxy SFR and that the intrinsic SFR is identical in absence of dust attenuation. The $H\alpha$ emission for AGN-dominated starbursts however seems to be mostly ionized by the AGN (see Fig. 4.1) while L_{FIR} mostly arises from star formation. To properly apply the IRX to AGN-dominated starbursts, an accurate decomposition has to be performed either on the emission lines, to deblend the broad and narrow components of the line, and in the far-IR, to remove the AGN contribution to L_{FIR} (expected to be minor anyway). The poor SN of our average spectrum does not allow to accurately fit a broad component to the $H\alpha$ emission. Therefore, it is not possible at this stage to accurately deblend the broad and narrow components and thus disentangle the line flux arising from the star-formation.

4.6 Discussion, preliminary conclusions and future developments

In the previous sections I described the preliminar analysis on a sample of 8 AGN located above the star-forming MS at $z \sim 1.6$ with $SFR \geq 4 \times SFR_{\text{MS}}$. These AGN were identified mainly from emission lines ratio in the optical through the BPT diagram from a parent sample of *Herschel*-selected MS outliers. The distribution of these AGN in the plane $M_{\star} - SFR$ is statistically similar to the one of the star-forming dominated starbursts, but the SFR for the AGN population is marginally lower than the one of the star-forming sources.

Since the individual spectra of these AGN are heavily impacted by the sky emission, I construct the average spectrum of these AGN to characterize their optical lines profiles. This exercise reveals the presence of a blue-shifted component in the $[\text{OIII}]_{4959,5007}$ emissions, a trace of outflowing gas. The $[\text{OIII}]_{4959,5007}$ traces the gas extended in the NLR of the AGN therefore this outflow can be extended over large scales and it can have an influence on the host system. The presence of this outflow suggests that these AGN are in the phase of expelling dust and gas obscuring the nuclear starburst, i.e. towards the final stages of the starburst-QSO evolutionary sequence. A visual inspection of the HST imaging of these AGN reveals that these objects are hosted in systems with extremely disturbed and/or interacting morphologies and, in most cases, more compact than the star-forming counterpart. This may further indicate that AGN are hosted in galaxies at late merger stages, which also corresponds to the blow-out phase in the Sanders et al. (1988) merger sequence. Measurements of the dust attenuation can give further indications on the evolutionary stage of these objects, as discussed for example in Ishibashi & Fabian (2016). These simulations show that feedback can disrupt dense gas in the optically thick regime and that the AGN can efficiently remove the obscuring dust cocoon. Since the feedback processes can progressively reduce the amount of dust around the nuclear regions, the attenuation can allow to define the evolutionary stage of our sources. If these objects are in a blow-out phase, I would expect to measure a lower attenuation with respect to the star-forming starburst sources. I therefore estimate the dust attenuation on this sample as performed for the parent sample of star-forming starbursts. The result of this test is that AGN have, on average, an attenuation similar to what measured on starbursts. However, measurements from the individual spectra show a substantial scatter and seem to disagree with the result from the average spectrum. This mismatch can be produced by object-by-object variations, due to the fact that each system is in a slightly different stage of the sequence: some galaxies could be immediately before the expulsion stage, thus being still heavily obscured, while others have already removed most of dust in the nuclear regions thus resulting less affected by dust attenuation. Individual measurements would be required to infer the attenuation of each object. Furthermore, it is still not clear how to interpret these dust attenuation measurements in the context of the Puglisi et al. (2017) results. In fact, I would expect in general that the absolute attenuation is lower in AGN dominated sources. On the other side, starburst galaxies host optically thick cores which prevent to measure dust attenuation from the optical (Puglisi et al., 2017). If AGN are clearing out these optically thick dust cocoons, dust attenuation can be fully recovered through rest-optical measurements: counter-intuitively, dust attenuation in AGN-hosts might then appear higher than for the starbursts.

To further complicate the general interpretation, the FMOS spectra have a low SN and do not allow to estimate crucial quantities as the outflow mass (for which a good quality detection of the blue-shifted emission on the $[\text{OIII}]_{5007}$ is required) nor the AGN bolometric luminosity on each source (from the $[\text{OIII}]_{5007}$ emission). Furthermore, these observations do not allow us to robustly estimate the attenuation in each source (individual $\text{H}\beta$ detections are highly uncertain) or to distinguish broad and narrow components on each emission line. Individual spectra with high SN are required to precisely constrain the properties of these sources and probe the evolutionary sequence. Finally, FMOS fiber-based spectroscopy does not allow a characterization of the outflow geometry but this information is essential for a proper estimate of the outflow energetic and thus to evaluate its impact on the surrounding system. For a complete characterization of outflows phenomena, spatially resolved spectra are required: I will deal with this issue in the following chapter.

Chapter 5

The SUPER survey and the role of IFS in outflow studies

Single slit or fiber spectroscopic techniques are a powerful tool for studying the properties of star-forming galaxies and embedded AGN. However, they lack of the spatial information, which is crucial to properly assess their extended properties. Integral field spectroscopy is the ultimate tool for assessing the role of the central AGN in the galaxy star formation, as it allows to study the extension and geometry of AGN-driven winds and their interaction with the star-forming regions of the galaxy.

In this chapter I will introduce the integral field techniques and their importance for galaxy evolution studies. I will present the SUPER survey, an ongoing large program to detect and study AGN-driven outflows at $z \sim 2$. I will introduce the observation strategy and data reduction. I will then demonstrate how to take advantage of these observations for studying AGN outflows by presenting the analysis on a test case. I will then discuss the future projects I intend to perform once SUPER observations will be completed.

5.1 Integral Field Spectroscopy

So far in this Thesis I explored different spectroscopic techniques to study several star-forming galaxy properties. Spectral information has been a key tool for deriving accurate estimates of redshifts, SFR, dust attenuation, metallicity and the dominant ionizing source of the sample analyzed. However, in the studies presented in the previous chapter an important ingredient is missing: the spatial information. Either in Chapter 2 and 3 the results are based on mono-dimensional spectroscopy, which samples only small portions of the object. This causes large flux losses because of the light of the source that falls outside the slit and implies that the observed spectrum gives details on restricted regions which might be not representative of the whole object (Belfiore et al., 2015, e.g.).

To overcome the limitations of 1D spectroscopy, it is possible to take advantage of Integral Field Spectroscopy (IFS) which allows to obtain 3-dimensional spectroscopy i.e. to obtain in a single exposure the spectrum of the full region observed. The main difference of Integral Field Units (IFU) with respect to traditional spectrographs is that multiple apertures, instead of a single one, are used to disperse the light from the targeted object. These apertures collect the light from different parts of the source. The collected light is sent to a grism where it is split to produce the actual spectra. The 3D spectrum is then reconstructed during the data reduction. The final product of IFS observations is a *cube* which contains in x and y directions the spatial information on the source plane and has along the z axis the wavelength vector.

5.1. INTEGRAL FIELD SPECTROSCOPY

To obtain a 3D spectrum, three main techniques exist that mainly differentiate for the approach used to collect the light from the source:

- **Lenslet array:** A microlens array splits and focuses the input image into a small dot. Then the light is dispersed directly into the CCD by the spectrograph. An instrument which uses this technology is, for example, SAURON
- **Fibers:** The input image is formed at the front surface of a bundle of optical fibers. The field of view is then reformatted into one or more pseudo-slits from where the light is directed to the spectrograph and thence on to the CCD. GMOS-IFU at Gemini uses this technique.
- **Image-slicer:** The input image is formed on a mirror that is segmented in horizontal sections. This mirror divides the image in slices and reflects each slice in slightly different directions. A second segmented mirror re-align these slices to be directed in the slit of the spectrograph. This system is especially suitable for the infrared as it uses inherently achromatic mirrors. It is also compact so that it can easily be contained and cooled to cryogenic temperatures. SINFONI at VLT or NIFS at Gemini take advantage of this configuration.

A schematic view of these techniques is shown in Fig. 5.1. For more details about IFU spectroscopy see (Westmoquette et al., 2009a) and <http://ifs.wikidot.com/da-extract>.

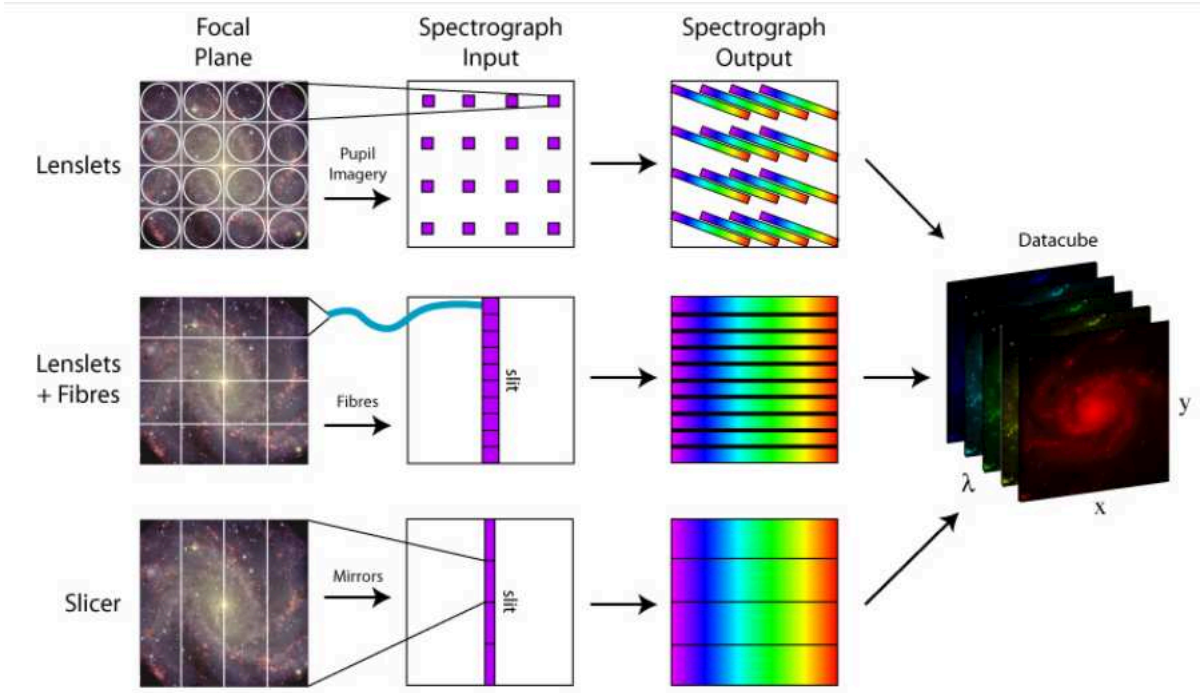


Figure 5.1: Schematic view of the different IFU techniques. For more details see the main text. From Westmoquette et al. (2009a)

IFU techniques are becoming progressively more popular in Galaxy Evolution studies as they provide a comprehensive overview of the extended properties of galaxies. As such, IFU observations enable key studies as metallicity gradient (Cresci et al., 2010; Swinbank et al., 2012; Troncoso et al., 2014; Stott et al., 2014; Wuyts et al., 2016a) spatially resolved kinematic (Gnerucci et al., 2011; Sobral et al., 2013; Tacchella et al., 2015; Wuyts et al., 2016b; Turner et al., 2017; Harrison et al., 2017; Genzel et al., 2017), spatially resolved dust attenuation patterns (Tacchella et al., 2017), to cite a few.

Most relevant for the discussion presented in this Chapter, is the study of galaxy-wide outflows. IFU techniques provide the ultimate way to probe the outflow geometry and extension, the key parameters to properly define the outflow energetic (see Introduction of this Thesis and references therein). In addition, IFU techniques can be used to sample the star-formation episodes in the host: this study combined with spatially resolved analysis of the outflow provides details on the interplay between the two phenomena and is an observational test of the action of the outflow on the host star-formation. IFU techniques have proven to be successful in studying ionized outflows either in the local Universe (Liu et al., 2014; Cresci et al., 2015b; Husemann et al., 2016) and at high redshift (Cano-Díaz et al., 2012; Harrison et al., 2014; Cresci et al., 2015a; Perna et al., 2015; Brusa et al., 2016; Kakkad et al., 2016): these pioneering studies have paved the way for a more complete census of the AGN-outflow activity at the peak of BH and SF activity in the Universe which will be presented in the following sections of this chapter.

5.2 The SUPER survey

The Survey for Unveiling the Physics and the Effect of Radiative feedback (SUPER) is an ongoing Large Program with SINFONI (Eisenhauer et al., 2003), aimed to study AGN-driven outflow at $z \sim 2$, corresponding to the peak of Black Hole Accretion Rate and SFR density of the Universe (Madau & Dickinson, 2014, see also Chap. 1.3). At around $z \sim 2$ any outflow process driven by an AGN is expected to be more efficient because AGN activity itself is at his maximum; moreover, at these epochs galaxies were experiencing a period of maximum $M_\star$ growth via star-formation and the effect of the outflow are expected to have a major impact in quenching this process.

The SUPER survey takes advantage of the Adaptive Optics capabilities of SINFONI to map the outflow and star formation in a sample of ~ 40 X-ray selected AGN equally divided in type-1 and type-2 AGN. In type-1 AGN the BLR is observed, enabling to study the AGN physics in the vicinity of the BH and link it to the outflow properties. On the other hand, the BLR is obscured in type-2 AGN allowing to study in details the host galaxy properties. The targets are selected in various extra-galactic fields (COSMOS, XMM-XXL, CDFS, STRIPE82) where a good multi-wavelength coverage is available. The ancillary photometry allows us to obtain a high quality characterization of the broad-band SED of the target and, in particular, an accurate measurement of $M_\star$ and SFR (Circosta et al. 2017, in preparation). The target selection favors, where possible, sources with a *Herschel* counterpart. *Herschel* data are in fact essential to obtain a dust-unbiased integrated estimate of the host SFR . Also, the AGN contribution to the far-IR emission is minor with respect to the SFR (Rodighiero et al., 2011, e.g.) so that the long-wavelength regimes gives the most robust estimate of the integrated SFR.

With respect to the outflow properties the targets are selected “blindly”, meaning that they are not individuated as sources with already known on-going outflows neither with high chances of being caught in an outflowing phase (see Brusa et al., 2015; Kakkad et al., 2016, for a discussion). Minimizing the selection bias is a fundamental step if one wants to understand if outflows are truly ubiquitous, what are the main drivers of outflow activity and how outflow processes are related to AGN and host-galaxy activity (Fiore et al., 2017). The sample is designed instead to cover a wide range of AGN properties. In particular our targets span a broad range in AGN bolometric luminosity L_{bol} (see left panel in Fig. 5.2) and the Eddington ratio (λ_{Edd} , see right panel in Fig. 5.2). This will allow to measure the occurrence of strong winds as a function of AGN properties and how the wind energetic is linked to the central BH activity.

In addition, since our interest is to study how these winds impact the life-cycle of a galaxy, the AGN hosts are selected to cover a sufficiently broad range in $M_\star$ and SFR, as shown in Fig. 5.3. The outflow properties will be then investigated also as a function of galaxy properties to understand how the outflow affects the star formation episodes in the host. Moreover SUPER will allow to reconstruct the relative outflow-star formation geometry, an exercise which is necessary to understand whether and how one phenomenon is impacting the other. Hints from sparse cases, either in the local Universe (Cresci et al., 2015b) and at high redshift (Cano-Díaz et al., 2012; Cresci et al., 2015a) show that outflow and star formation are spatially anti-correlated suggesting that the AGN is preventing stars to form in the direction of the outflow.

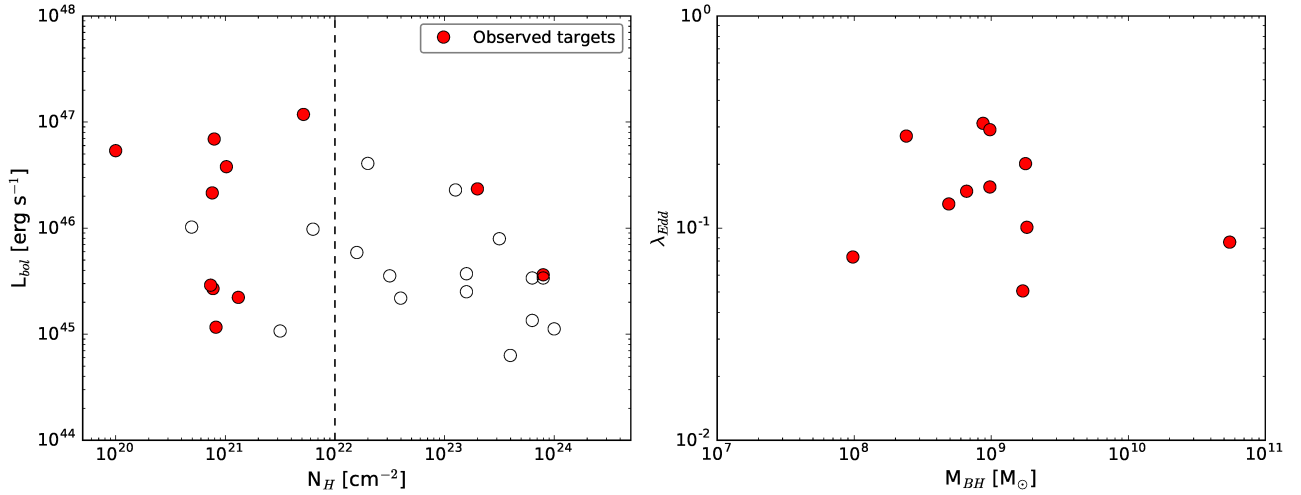


Figure 5.2: *Left:* Bolometric AGN luminosity versus column density of the SUPER targets. The dashed line highlight the threshold of $N_{\text{H}} = 10^{22} \text{ cm}^{-2}$, above which AGN are classified as Type-2. *Right:* Eddington ratio as a function of Black Hole mass for the Type-1 AGN.

To define if these outflows are rare episodes or rather represent a common process through which galaxies may stop to form stars larger statistics is required. Some studies show also that AGN can play a positive feedback role, triggering episodes of star formation at the edge of the outflow because of gas compression (Cresci et al., 2015b,a) or within the outflow itself (Maiolino et al., 2017). SUPER will allow to establish the relative importance of positive and negative feedback from the AGN on the host galaxy.

The combination of a blind selection and of IFU observations with high spatial resolution are the major step forward of this survey with respect to previous programs, and are the key ingredient for unveiling the interplay between the outflow-driven AGN and its host. Many studies report an outflow detection, confirming that outflows are a common activity for AGN but the proof that this activity is affecting the galaxy is still lacking in most cases. As already discussed, two ingredients are required for understanding which effect is perceived by the surrounding galaxy: the outflow energetic and its extension. To be able to affect the galaxy ISM, the outflow has to be sufficiently extended to reach a conspicuous portion of the galaxy: the AGN has an extension of few parsecs while the galaxy has a size of the order of some kilo-parsecs thus the wind has to cover at least two orders of magnitudes of distance. Furthermore its power has to be sufficient to overcome the gravitational potential of the host to properly expel the gas from it.

A careful analysis of the outflow geometry and energetic requires to take into account the *beam smearing* effect which is the smearing of the signal from a point source (as the BLR emission from the AGN is) by the atmospheric seeing. The beam smearing causes a correlation between distant spaxels because of the flux that leaks from the wing of the smeared Point Spread Function (PSF). This effect can lead to a substantial overestimate of the outflow energy and geometry (Husemann et al., 2016) thus has to be taken into account and removed for an accurate investigation of the phenomenon. The beam smearing problem is minimized in SUPER AO-assisted observations as adaptive optics reduces the extension of the PSF but still affects the observations and has to be removed. I will remove the beam smearing by modeling the seeing PSF and deblending it from the emission of the object. The seeing PSF is sampled by the BLR emission itself in type-1 AGN; in type-2 AGN a standard star will be used instead to measure the seeing PSF.

To summarize, the general goals of SUPER are threefold: first, studying the outflows demography and their geometry and energetic, taking advantage of the AO capabilities of SINFONI; second, understanding how these outflow properties are related to AGN parameters (L_{bol} , λ_{Edd} , M_{BH}); finally, understanding if these outflow are actually capable to affect the star formation in the host and in which way (positive or negative feedback).

To fully understand the impact of the outflow on the host galaxy it is necessary to study its features as a function of the host galaxy integrated properties. In the previous chapters of this Thesis I showed that the galaxy position with respect of the MS is an important reference system (see Sect. 1.2 and references therein). As broadly discussed, the position of a galaxy along the MS sequence sets its evolutionary stage and correlates with other galaxy parameters like the dust content, the metallicity or the gas fraction. In addition, the few outliers from the MS have different features probably driven by the extreme, merger-driven, SFRs (see Sect. 1.2.2 in the Introduction and Chap. 3). Galaxy ISM conditions are varying across and above the MS (see Gao et al. 2001; Juneau et al. 2009; Farrah et al. 2013 for studies in the nearby Universe, Sturm et al. 2010; Danielson et al. 2011; Puglisi et al. 2017; Wardlow et al. 2017 at high redshift). Reasonably, the effect of the wind that blows in starburst systems will be different than the same wind occurring in a “quiet” star-forming galaxy sitting on the MS. For example, the large dust concentrations in starbursts can likely favor the expulsion of material, because of the efficient coupling with the radiation (Ishibashi & Fabian, 2016), but high-density gas clouds may feel less the effects of the wind (Gabor & Bournaud, 2014). Other than constraining the outflowing gas conditions, which determine the efficiency through which the wind can propagate (Perna et al., 2015), it is thus important to define the condition of the host ISM, as the density of the medium affects the final impact of the outflow on the system. Studying the properties of AGN driven outflows in host galaxies with different offsets with respect of the MS can allow to shed light on the interplay between outflow and host in different galaxy environments. Studies of the outflow occurrence and energy as a function of the MS-position have been performed in the local Universe showing that outflows appear to be more common when moving off from the MS towards the starburst region but in star-forming galaxies (Cicone et al., 2016), thus suggesting star formation as the main driver for the outflow activity. A cleaner classification on the same sample however, shows that galaxies exhibiting outflows are rather composite systems hosting an AGN which is powering the outflow (Concas et al., 2017). Therefore, these studies confirm the important role of the central engine in driving galactic winds. Analysis in the nearby Universe are however not sufficient to understand in-depth the galaxy-AGN interplay as both star-formation and AGN occur at moderate-low rate in local systems. Outflows at low- z have a minor impact on the life of the galaxy. Furthermore, the ISM conditions of galaxies are fairly evolving with redshift (see Kashino et al., 2017a, and references therein) and distant galaxies appear to have a higher electron density in HII regions. Star-forming galaxies also have progressively increasing gas fractions which, at high- z , lead to the formation of star-forming clumps. It is reasonable to believe that, in parallel, the impact of an AGN-driven outflow will evolve with redshift. As such, local studies are not sufficient to properly interpret high- z observations, where instead the bulk of AGN and Star Forming activity are concentrated.

Moreover, the statistical studies presented in Cicone et al. (2016) and Concas et al. (2017) are useful to unveil average trends in the population but do not allow to study the details of the interaction. A promising step forward will be allowed by SUPER observations. These observations will sample a wide region in the $M_{\star} - SFR$ plane thus allowing to investigate in details from spatially resolved spectroscopy the properties of the outflow as a function of the position of the host with respect the MS itself. In particular, these observations will enable a study of the outflow as a function of the MS offset, i.e. the starburstiness, to trace the dependence of the outflow properties with respect to the galaxy $sSFR$ up to the starburst region. For this analysis the best candidates are the type-2 AGN in the SUPER sample, where the emission from the BLR is strongly obscured by the AGN torus and does not overshadow the host galaxy, enabling an accurate study of it. These targets are intrinsically faint so that they require exposures with long integration times. SUPER observations are in a preliminary stage and do not allow, at present, to reach the SN required for this challenging analysis. Thus, this study will be performed once the full observations will be completed.

In the remaining of this chapter I will describe the SUPER observations and data reduction technique and I will then focus on the analysis of one target as a test case. For this target I will present the spectral analysis, i.e. the integrated spectrum extraction, the line fitting, the emission line maps creation and a non-parametric analysis of the [OIII]_{4959,5007} line profiles. Finally, I will briefly discuss the outflow parameters computation before presenting the summary.

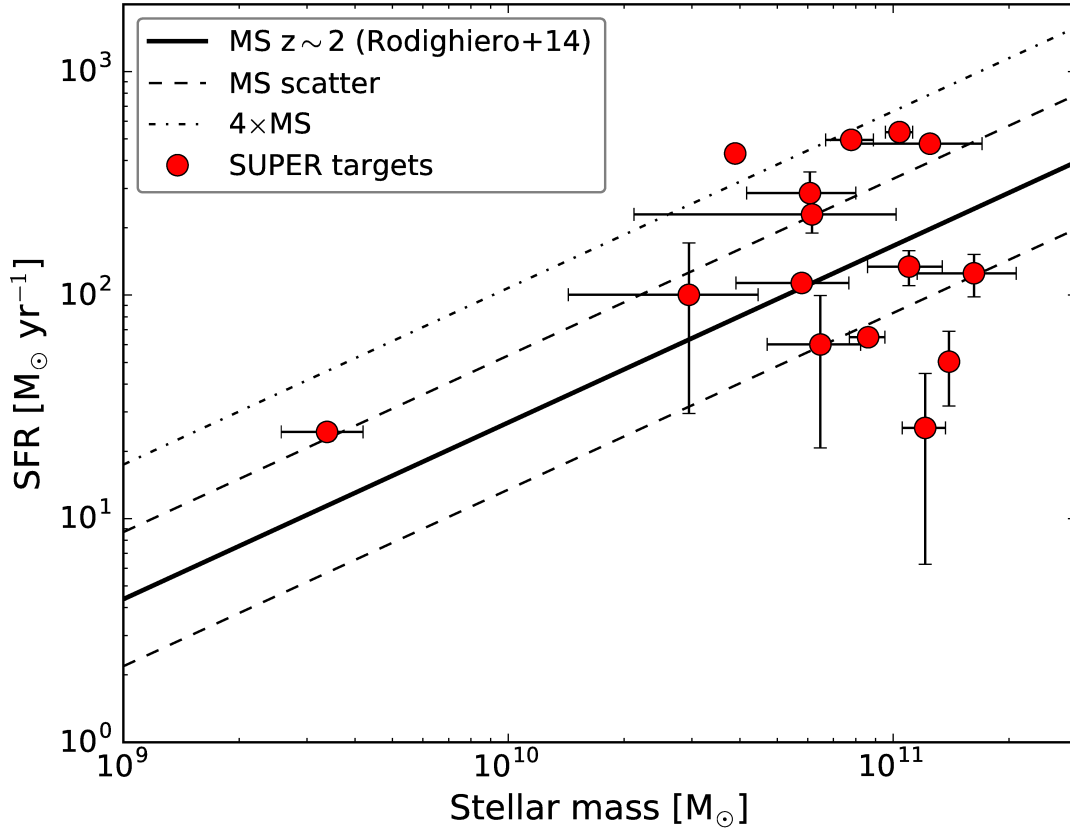


Figure 5.3: SFR vs M_* for the SUPER targets in COSMOS, i.e. the sources with reliable estimates of stellar masses and SFRs. The solid line highlights the position of the $z \sim 2$ MS, as derived by Rodighiero et al. (2014), while the dashed and dot-dashed lines indicate the scatter and the $4\times$ MS locus respectively.

5.2.1 Observations and data reduction

The immediate aim of SUPER observations is to detect outflowing material in the ionized phase on galaxy scale. To this purpose, SUPER observations are designed to observe the $[\text{OIII}]_{5007}$ emission line in our targets, as this line traces the ionized gas from the NLR individuating material extended on $\sim kpc$ scales. SUPER observations to detect this emission line are carried out using the *H-band* grating that covers a wavelength range $\lambda_{\text{rest}} \in [1.47 - 1.88] \mu\text{m}$. SINFONI *H-band* observations allow to detect, in addition to the $[\text{OIII}]_{5007}$ emission, the $\text{H}\beta$ line from which M_{BH} can be estimated. The spectral resolution of this grating $R \sim 3000$ is sufficient to resolve the $[\text{OIII}]_{4960,5007}$ and $\text{H}\beta$ emission lines, that can be extremely broad in type-1 AGN.

The other key feature in SUPER observations is the observation of the $\text{H}\alpha$ emission line which allows to study the spatially resolved star-formation in the host. Although potentially contaminated by the AGN emission, its narrow component traces the star-formation episodes in the host in a time-scale of $t \sim 20 \text{ Myr}$ comparable to the typical AGN duty cycle. To detect the $\text{H}\alpha$ emission SINFONI observations with the *K-band* grating are used, sampling the wavelength range $\lambda_{\text{rest}} \in [1.9 - 2.4] \mu\text{m}$ with a spectral resolution of $R \sim 4000$. *K-band* spectroscopy also covers the wavelength range around the $[\text{NII}]_{6549,6583}$ lines and the $[\text{SII}]_{6717,6732}$ doublet, which may be used to trace the ionizing source (i.e. star-formation, AGN or shocks). The $[\text{SII}]_{6717,6732}$ doublet gives also an estimate of the electron density (Sanders et al., 2016; Kashino et al., 2017a, and references therein) which is an essential ingredient to properly measure the mass outflow rate (Perna et al., 2015).

SINFONI observations in both *H* and *K* band are performed using the 100 mas/px scale, corresponding to a physical scale of $\sim 1 kpc$ at $z \sim 2$. To obtain high spatial resolution 3D spectroscopy, SINFONI is used in AO mode with a Laser Guide Star in most cases because of the lack of bright Natural Guide Stars in the vicinity of our targets. During the observation, each object is dithered across the SINFONI field of view: this allow us to sample the sky without losing observing time to obtain sky frames.

A standard star, bright in the near-IR, is typically observed for telluric and PSF correction before and after each science observing block. According to the observing strategy, all the objects are observed initially for 1 *hour* exposure, to obtain a line detection at least in the integrated spectrum and re-derive a robust estimate of the AGN luminosity from the emission line fluxes. The total exposure time will be re-adjusted accordingly on each source optimizing the observing time available.

The data-cubes are reduced with the ESO-SINFONI pipeline (version 3.0.0, Modigliani et al., 2007). This pipeline corrects the cubes for the non-uniform response of the detector, it corrects the image for distortions induced by the optics, it calibrates the spaxels in wavelength and finally it reconstruct the science cubes. The sky subtraction is performed through the external `IDL` recipe by Davies (2007). This recipe is applied to each of the 6 science cubes, considering the adjacent science observation as a sky frame. Finally, individual exposures are combined within the ESO pipeline to produce the final science cube. A similar procedure is applied to the telluric standard star. The spectrum of this telluric standard star is then used to correct for atmospheric absorption lines and to perform the flux calibration in the science observation. The telluric star spectrum is then treated externally using the `SPLIT` task in IRAF to remove the intrinsic absorption lines of the star and obtain a spectrum in which only the atmospheric absorption lines are present. This spectrum is divided by a black body spectrum with the same effective temperature of the star and then normalized to obtain the response function. This response function is divided afterwards to the telluric cube (i.e. spaxel by spaxel) and the 1D spectrum of the telluric star is finally extracted from its normalized cube using QFitsview. The science cube is then divided by the 1D-spectrum of the telluric star to simultaneously correct for the atmospheric absorption and perform a flux calibration.

5.2.2 A test case

As discussed in the previous sections, SUPER observations are at a preliminary stage and data-cubes with 1 *hour* of integration time are available for only half of the sample (see also Fig. 5.2). The scientific analysis introduced in Sect. 5.2 cannot be performed with the current data-set, as it requires observations of type-2 AGN i.e. faint sources for which long integration times are needed. This analysis will be presented in a future work once the full SUPER observations will be completed.

To show an example of the data analysis that I will perform with the complete data-set and demonstrate the capabilities of this survey for unveiling the properties of AGN-driven outflows, in the following of this subsection I will present as a test case the analysis performed on XN_115_23, one of the brightest SUPER target observed so far. Observations and data-reduction for this source were performed as described above for the entire program. The exposure times of the OB presented here for XN_115_23 is 1 *hour* in both bands, with these OBs having an air mass of 1.5. The average seeing during these observations varies between 0.55 and 1.2 *arcsecs*, but below ≤ 0.6 for most of the observation. SINFONI AO assisted observations however allow to reach a spatial resolution of ~ 0.3 *arcsecs*, as derived by measuring the full width half maximum of the telluric star observed before and after the science cubes.

Data analysis: Gaussian fit to the emission lines

The reduced science cube (see Sect. 5.2.1) is visually inspected using QFitsview, to assess the data quality and also determine the extension of the object. With QFitsview I extract from the science cube the spatially-integrated spectrum of the object using a pseudo-circular region whose radius has been defined to maximize the SN and contemporarily enclose the highest amount of light from the science object. The integrate spectra of the object are shown in Figure 5.4. Panel A shows the *H*-band spectrum, with the $H\beta$ and $[\text{OIII}]_{4959,5007}$ emission lines. Panel B shows the *K*-band one with the $H\alpha$ line and the $[\text{NII}]_{6583}$ emission, blended with the broad $H\alpha$ emission.

5.2. THE SUPER SURVEY

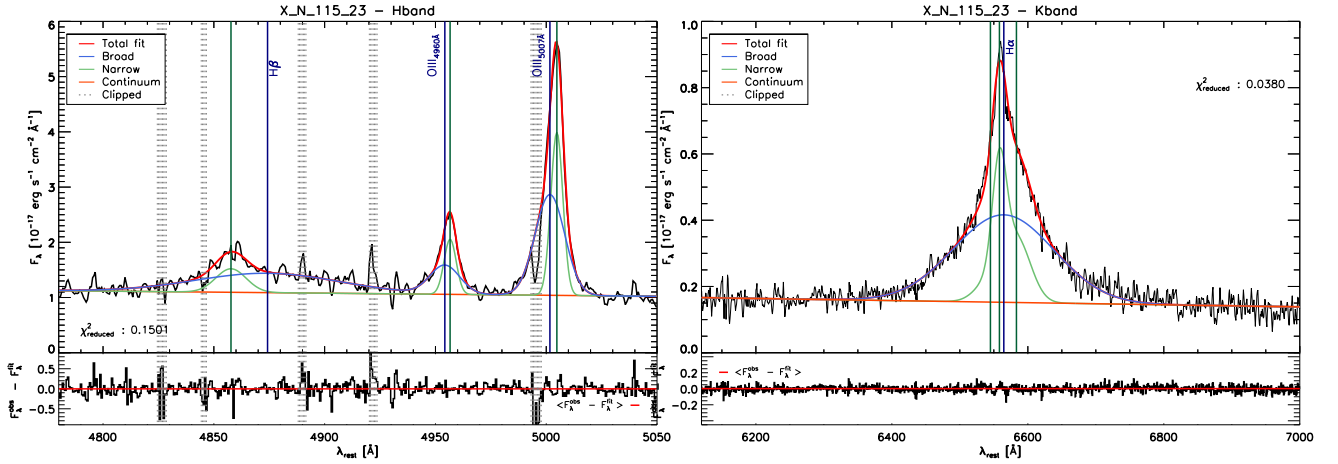


Figure 5.4: Integrated spectra for XN_115_23 in *H* and *K*-band (left and right panel respectively). The two spectra are extracted within a pseudo-circular aperture of 3 and 5 *pixels* radius for *H* and *K*-band. In both panels, the fit to the emission lines and the residuals are also plotted (bottom panels). For details about the emission line fitting see the main text.

Emission lines on the integrated spectrum are fitted using an *IDL*-based tool which takes advantage of the *MPFITFUN* routine (Markwardt, 2009). In particular, in the *H*-band spectrum I fit a broad and narrow component to the $H\beta$ and $[OIII]_{4959,5007}$ emission lines. In addition, the widths of both narrow and broad components of the $[OIII]_{4959,5007}$ features are tied together to improve the quality of the fit. Also, the ratio $[OIII]_{5007}/[OIII]_{4959}$ is fixed to the theoretical ratio of 2.96. The level of the underlying continuum is evaluated in a wavelength range free of emission lines and it has been removed before performing the emission line fit. A similar procedure is used to fit the $H\alpha$ and $[NII]$ emissions in the *K*-band spectrum. The routine is designed to fit the $[NII]_{6549+6583}$ doublet in the *K*-band spectrum. However, these lines are blended with the $H\alpha$ emission. As such, no solution can be obtained for the $[NII]_{6549}$ emission and the $[NII]_{6583}$ parameters are highly degenerate. Therefore, the results for the $[NII]$ doublet should not be considered reliable at this stage.

By fitting the integrated spectrum of the source I obtain quantitative information on the emission lines width and their integrated fluxes: these information are then fed to the spaxel-by-spaxel fitting routine in order to create the 3D maps of flux and velocity. Tables 5.1 and 5.2 list the main emission line parameters derived from the fit of the integrated spectra shown in Fig. 5.4.

I clearly detect in the integrated *H*-band a broad component in the $[OIII]_{4959,5007}$ emission lines, which traces the ionized outflow.

Table 5.1: Emission line parameters as derived from the Gaussian fit to the integrated spectra of XN_115_23 shown in Fig. 5.4. Column one specifies the emission line component for which I report the centroid position (column 2), the integrated flux (column 3) and the line width (column 4).

Line —	$\lambda_0 \pm 1\sigma$ [Å]	Flux $\pm 1\sigma$ [$10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$]	Line width $\pm 1\sigma$ [km s^{-1}]
Broad $H\beta$	4874.2 ± 8.8	28.5 ± 10.8	2004.2 ± 558.8
Narrow $H\beta$	4857.7 ± 2.1	7.3 ± 3.5	421.6 ± 164.6
Broad $[OIII]_{5007}$	5001.7 ± 0.9	30.6 ± 6.7	400.9 ± 46.4
Narrow $[OIII]_{5007}$	5004.8 ± 0.3	20.2 ± 5.7	163.6 ± 22.8
Broad $H\alpha$	6564.6 ± 7.0	48.8 ± 7.9	3371.5 ± 515.5
Narrow $H\alpha$	6558.2 ± 2.0	8.1 ± 2.1	462.6 ± 102.2
$[NII]_{6583}$	6583.2 ± 0.0	9.9 ± 6.3	950.3 ± 432.1

Table 5.2: Offset in velocity space of the emission line broad components with respect to the narrow ones as measured on the integrated spectra of Fig. 5.4 through the Gaussian fit.

Line	Δv [km s^{-1}]
Broad H β	1018.2
Broad [OIII] $_{5007}$	-187.3
Broad H α	295.9

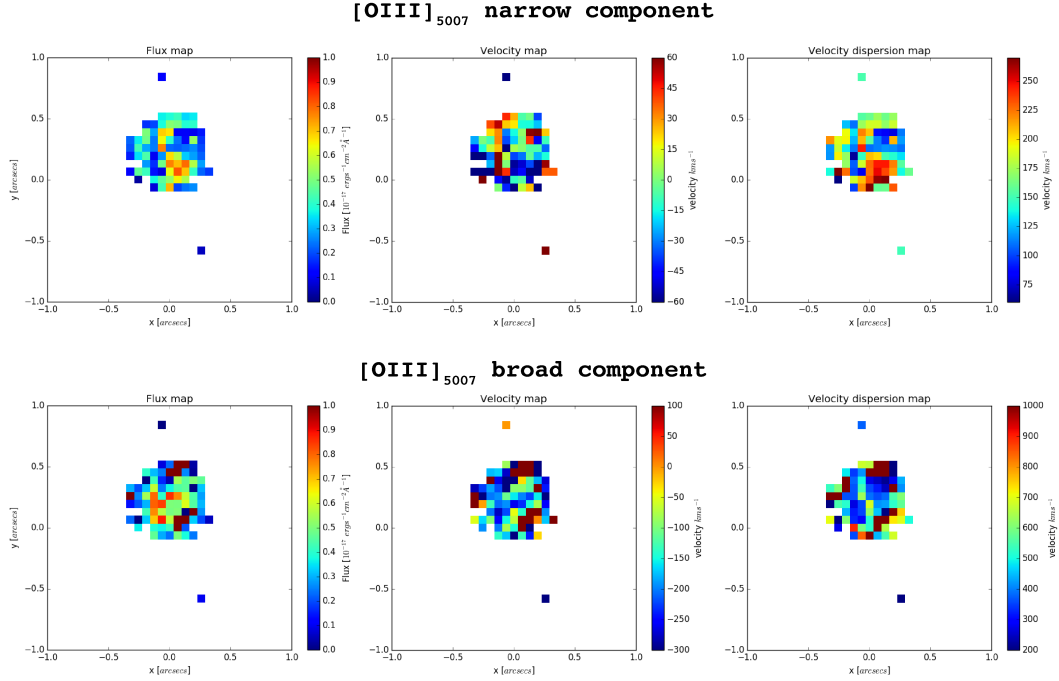


Figure 5.5: From left to right: flux, velocity and velocity dispersion maps of the [OIII] $_{5007}$ emission line for the target X_N_115_23. The upper panel shows the maps for the narrow component, while in the bottom panel the maps are produced for the blue-shifted component detected in the integrated spectrum shown in left panel of Fig. 5.4.

To create the maps, I fit the spectrum in each spaxel using a procedure similar to the one used for individual spaxels in the science cube. To avoid regions containing no signal from the source, I apply a SN cut for the fitting procedure, and all the spaxels with $SN \leq 7$ in the [OIII] $_{5007}$ emission are not fitted by our routine. A co-adding of nearby spaxels might be implemented to improve the SN across the field-of-view specially the outermost regions of the object, where the emission is fading. To improve the SN of the maps, I thus re-bin the cube with a 2×2 grid using QFITSVIEW. However, this procedure causes a downgrade of spatial resolution and does not improve dramatically the SN of the final science cube. I thus decide to not apply any re-binning for creating our maps. Figure 5.5 shows the results of the spatially resolved fit on the [OIII] $_{5007}$ emission line in its narrow (*upper row*) and broad component (*bottom row*). The broad [OIII] $_{5007}$ component tracing outflowing material is peaked towards the nuclear region even if is difficult to study the outflow geometry. Longer integration time would be required to establish the outflow geometry, extension and maximum velocity.

In Figure 5.6 I show the maps for the H α narrow emission: the high velocity dispersion suggests that this component is ionized by the AGN, as expected given that the map samples the nuclear region of the object.

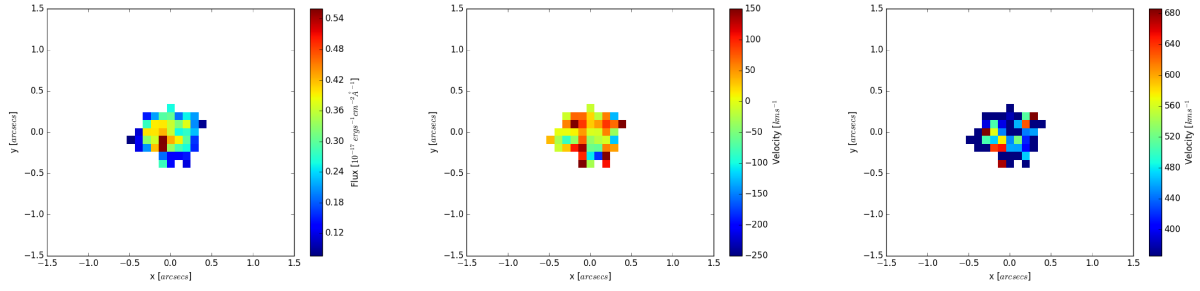


Figure 5.6: From left to right: flux, velocity and velocity dispersion maps of the narrow component of the $H\alpha$ emission line for the target X_N_115_23.

Data analysis: non parametric analysis of the emission line profile

The Gaussian fit discussed above is highly model dependent in case of complex spectra and the results on the derived emission line parameters suffer of degeneracy.

I thus apply a non-parametric analysis to minimize the dependence of our measurements on the fitting procedure and on the parameters of the individual Gaussian profiles (Harrison et al., 2014; Perna et al., 2015; Zakamska & Greene, 2014) for the $[OIII]_{5007}$ emission line only. This analysis allows to study the emission line profile, its width and its skewness with poor dependence on the modeling details.

After subtracting the continuum, I reproduce the full line profile with a series of Gaussian functions and I measure the flux of the line simply integrating below the curve. Once I reproduced the line profile, I then measure the position in the velocity space at which a certain percentage of the line flux is contained using the cumulative function $F_{tot} = \int_{-\infty}^{+\infty} F_{v'}(v')dv'$. The central position of the cumulative flux was defined from the systemic redshift derived in the integrated spectrum from the narrow $[OIII]_{5007}$ component. I then estimated the positions at which 5%, 10%, 50%, 90% and 95% of the total flux are contained, $v_5, v_{10}, v_{50}, v_{90}$ and v_{95} respectively. Figure 5.7 gives a visual representation of the method. The velocity values derived from the integrated spectrum are listed in Table 5.3. In Table 5.3 I list also the parameters $\Delta v = (v_{90} + v_5)/2$, $\delta w_{80} = v_{95} - v_5$ and v_{peak} . The quantity δw_{80} represents the width of the line, in the velocity space, in which the 80% of the total flux is comprised. For a single Gaussian profile, it would correspond to the FWHM of the line. The parameter v_{peak} is instead the position of the emission line peak in the velocity space and it corresponds in this case to the position of the $[OIII]_{5007}$ narrow component. Finally, Δv gives an estimate of the line asymmetry and corresponds to the peak of the blue-shifted tail of the $[OIII]_{5007}$ emission line so that it can be compared with the velocity offset of the blue-shifted component derived from the Gaussian fit. From the non-parametric analysis I obtain $\Delta v \sim -282 \text{ km s}^{-1}$ which is slightly higher than the velocity offset of the blue-shifted $[OIII]_{5007}$ component derived through the Gaussian modeling $v \sim -187 \text{ km s}^{-1}$. This means that according to the non-parametric analysis, the outflowing material is moving at higher speed with respect to the systemic velocity of the target. However, the discrepancy is somehow small and it can be explained by the relatively low SN of the spectrum. In particular, I highlight the presence of a feature in absorption on the left-hand side of the $[OIII]_{5007}$ emission line (see left panel of Fig. 5.4) probably due to a bad sky subtraction. Pixels in this region are flagged when reproducing the emission line profile but this feature likely introduces an uncertainty in the analysis. I conclude that the two measurements are in fair agreement given the SN of the spectrum at this stage.

The non-parametric analysis is also applied on the spatially resolved spectrum to produce maps of the emission line profile. The maps for the velocity peak v_{peak} , line width δw_{80} , maximum velocity v_{10} and velocity offset Δv are shown in Fig. 5.8.

By comparing the velocity peak map (top-left in Fig. 5.8) with the kinematic of the narrow $[OIII]_{5007}$ component (upper-central panel of Fig. 5.5) is it possible to spot a similar pattern. However, the dynamic range in the two maps is extremely different.

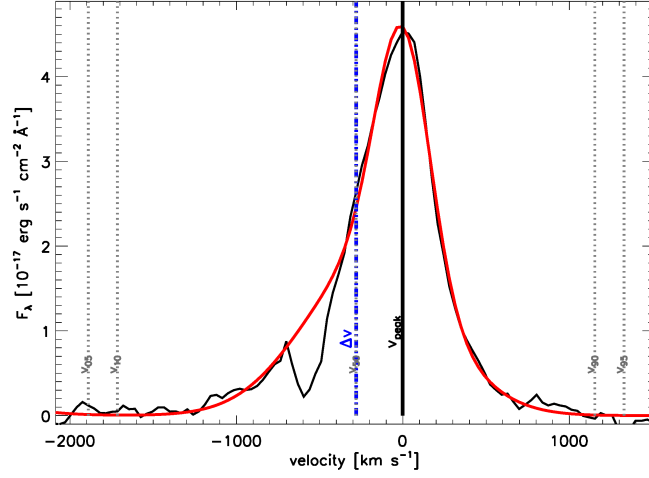


Figure 5.7: Integrated spectrum for XN_115_23 around the $[\text{OIII}]_{5007}$ emission in the velocity space. The emission line profile derived from the Gaussian fit is shown in red. Dotted vertical lines in grey highlight the position in the velocity space where the 5, 10, 50, 90 and 95 % of the emission line flux is contained, as defined in Harrison et al. (2014). The thick black line highlight the position of the emission line peak, while the blue dashed line represent the velocity offset of the blue wing.

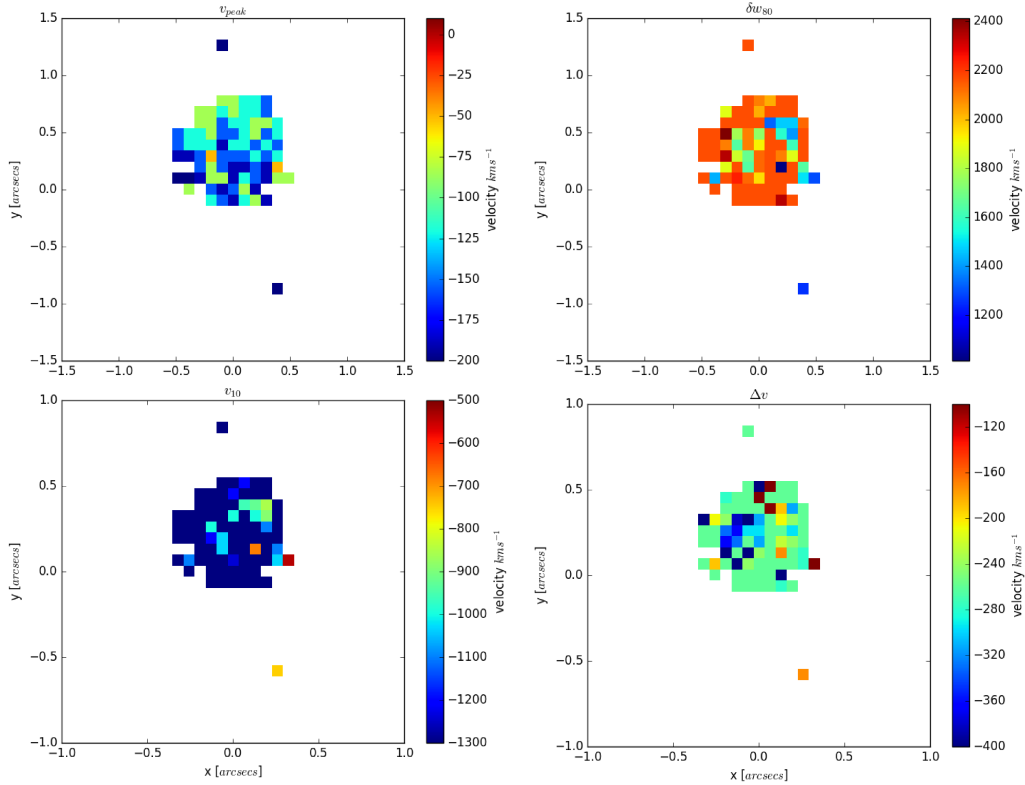


Figure 5.8: Spatially resolved maps of v_{peak} (upper-left), Δw_{80} (upper-right), v_{10} (lower-left) and Δv (upper-left) as derived from the non parametric analysis around the $[\text{OIII}]_{5007}$ emission line.

Table 5.3: Results of the non parametric analysis on the [OIII]₅₀₀₇ emission line. See text for more details.

Velocity	Position [$km s^{-1}$]
$v_{5\%}$	-1890.5
$v_{10\%}$	-1715.7
$v_{50\%}$	-281.7
$v_{90\%}$	1152.3
$v_{95\%}$	1327.1
v_{peak}	-1.9
$\Delta w_{80\%}$	2867.9
Δv	-281.7

This is likely due to the high noise which makes hard to study the line profile on the spatially resolved spectrum. This discrepancy may also reflect the fact that the analysis performed through the Gaussian fit is strongly dependent on the constraints imposed on the Gaussian parameters.

The v_{10} map shows a quite uniform maximum velocity field with $\langle v_{10} \rangle \sim -1300 km s^{-1}$, slightly lower than the value measured on the integrated spectrum (see Tab. 5.3).

From the map of δw_{80} the [OIII]₅₀₀₇ emission is $\sim 2000 km s^{-1}$ across the whole region mapped, suggesting that the outflow is extended.

The Δv map, similarly to the velocity map of the broad [OIII]₅₀₀₇ component, shows that the emission line has a tail blue shifted with respect to the system and in motion toward the observer with $\langle \Delta v \rangle \sim -240 km s^{-1}$, tracing outflowing material.

To conclude, the analysis of the SINFONI spectrum reveals that XN_115_23 has an outflow with moderate speed. The low SN on the spatially resolved SINFONI spectrum prevents to precisely define its geometry. Small scale fluctuations due to high noise in individual spaxels and a non-optimal sky subtraction prevent to reconstruct any geometric pattern. I will rely on future observations with longer integration time to a spatially resolved analysis of the outflow in this object. In the following of this section, for the computation of the outflow energetic I will use the parameters derived from the integrated spectrum only.

Computation of the outflow parameters

The physical parameters of the outflow can be estimated from the broad component of the [OIII]₅₀₀₇ emission line. As previously discussed, this emission line traces the NLR of the AGN thus does not experience the gravitational force from the central BH and is expected to be narrow. A broad component in this emission line component traces therefore high speed material on large scales. Following the derivation presented in Cano-Díaz et al. (2012), I can use the [OIII]₅₀₀₇ line as an indicator of the outflow mass in its ionizing component:

$$M_{out}^{ion} = 5.3 \times 10^7 \frac{L([OIII]_{5007,broad})}{10^{44} erg s^{-1}} \frac{100 cm^{-3}}{n_e} 10^{-(O/H)-(O/H)_\odot} [M_\odot] \quad (5.1)$$

where $L([OIII]_{5007,broad})$ is the luminosity of the [OIII]₅₀₀₇ broad component, which can be estimated by the SINFONI spectrum, n_e is the density of the outflowing gas while $10^{-(O/H)}$ is the oxygen abundance. I must notice here that the [OIII]₅₀₀₇ line traces the ionized phase of the outflow that could be a minor component of the outflowing material. In fact, there are suggestions in few objects that the majority of outflow mass is in a molecular phase (Feruglio et al., 2010; Ciccone et al., 2014) even if this could not be the case a high L_{bol} (Fiore et al., 2017). A complementary program with ALMA targeting the CO[3-2] transition (Program 2016.1.00798.S, P.I. Mainieri) will allow to trace the molecular gas content of SUPER-AGN targets and trace the different phases of the outflowing material in these sources. With the current data-set from SINFONI I can however have already a first estimate of the outflow mass.

From Eqn. 5.1 one can see that the outflow mass depends on the oxygen abundance and the electron density. The latter parameter is the main uncertainty when estimating $M_{\text{out}}^{\text{ion}}$ as it is difficult to estimate from observations. One could use the [SII]_{6717,6732} doubled (Osterbrock & Ferland, 2006), when resolved, but this feature is intrinsically faint and can be observed with long integration or from stacked spectra only (Puglisi et al., 2017, e.g.). This parameter is not well constrained in literature either as different studies report a broad range of values for n_e , from few cm^{-3} up to $\sim 1000 \text{ cm}^{-3}$ (see discussion in Kakkad et al. 2016) and it is not clear if and how n_e varies with galaxy properties and redshift (Kashino et al., 2017a). Perna et al. (2017) recently reported $n_e \sim 1200 \text{ cm}^{-3}$ for moderately luminous AGN at $z \leq 0.8$ warning that the typical value of $\sim 1000 \text{ cm}^{-3}$ can lead to substantial overestimates of the outflow parameters. However, the analysis of Perna et al. (2017) is performed at lower redshift than SUPER target and there are indications that n_e is an evolving function of redshift (Kashino et al., 2017a, e.g.). I thus adopt $n_e = 200 \text{ cm}^{-3}$, a typical value for star-forming galaxies at $z \sim 2$ (Steidel et al., 2014; Kashino et al., 2017a). The final SUPER observations will be deep enough to detect the [SII]_{6717,6732} in the integrated spectrum of the source, so that to mitigate this uncertainty.

For X_N_115_23 I estimate $M_{\text{out}}^{\text{ion}} \sim 3.4 \times 10^6 M_{\odot}$ by assuming a solar metallicity for the outflowing gas (Perna et al., 2015) and without applying a dust attenuation correction. In principle, a dust attenuation measurement can be derived by using the narrow H α /H β emission line ratios (the Balmer Decrement, see Introduction and previous chapters for more details) that traces the gas on larger scales as the [OIII]₅₀₀₇ emission. However, by computing the Balmer Decrement using the values listed in Table 5.1 I obtain H α /H β = 1.1 which would imply a negative dust correction. This is clearly nonphysical and it is probably due to the high uncertainties in estimate of the narrow emission line fluxes. I then assume that the narrow lines are extinction free and I do not correct the [OIII]₅₀₀₇ luminosity but a more accurate estimate of the dust attenuation will be derived when new observations will be available.

From Eqn. 5.1 it is possible to determine the ionizing gas outflow rate, assuming an outflow geometry and a density distribution within the area of the outflow itself. Still following the Cano-Díaz et al. (2012) derivation, I assume a (bi)-conical geometry as this is the typical geometry observed in the local Universe (Müller-Sánchez et al., 2011). I also assume that the outflowing gas is made of ionized gas clouds with constant density and uniformly distributed within the outflow region. I then derive:

$$\dot{M}_{\text{out}}^{\text{ion}} = 164 \times C \times \frac{L([\text{OIII}]_{5007, \text{broad}})}{10^{44} \text{ ergs}^{-1}} \frac{100 \text{ cm}^{-3}}{\langle n_e \rangle} 10^{-(\text{[O/H]} - \text{[O/H]}_{\odot})} \frac{v_{\text{out}}}{1000 \text{ km s}^{-1}} R_{\text{kpc}} [M_{\odot} \text{ yr}^{-1}] \quad (5.2)$$

where v_{out} is the outflow velocity measured from the SINFONI spectrum, and C is a factor which subsumes spatial variations in the electron density (Cano-Díaz et al., 2012). Following Harrison et al. (2012), I consider here for the outflow velocity the offset of the blue-shifted component with respect to the systemic redshift, as derived from the non-parametric analysis which is less dependent on the fit parameters. From the non-parametric analysis on the integrated spectrum shown in the left panel of Fig. 5.4 I get $\Delta v_{\text{out}} = -281.9 \text{ km s}^{-1}$, as reported in Table 5.3. From the emission line flux map of the [OIII]₅₀₀₇ broad component I derive an extension of the outflow of $R_{\text{kpc}} \sim 3 \text{ kpc}$ which is roughly the radius at which this flux starts to fade (see Fig. 5.5, bottom-left panel). This value is likely a lower limit for the outflow extension: with longer integration time I will be able to map the emission to larger distance from the center with higher accuracy. However, the emission line map of Fig. 5.5 is not corrected for the beam smearing and this can lead to an overestimate of the outflow extension (Husemann et al., 2016). Given the other uncertainties, I conclude that this effect is not a major issue in our computation but it will be carefully taken into account for future analyses. With these assumptions I get $\dot{M}_{\text{out}}^{\text{ion}} \sim 10 M_{\odot} \text{ yr}^{-1}$.

It is useful to derive the kinetic power of the outflow which is easily compared with the AGN bolometric luminosity L_{bol} and the kinetic energy injected into the ISM by star-formation: this comparison allows to understand the driving source of the outflow. The kinetic power can be simply obtained as:

$$P_{\text{k}}^{\text{ion}} = \frac{1}{2} \dot{M}_{\text{out}}^{\text{out}} v_{\text{out}}^2 = 5.17 \times 10^{43} \frac{L([\text{OIII}]_{5007, \text{broad}})}{10^{44} \text{ ergs}^{-1}} \frac{v_{\text{out}}^3}{1000 \text{ km s}^{-1}} \frac{100 \text{ cm}^{-3}}{\langle n_e \rangle} 10^{-(\text{[O/H]} - \text{[O/H]}_{\odot})} R_{\text{kpc}}^{-1} \quad (5.3)$$

I get here $P_{\text{k}}^{\text{ion}} \sim 2.6 \times 10^{40} \text{ ergs}^{-1}$ which is much lower ($\sim 2 \times 10^{-6}$) than the bolometric luminosity of the AGN $L_{\text{bol}} = 3.8 \times 10^{45} \text{ ergs}^{-1}$, derived from the X-ray luminosity.

This value for the kinetic power is much lower than what reported by Cano-Díaz et al. (2012) on a unobscured QSO at similar redshift and with similar bolometric luminosity. However, this estimate is extremely uncertain due to the various assumptions and the low SN of the maps. The final SUPER observations will allow to certainly improve these estimates.

5.3 Summary and future prospects

In this chapter I introduced the Integral Field Spectroscopy techniques, which are the ultimate tool for understanding the properties of star-forming galaxies at high redshift and are essential to study the interaction between the central AGN and the surrounding galaxy.

In this context I presented the SUPER survey, an ongoing Large Program at ESO-VLT to detect outflows in a statistically significant sample of AGN-host galaxies at $z \sim 2$ taking advantage of high spatial resolution IFU observations with SINFONI. I presented the observing strategy, the observations and the data reduction. These observations are still at an early stage due to the challenging observing conditions required, even for an excellent site as Paranal. For this reason, SINFONI data-cubes of 1 hour of integration time are available only for a restricted sample and the science results will be presented in future works.

To show an example of the analysis I will perform, I presented as a test case the analysis of the preliminary observations for XN_115_23, a luminous type-1 AGN. I showed the spatially integrated spectra extracted from the SINFONI data-cube in both H and K -band (sampling the $H\beta$ + $[\text{OIII}]_{4959,5007}$ and $H\alpha$ + $[\text{NII}]_{6549,6583}$ emission lines respectively) and the corresponding emission line maps obtained by fitting the spectrum at each spaxel.

In the K -band integrated spectrum I detected both a broad and a narrow component for the $H\alpha$ emission line: the narrow component is important for our studies of feedback as it allows in principle to sample the star-formation in the host on a timescale comparable with the AGN activity (when not contaminated by AGN emission). However, the de-blending of the $H\alpha$ broad and narrow emission on the spatially resolved spectrum is currently restricted to the central regions of the target, where the ionization from the AGN dominates the emission. Longer exposures will allow to extend this exercise to larger scales where the AGN contribution should be minor.

The H -band integrated spectrum shows a bright $[\text{OIII}]_{5007}$ emission with a clear blue-shifted tail which I interpret as a signature of the outflow. This component is shifted of $v_{\text{out}} \sim 400 \text{ km s}^{-1}$ with respect to the narrow $[\text{OIII}]_{5007}$ emission thus the speed of this outflow is relatively modest compared to what found on a luminous QSO with similar bolometric luminosity and at similar redshift by Cano-Díaz et al. (2012).

We estimated the mass of this ionized outflow to be $M_{\text{out}}^{\text{ion}} \sim 3.4 \times 10^6 M_{\odot}$ and an outflow rate of $\sim 13 M_{\odot} \text{ yr}^{-1}$. This outflow has a kinetic power which is $\sim 10^{-6}$ the bolometric luminosity of the AGN. Unfortunately, a reliable estimate of the integrated SFR of the source is still lacking thus preventing from establish if this energy is consistent with star-formation as a main driver of the outflow or it is rather powered by the AGN. These estimates are however highly uncertain as the mass of the outflowing gas strongly depends on the electron density of this gas and the Oxygen abundance and both these quantities have to be assumed. This is a common caveat for studies of AGN outflows, in particular at high redshift.

We also note that the outflowing gas mass is estimated from the luminosity of the $[\text{OIII}]_{5007}$ which is in principle affected by dust attenuation. However, the $H\alpha/H\beta$ narrow components ratio (probing the gas extended on large scales as the $[\text{OIII}]$) yields a negative Balmer Decrement. This would imply a negative dust correction, clearly nonphysical. We conclude that this result is due to the large uncertainty on the narrow $H\beta$ emission. We thus not correct the $[\text{OIII}]_{5007}$ luminosity for dust attenuation. Finally, the spatially resolved maps of this broad $[\text{OIII}]$ component result quite noisy with one hour of integration time only, not allowing to properly sample the outer region of this source. Therefore, the estimate of the outflow extension is likely a lower limit to the real extension of the outflow. Once again, future SN observations will allow to derive a robust estimate of the outflow extension as well as its geometry: this will be crucial to firmly establish the outflow mass and kinetic energy.

As extensively discussed in literature, the ionized component could be only one of the various components of the outflowing gas, perhaps a minority one as argued by some authors. The shock front is highly unstable and the gas can be efficiently cooled in the vicinity of the shock-front (see Introduction): the majority of the outflow mass can be in a molecular form (Feruglio et al., 2010). This possibility can be tested by searching for molecular outflows in SUPER targets that are observed with ALMA around the CO 3-2 transition. These observations will also allow to measure the molecular gas mass of these objects. This test will be crucial to evaluate whether the outflow is really capable to affect the fuel of star formation in this galaxy (Kakkad et al., 2017).

Assuming that our computation is a reliable estimate of the outflow parameters, it is not surprising I detected an outflow with such moderate energetic. The SUPER targets were in fact selected blindly in the sense that I did not preferred sources with an high chance of detecting a powerful outflow: therefore we do not expect to detect an outflow in all our targets. The challenging questions I will address are *why* this outflow has this energetic, *how* this relates with AGN properties and *what* is this impact on the surrounding galaxy, if any. By extending this analysis to the full sample I will moreover go beyond source-by-source effects and we will derive trends as a function of AGN and galaxy properties.

Once the full sample will be observed, I will perform a complete census of the outflow properties of these AGN at $z \sim 2$ as a function of the MS position, as performed statistically in Ciccone et al. (2016) and Concas et al. (2017) in the local Universe. With this analysis U will study how the outflow properties and their effects on the host galaxy vary as a function of the distance of the host with respect to the MS. The SUPER data will allow to address this problem and obtain a clear and more detailed picture of the outflow physics as a function of galaxy properties.

Chapter 6

Conclusions

This Thesis presented a detailed study of the spectral properties of far-IR selected star-forming galaxies at $0.7 \leq z \leq 2.5$, also including AGN hosts, placed in different positions with respect to the star-forming Main Sequence. Spectroscopic observations sampling the rest-frame optical spectra of these sources have been revealed as a powerful tool for investigating their dust attenuation, gas-phase metallicity, ISM conditions, AGN content and the impact of the latter on the host galaxy.

In the following of this Chapter, I summarize the main outcome of this study and discuss its potential or ongoing developments.

6.1 A critical analysis of the nebular dust attenuation on $z \sim 1$ MS galaxies

In Chapter 2, I presented a sample of 79 *Herschel*-selected star-forming galaxies on the MS at $z \sim 1$ for which I studied the attenuation on the $H\alpha$ emission line, using near-IR spectra from the 3D-HST survey. The excellent quality of broad-band photometry, along with a wide spectral coverage, allowed to firmly constrain the SED of these objects and derive $M_\star$, L_{FIR} , L_{UV} and the UV reddening β . From this analysis, I showed that different dust attenuation indicators on the continuum are in remarkable agreement. I further showed that lines and continuum are attenuated by a similar amount, unlike in the local Universe, probably because of a large filling factor of HII regions in our galaxies. I also found that the $H\alpha$ dust attenuation grows with stellar mass and this trend diverges, with a substantial scatter, from the local relation, suggesting an evolution of $A_{H\alpha}$ with redshift. However, the evolution seems rather connected on intrinsic features of the galaxy. I showed indications that the differential attenuation is a function of $M_\star$ and SFR .

6.2 The first study of ISM properties of high- z MS outliers in light of their optically-thick attenuation

In Chapter 3, I presented a study of the near-IR spectra of a statistically significant sample of starburst galaxies selected from *Herschel* observations as outliers from the MS at $z \sim 1.6$. I measured, for the first time in this class of objects, their metal content from the $[\text{NII}]_{6583}/H\alpha$ ratio showing that it is consistent with that derived from the Mass-Metallicity relation at the same z but it is much higher than what predicted from the Fundamental Metallicity Relation given the $M_\star$ and SFR . The results presented in this chapter support the scenario in which the starbursts are triggered by a merger rather than a major event of gas inflow.

The latter in fact would induce a dilution of the metal content of the galaxy.

I also presented the detection of the $[\text{SII}]_{6717,6732}$ doublet in the average spectrum of these objects. The ratio $[\text{SII}]_{6717}/[\text{SII}]_{6732}$ traces the electron density of HII regions, which result marginally higher than the MS, indicating the compact nature of star-formation in off-MS galaxies. By combining measurements of the $\text{H}\beta$, $[\text{OIII}]_{5007}$, $\text{H}\alpha$, $[\text{NII}]_{6583}$, $[\text{SII}]_{6717,6732}$ lines I also show tentative indications that starburst have larger ionization parameter with respect to MS galaxies with the same $M_\star$. This enhancement could be produced by a larger amount of ionizing photons and it would suggest that our sources have a large star-formation efficiency, in line with our previous findings from ALMA measurements of their gas content via CO 2-1 observations (Silverman et al., 2015a, 2017 in preparation). These results however cannot be interpreted appropriately without considering the effects of dust which can be dramatic in this class of objects. From a comparison between dust attenuation indicators, I showed in fact that the optical emission from the starbursting regions is attenuated by $A_{\text{H}\alpha} \geq 4.5 \text{ mag}$. Therefore, our aforementioned results refer to the less obscured regions and do not sample the region where $\sim 90\%$ of the star-formation is buried. The metal content and ISM conditions of the most star-forming regions in starbursts remains unconstrained.

6.3 The role of AGN in the starburst region of the $z \sim 1.6$ MS

In Chapter 4 I presented a preliminary study of the AGN-dominated sources in the starburst region of the MS at $z \sim 1.6$. These AGN are the parent sample of the star-forming dominated starbursts discussed in the previous chapter. These AGN have been identified by optical diagnostics (i.e. the BPT diagram) despite the strong attenuation expected. This can represent a hint that dust attenuation in AGN-dominated sources is lower. To better understand this issue, I built their average spectrum and repeated the same analysis on the dust attenuation performed on the star-forming dominated sample. Through this method I found first indications that dust attenuation on these AGN is lower than in the star-forming sample. However, these measurements are affected by a large scatter, probably because we are sampling phenomena occurring on very short timescales, and it is not clear if the methodology is applicable on a sample dominated by AGN. In addition, the SN is poor even on the average spectrum. This prevented to accurately de-blend the broad and narrow AGN components thus producing very uncertain measurements. I then refer to future studies with higher quality spectra to confirm this result. If confirmed, it would provide strong support to the classical evolutionary picture from a major-merger induced starburst to an optically bright QSO (Sanders et al., 1988) as it would suggest that AGN are cleaning their environment from dust after a buried star-formation dominated phase. The presence of an outflowing component on the $[\text{OIII}]_{5007}$ emission line seems to support this hypothesis of AGN being in a “blow-out” stage. Furthermore, a visual inspection of the morphology reveals that AGN reside in interacting systems, as star-forming dominated starbursts, but the former seem to reside in more compact pairs.

6.4 Benefitting of IFU resources for galaxy evolution studies

In Chapter 5, after introducing the integral field spectroscopic techniques, I described the SUPER survey, an ongoing large program with SINFONI designed to unveil the role of the AGN in the life-cycle of $z \sim 2$ star-forming host galaxies. I described the observation strategy, the data-reduction and the analysis on a test case. As an active member of this collaboration, I will use these observations, which are still in a preliminary status, to quantify the occurrence of ionized outflows as a function of the MS distance and then to study the properties of such outflows in different galaxy environments.

SUPER observations in conjunction with the ancillary ALMA program to detect the CO as well as the characterization of the host-galaxy and AGN integrated properties (Circosta et al. 2017, in preparation) will allow to obtain a complete overview of the AGN-driven outflow physics, its link with the AGN and galaxy properties and its impact on the life of the latter.

6.5 General considerations and future prospects

The work presented in this Thesis has demonstrated the power of spectroscopic observations to constrain the properties of high- z dusty star-forming galaxies, selected via *Herschel* far-IR observations. In particular, it allowed to demonstrate that recipes for dust attenuation corrections calibrated in the local Universe hold qualitatively in “normal” star-forming galaxies at high redshift, even if some evolution is observed. It also allowed to demonstrate that these recipes do not hold true for starbursting galaxies with SFRs much larger than the average for their $M_\star$ and redshift. These findings have revealed that outliers from the MS at $z \sim 1.6$ have a peculiar dust distribution with compact, optically thick cores resembling the conditions observed in local merger-driven ULIRGs. Observed frame near-IR spectroscopy has also enabled to measure the metal content and the ISM conditions of the less obscured regions of such violent objects. The results of this thesis are thus helping to solve, at least partially, the debate on what powers high- z galaxies above the MS.

Spectral observations have also allowed to quantify the role of AGN among MS outliers, whose activity seems to be enhanced above the MS. Initial indications on the properties of such sources seems consistent with an evolutionary sequence from SBs to QSOs driven by mergers. Spectroscopic observations have also been the ultimate tool for detecting the interaction between these AGN and their host, occurring via outflow. Furthermore, I showed that only IFU techniques provide the information required to firmly establish the impact of the AGN activity on the galaxy.

None of the aforementioned results however, would have been possible without, in parallel, a careful study of the multi-wavelength SED of our galaxies spanning the electromagnetic spectrum from the UV to the far-IR. Multi-wavelength techniques are the ultimate approach to address the open problems of Galaxy Evolution in this era, where the community can benefit of large data-sets from various archives (e.g. ALMA and ESO) and multi-band catalogs, including *Herschel* deep observations in various extra-galactic fields.

Nevertheless, several questions in our analysis remain unanswered and I will give in the following few ideas for future experiments that can help to address them in the future.

First of all, it has to be tested the robustness of the results presented in Chapter 2 against the sample selection. I argued that the result of our f -factor ($f = E_{\text{neb}}(B - V)/E_{\text{star}}(B - V) \sim 0.9$) was possibly driven by the sample selection which favors objects with high attenuation (because of the *Herschel* selection) but with a moderate amount in the emission line (because of the requirement of the $H\alpha$ detection). Moreover, there were two additional caveat in the analysis as an individual detection of the $H\beta$ emission was lacking (so that the f -factor was derived by indirect comparisons) and the $H\alpha$ emission was contaminated by the $[\text{NII}]_{6583}$ line. Data from the FMOS-COSMOS survey offer the possibility to asses the role of the assumptions in my previous results by providing a detection of the $H\beta$, which allows to directly measure the nebular attenuation, and a high spectral resolution, which minimizes the uncertainty introduced by the $[\text{NII}]_{6583}$ contamination. Furthermore, the FMOS-COSMOS survey allows to test the sample selection effects as it offers spectroscopy for both *Herschel* and mass-selected samples.

Concerning the physics of starburst galaxies, this work has made clear the peculiar nature of this class of systems which implies that normally employed techniques have to be revised to properly study them. In view of the two component model discussed in Chapter 3, it has to be tested in particular whether energy balance techniques (applied in studies of buried objects, see e.g. Danielson et al. 2017 on high- z SMGs) apply correctly to heavily obscured starbursts. These results suggest that the energy balance approach should not be applied blindly otherwise it can produce “bizarre results” (see e.g. the catastrophic photometric redshift solutions of Casey et al. 2017, qualitatively explained by my model). A complete understanding of the behavior of dust and its impact on the multi- λ SED in these systems is required. This appears to be crucial at high- z where the contribution of the obscured SF to the cosmic SFH increases (Madau & Dickinson, 2014). A mandatory step is thus to extend the phenomenological model of Chapter 3 including a physically motivated treatment of the optically thick attenuation. For this reason, I intend to improve this simple toy model to better understand the behavior of dust attenuation recipes in these peculiar systems and the implication of optically thick attenuation in their multi-wavelength SED.

6.5. GENERAL CONSIDERATIONS AND FUTURE PROSPECTS

Another important, perhaps discouraging at a first glance, implication of the work discussed in Chapter 3 is that our high- z outliers are still hidden to our optical eyes. But this means that we have to wide our view and push our studies at rest-frame near-IR wavelengths. Motivated by the results of Puglisi et al. (2017), my team has undertaken a pioneering project aimed to study the physics of $z \sim 0.6$ starbursts by using spectral data from FIRE-Magellan (PI Paolo Cassata) and KMOS (PI Emanuele Daddi). These data-sets will enable to constrain the attenuation, metallicity, ISM conditions and AGN content benefiting from the lower obscurations at near-IR wavelengths (Calabrò et al. in preparation). These efforts will help to answer to the question if the obscured SF core is enriched and dense, as argued but not yet proved in Puglisi et al. (2017).

Finally, to firmly trace the properties of our merging galaxies from an observational perspective, IFU observations are required. A spatially resolved approach is necessary to fully unveil the structure of high- z SFHs and gain insights also on their formation mechanism (Nelson et al., 2016; Tacchella et al., 2017). In particular, spatially resolved observations in this case will help to better constrain the attenuation $A_{H\alpha}$ of the optically thick core for which I can now place only lower limits. Furthermore, these observations will allow to characterize the dust attenuation pattern in the starbursts and recover their complex geometry. I will use IFU observations in combination with high-resolution imaging from ALMA (Silverman et al. in prep) to construct spatially resolved dust attenuation maps and thus implement the analysis presented in Chapter 3 on a spatially resolved basis. This will solve the interrogative of whether the star-formation comes from a heavily obscured part and will also help to address the role of optically-thick attenuation on the multi-wavelength SED (see also discussion above).

Spatially resolved spectroscopy will be decisive to address the role of the AGN in the life of the galaxy. I have detected outflows in our sample of off-MS AGN as well as in a X-ray QSO at $z \sim 2$ but no accurate information is available yet on the energetic of such phenomenon mainly because of lack of spatially resolved information. Deep adaptive-optics assisted observations from SINFONI will be used in both samples to study the outflow physics and address its relation with the galaxy star-formation. In particular, I will use the exquisite data from the SUPER survey, presented in Chapter 5, to investigate the relationship between AGN-driven outflows and the host galaxy star-formation, focusing on episodes occurring above the $z \sim 2$ MS. The results from this analysis will provide important insights on the impact of these winds in such extreme sources. Moreover, SUPER data sampling a wide range of SFR on the MS plane will allow to compare outflow phenomena in galaxies with different ISM conditions since they are likely varying as a function of the MS-position, as suggested in Chapter 3. This exercise will offer the possibility to probe the effects of outflows in different galaxy environment and, moreover, will allow to understand the impact of outflows in the galaxy life as the MS gives an important reference system for the evolutionary stage of the galaxy.

Studies of the AGN/host galaxy interaction cannot be restricted to a “simple” spectral analysis. To firmly understand if AGN are really capable of affecting the life of galaxies, in particular of starburst sources, it is important to look at the overall behavior of the system. Also, it is necessary to analyze the properties of these AGN in comparison with those of the star-formation dominated population: this is mandatory for interpreting these studies in an evolutionary context. I then plan to improve the analysis of the dust attenuation properties of AGN above the MS presented in Chapter 4 by applying for observing time to obtain higher quality data covering the emission lines of interest (mainly $H\alpha$ and $H\beta$). I will also take advantage of the exquisite coverage of the COSMOS field and I will exploit the ancillary data available to improve the SED fitting decomposition and better characterize the central AGN (i.e. measuring M_{BH} , L_{Edd} , L_{bol}). Also, following the first results from our visual inspection presented in Chapter 4, I will implement a quantitative morphological analysis and I will measure the merger rate and the nuclear separation in the AGN dominated starbursts. When doing this exercise, I will compare this study with the same analysis performed on the star-formation dominated starbursts. In this case I will take advantage of HST UV rest-frame observations, available from the COSMOS archives. I will also characterize the gas content of these AGN above the MS, following the approach of Kakkad et al. (2017), whose analysis was focused on the MS. Studies of the gas content in fact can give further indications on how the AGN affects the fuel of star-formation in our systems.

This exercise will be implemented on archival data from ALMA in the dust continuum (i.e. using the approach of Scoville et al. 2016 for deriving the gas masses) but I also plan to apply for ALMA time to observe the CO emission in these AGN, thus complementing the Silverman program focused on the star-forming off-MS population. To improve the statistics, in collaboration with my team in Padova led by Giulia Rodighiero, I will also extend the analysis of the gas content of AGN above the MS to the redshift range $1.4 \leq z \leq 2.5$.

6.6 Concluding remarks

This work has demonstrated the pivotal role of large surveys for our understanding of the evolution of star-forming galaxies at high redshift by providing large data-set on statistically significant samples of galaxies. The availability of data for large galaxy samples has the power to improve our understanding of the overall galaxy population but it also provides the sufficient statistics to identify rare objects as starburst galaxies or AGN. In addition, the studies of rare objects in large surveys benefit from statistical studies for having a well characterized control sample, as extensively discussed in this manuscript. This Thesis has also showed that the outcome from large surveys at various wavelengths has to be connected to obtain an overall picture of the galaxy physics. This work has firmly demonstrated the crucial role of combining data up to the far-IR to unveil all the properties of a galaxy and properly interpret its multi-wavelength SED, minimizing the assumptions and degeneracies of the models. In particular, the synergy between *Herschel* and FMOS, along with the aid of a high-quality photometric coverage, has pushed forward our understanding of high- z dusty starbursts.

This work is only the first step that will be followed-up by works exploiting the upcoming next generation facilities as Subaru-PFS and VLT-MOONS to unveil the properties of such elusive objects. The future Multi-Object Spectroscopic (MOS) surveys, complemented by multi-wavelength photometry, will be fundamental for characterizing the galaxy population at high- z . They will provide a statistical characterization of the overall star-forming galaxy population at high- z , as we largely demonstrated with our efforts from the FMOS-COSMOS survey (Kashino et al., 2013; Zahid et al., 2014; Silverman et al., 2015b; Kashino et al., 2017a,b; Valentino et al., 2017), from which it will be possible to select rare targets with improved statistics at various redshifts. These efforts will allow to establish eventual evolutionary trends for these rare objects.

With this work I also showed that future MOS surveys will serve as a “pathfinder” for interesting targets to be followed up with spatially resolved observations, that require longer integration times. In fact, this work has allowed e.g. to select peculiar targets as PACS-787 (Silverman et al. in prep, see also Fig. 3.8). Targets as PACS-787 are the best candidates to be studied with cutting edge IFU facilities as JWST-NIRSpec to unveil their peculiar ionized gas properties. The detailed study of these peculiar objects will certainly provide a more deep understanding of the physics regulating star-formation at early times. Forthcoming MOS and IFU instruments are complementary tools that will have to work in tight synergy for really pushing forward our census of star-forming activity at high redshift.

Acknowledgment

List of Figures

1.1	Overview of the stellar population synthesis technique. The upper panels highlight the ingredients necessary for constructing simple stellar populations (SSPs): an IMF, isochrones for a range of ages and metallicities, and stellar spectra spanning a range of effective temperatures T_{eff} , bolometric luminosity L_{bol} , and metallicity. The middle panels highlight the ingredients necessary for constructing composite stellar populations (CSPs): star formation histories and chemical evolution, SSPs, and a model for dust attenuation and emission (see also Sect. 1.1.3 and 1.1.4). The bottom row shows the final CSPs both before and after a dust model is applied. From Conroy (2013).	4
1.2	Extinction curves for local galaxies. The MW extinction curve is shown for three different values of R_V , 3.1 (solid red line), 5.0 (dashed red line), and 2.0 (dotted red line) (Cardelli et al., 1989; Fitzpatrick, 1999). The extinction curves of the Large Magellanic Cloud's 30 Doradus region (dashed black line) and of the Small Magellanic Cloud's bar (solid black line) are reported for $R_V = 2.7$ (Gordon & Clayton 1998; Misselt et al. 1999). The starburst obscuration curve (Calzetti et al., 2000, blue line) is shown here for a purely illustrative comparison because it refers to the dust obscuration of galaxies which is conceptually different from the dust extinction of stars. From Calzetti (2001a).	7
1.3	<i>Left</i> : relation between A_V derived from the Balmer Decrement ($H\alpha/H\beta$, x -axis) and from the $H\alpha/\text{Pa}\beta$ ratio (y -axis) in HII regions of M83, from Liu et al. (2013). Measurements are compared to five models considering different dust geometries (1-foreground screen; 2-clumpy dust screen; 3-uniform scattering slab; 4-clumpy scattering slab; 5-uniform mixture). The inset shows the same comparison but averaged over ~ 180 pc, corresponding to a 30×30 grid: all data points become consistent with model 1 because small scales fluctuations are averaged out. <i>Right</i> : Schematic view of the five configurations of dust/ionizing stars considered in Liu et al. (2013). Models are numbered in the same fashion as in the left panel. From Calzetti et al. (1994).	8
1.4	Schematic plot summarizing the physical effects driving variations in the IRX- β relation. Geometrical effects as turbulence in the dust screen, a patchy dust distribution, a different dust-stars distribution or a more realistic assumption of a two component dust model (Charlot & Fall, 2000) produce shift towards high IRX (dust attenuation) for a fixed β slope (dust reddening, above the black curve). Variations in the intrinsic properties of dust or in the stellar population age produce shifts below the black curve (i.e. towards redder β for a given IRX). From Popping et al. (2017).	11
1.5	$M_\star - SFR$ plane and the star-forming MS as a function of redshift up to $z \sim 2.5$ from Whitaker et al. (2014).	15
1.6	<i>Left</i> : Gas-phase metallicity as a function of $M_\star$ for local star-forming galaxies, from Tremonti et al. (2004). <i>Right</i> : $M_\star$ -metallicity relation for the stellar component in local galaxies. From Panter et al. (2008).	16

1.7	<i>Left: $M_\star - SFR$ relation at $1.5 \leq z \leq 2.5$. The solid black line indicates the main sequence (MS) for star-forming galaxies at $z \sim 2$, while the dotted and dashed lines mark the loci 10 and 4 times above the MS, respectively. Sources above the $4\times$ MS are classified as starbursts. <i>Right: SFR density (top panel) and number density (bottom panel) of on-sequence sources (blue open squares) and off-sequence sources (red filled squares), in four mass bins. MS outliers yield a minority contribution to the SFR. Both plots are from Rodighiero et al. (2011)</i></i>	18
1.8	Summary of the episodes that a source could experience along the $M_\star - SFR$ plane. Rotationally supported star-forming galaxies on the MS could merge with similar systems and increase their “starburstiness”, i.e. being pushed above the MS. Similarly, disks through violent disk instabilities could reach similar high specific SFR. MS sources are continuously fed by pristine gas inflows that sustain their SFR on long timescales. Natural fading of SFR or AGN winds can eventually quench galaxies driving them on the elliptical situ situated below the MS.	19
1.9	Cosmic SFH (black solid curve) compared with the SMBH accretion history from X-ray (red and light green curves) and infrared (light blue curve). From Madau & Dickinson (2014).	21
1.10	Role of feedback in modifying the galaxy luminosity function. From Silk & Mamon (2012).	22
1.11	The standard evolutionary scenario for the formation of a passive elliptical galaxy: two disk-like, gas-rich galaxies undergo a major merger triggering a nuclear starburst (SMG/ULIRG phase) that will further evolve in a obscured QSO. At the final stage of the evolution, the QSO clears the surrounding from dust (blow-out stage) revealing itself as an optical bright QSO. The powerful winds from the QSO can couple with the host ISM, thus removing the residual gas and lead the system as a passive evolving elliptical. From Alexander & Hickox (2012).	23
1.12	Shock pattern of a (top) momentum-driven and a (bottom) energy-driven outflows impacting the host-galaxy ISM from King & Pounds (2015). For more details about the outflow models see the main text.	26
2.1	Overlay showing the spatial distribution of the PACS/MUSIC/3D-HST source sample.	37
2.2	Location of our sample (red filled circles) in the $SFR-M_\star$ space, compared with the distribution of the all 3D-HST galaxies (black dots) in the same redshift range. The blue solid line represents the Main Sequence at $z \sim 1$ (Elbaz et al., 2007) and the dot-dashed blue line is the $4\times$ MS. The grey dashed line represents the SFR corresponding to the 3σ flux limit at $160 \mu\text{m}$ ($f_\lambda=2.4 \text{ mJy}$) for a typical main-sequence galaxy, derived using the median SEDs of Magdis et al. (2012). The inset shows the redshift distribution for this work sample (red curve) compared to the complete 3D-HST sample in the same redshift range (black curve). The lower panel on the left is the distribution of the observed $H\alpha$ luminosities for our sample (not corrected for dust attenuation), the lower panel on the right shows the distribution of L_{IR} .	38
2.3	Total infrared luminosity L_{IR} as a function of redshift for the PEP sample. The magenta filled circles are the 378 PEP sources with a counterpart in the 3D-HST observations. The blue filled circles highlight the 79 sources of our final sample, located in the redshift range $z \in [0.7 - 1.5]$	39
2.4	<i>Upper panel:</i> image of the 3D-HST bi-dimensional spectrum for source 4491 (ID-MUSIC), as displayed by the IDL routine. The red horizontal lines define the “virtual slit”. <i>Lower panel:</i> 1D spectrum of source 4491, obtained collapsing the 2D spectrum along the columns inside the virtual slit. The flux is in $\text{erg/sec/cm}^2/\text{\AA}$. The black thicker histogram is the observed spectrum, the red curve is a spline interpolation to the observed spectrum. The grey thin histogram, almost overlapping the black one, represents the “decontaminated spectrum”, i.e. the contamination model by Brammer et al. (2012) subtracted to the observed spectrum. The overlap between the observed and the decontaminated spectrum highlight the fact that the contamination flux in the region defined by the virtual slit is negligible. The vertical blue line highlights the position of the $H\alpha$ emission while the pale blue lines correspond to the position of the [NII] doublet.	40
2.5	Redshift distribution for the 3D-HST sources in the GOODS-South field. The sources are distributed in a redshift interval $z \in [0.65 - 1.53]$, according to the features of the WFC3/G141 grism.	41

- 2.6 *Upper panel:* relation between 3D-HST spectroscopic redshifts (x -axis) and MUSIC redshifts. In the inset, the distribution of the absolute scatter $\Delta z = (z_{3D-HST} - z_{MUSIC})$ is shown. The standard deviation for this distribution is $\sigma = 0.031$. The red histogram highlights the absolute scatter for photometric MUSIC redshifts. The blue histogram represents the absolute scatter between our measurements and the redshifts from Morris et al. (2015). *Lower panel:* relative scatter $(z_{3D-HST} - z_{MUSIC}) / (1 + z_{3D-HST})$. The data points in red are the photometric redshifts in the MUSIC catalog, the black dots are the sources with spectroscopic redshift also in the MUSIC catalog from ground based measurements. The blue open diamonds are the redshifts measured by Morris et al. 42
- 2.7 Spectral Energy Distribution from MAGPHYS (black curve) with the observed photometry (blue filled circles) and the 3D-HST spectrum (red line). The 3D-HST spectrum is corrected for the flux loss outside the slit, as described in the text. The plot also reports the MUSIC ID of the source and its redshift, measured from the near-IR spectrum. The inset shows a zoom on the 3D-HST spectrum, close to the $H\alpha$ emission line. 43
- 2.8 Example of a Spectral Energy Distribution in output from MAGPHYS. The black solid line is the best-fit model to the observed SED (data-points in red). The blue solid line shows the unattenuated stellar population spectrum. The bottom panel shows the residuals $(L_{\lambda}^{obs} - L_{\lambda}^{mod}) / L_{\lambda}^{obs}$. 45
- 2.9 Comparison between the continuum extinction $E_{star}(B - V)$ derived from the UV spectral slope β (x -axis) and the continuum extinction derived from the infrared excess IRX (y -axis). The red line is the 1:1 correlation relationship. In the lower part of the plot on the right are indicated the typical size of the errorbars. 48
- 2.10 Ratio of $H\alpha$ to UV-based SFRs (not corrected for dust extinction) as a function of $E_{star}(B - V)$ derived from the IRX ratio. The lines are the equation 2.7 with different values of f from Kashino et al. (2013) and Calzetti et al. (2000), as the legend indicates. The grey shaded area marks the confidence interval for our estimate of the f -factors. 49
- 2.11 Same as Fig. 2.10. Here our data-points are color-coded by $M_{\star}$. A trend seems to emerge for which galaxies with the lowest $M_{\star}$ are in agreement with the Calzetti et al. (2000) local relation, while galaxies at the highest $M_{\star}$ require a larger f -factor to reconcile the $H\alpha$ and UV SFR indicators. 50
- 2.12 Comparison between SFR_{IR+UV} and $SFR_{H\alpha}$ when varying the dust correction for the $H\alpha$ emission. The lower panel shows the case in which $L_{H\alpha}$ are corrected for dust attenuation by using the classical prescription of Calzetti ($f=0.58$) while in the upper panel the $H\alpha$ luminosities are corrected with our dust correction ($f=0.93$). The black solid line is the 1:1 correlation line and the different colors mark the stellar masses, as indicated in the vertical color-bar. In the lowest part of each panel are also shown the median errors on the SFR measurements. 51
- 2.13 $A_{H\alpha}$ as a function of stellar masses. The black filled circles are the sources at $z < 1$ while red filled squares are objects with $z > 1$. The attenuation is computed from $E_{star,IRX}(B - V)$ by using $f=0.93$. The grey filled circles are the median values of $A_{H\alpha}$ in three mass bins ($M_{\star} < 3 \times 10^{10} M_{\odot}$, $3 \times 10^{10} \leq M_{\star} < 1.7 \times 10^{11} M_{\odot}$, $M_{\star} \geq 1.7 \times 10^{11} M_{\odot}$) and the errorbars are the median scatter for $A_{H\alpha}$ and $M_{\star}$ in each mass bin. The two vertical dashed lines highlight the mass bins ($M_{\star} < 3 \times 10^{10} M_{\odot}$, $3 \times 10^{10} \leq M_{\star} < 1.7 \times 10^{11} M_{\odot}$, $M_{\star} \geq 1.7 \times 10^{11} M_{\odot}$). 52
- 2.14 $SFR_{H\alpha}$ versus $M_{\star}$ with $L_{H\alpha}$ corrected by dust with our recipe. The blue solid line reports the MS relationship from Elbaz et al. (2007) at $z = 1$ and the blue dashed line is the corresponding $4 \times MS$. The black filled circles are the sources at $z < 1$ while the red filled squares are the objects at $z > 1$. The median errors for $M_{\star}$ and $SFR_{H\alpha}$ are reported in the lower part of the plot on the right. 53
- 2.15 Linear fit (red line) to the best-fit SED in the plane $\log(\lambda), \log(F_{\lambda})$ 57

2.16	The plot displays the method for the computation of β_{phot} for the source 3213 (ID MUSIC). In the figure it is specified also the redshift of the source. The black open diamonds are the observed photometry, connected with a linear interpolation (black solid line). The green vertical lines highlight the rest-frame spectral range considered to compute M_1 while the blue vertical lines mark the range for the computation of M_2 . The two dash-dot red lines mark respectively the positions of 1600 Å and 2800 Å rest-frame.	58
2.17	The plot is analogous to the previous. In this case we do not have the photometric coverage to derive β_{phot}	59
2.18	Comparison between β_{model} , derived from the SED fitting, and β_{phot} , computed by fitting the observed photometry, for the 15 sources with photometric coverage in the rest-frame range $\lambda \in [1200 - 3500]\text{Å}$. The blue line is the 1:1 line. The linear Pearson correlation coefficient is $r=0.96$	60
3.1	SFR as a function of $M_\star$ for the <i>Herschel</i> -FMOS sources. Small grey dots are the sBzk sources used to define the MS. Red filled circles indicate the <i>Herschel</i> SBs with $H\alpha$ detection. Those with a <i>J</i> -long follow-up are highlighted with blue circles.	67
3.2	<i>Upper panel</i> : average <i>H</i> -long spectrum of the 12 $H\alpha$ -detected SB sources. <i>Lower panel</i> : average <i>J</i> -long (<i>left</i>) and <i>H</i> -long (<i>right</i>) spectra for the 8 $H\alpha$ -detected SBs with <i>J</i> -long follow-up. The red curve is the emission lines + continuum fit.	69
3.3	Individual <i>J</i> -long (<i>left</i>) and <i>H</i> -long (<i>right</i>) spectrum with emission line fits (red curve) for one of the sources in our starburst sample. The upper panel shows the FMOS spectra, while the bottom panel displays the noise in output from the data-reduction pipeline. In all the panels, the position of the emission lines is highlighted with red dashed lines. The dotted vertical regions highlight the position of flagged pixels, i.e. pixels heavily affected by residual sky emission. Bad pixels are identified as pixels with a noise larger than 2σ the average noise spectrum: the threshold is highlighted with a horizontal dashed line in orange.	69
3.4	Distribution of emission line fluxes from the average spectra resulting from the resampling technique described in the main text. The red lines highlight the median value and the confidence intervals of the distribution (continuous and dashed, respectively). The green lines indicate the line flux and error measured from the average spectrum of the full sample, i.e. 168 sources. . .	71
3.5	Individual emission lines distributions and median emission line fluxes (grey vertical line) for the sample of Kashino et al. (2013), compared with the average flux derived from the average spectrum (red vertical line). Dashed grey vertical lines highlight the 50 th percentile of each distribution.	72
3.6	$H\alpha$ attenuation as a function of $M_\star$ for $z \sim 1.6$ SBs, derived from the BD and the IRX. Our measurements are compared with the MS-trend at $z \sim 1.6$ and in the local Universe (solid and dashed lines respectively).	73
3.7	Cartoon sketching our two-component dust model in the two limiting solution discussed in the main text. <i>Left panel</i> : In this case the extended component is dust-free and the starburst has $A_{H\alpha, \text{thick}} \geq 4.5 \text{ mag}$. <i>Right panel</i> : the starbursting core is fully obscured ($A_{H\alpha, \text{thick}} \sim \infty$) and the diffuse component has $A_{H\alpha, \text{thin}} \sim 0.9 \text{ mag}$. In both cases, the optical emission is dominated by the less obscured regions while the starbursting core is bright in the far-IR.	74
3.8	HST/ACS F814W image of source PACS-787 with CO J = 5-4 overlaying contours (at 3, 5, 10, 20, 30, 40, $50\sigma_{\text{rms}}$, in red). The beam size of $0.33'' \times 0.3''$ is indicated in the lower left. The majority of the CO and mm emission are essentially unresolved with two well-separated components, illustrative of very compact starbursts. The HST/ACS image has diffuse emission possibly indicating tidal features from the interaction. In yellow we show the ALMA map of the emission with the two individual source removed. Extended low surface brightness emission is seen that extends between the positions of the two nuclei as indicative of an interaction. The blue circle indicates the position of the FMOS fiber (diameter $1.2''$). Courtesy of John Silverman.	75

- 3.9 *Left:* Metallicity as a function of $M_\star$ for the SB sample based on individual and stacked spectra, compared with the MZR and data points at $z \sim 1.6$ from the FMOS-MS sample of Kashino et al. (2017a) and Zahid et al. (2014). The shaded area marks a range of $\sim 0.1 \text{ dex}$, roughly the scatter of this relation. *Right:* FMR for SB galaxies compared with the Mannucci et al. (2010) equation and its scatter of $\sim 0.05 \text{ dex}$. The color code is as in the left panel. The right axis indicates the $[\text{NII}]_{6583}/\text{H}\alpha$ ratio. 76
- 3.10 Metallicity evolution for a galaxy with $\log(M_\star/M_\odot) \sim 10.2$ experiencing a burst of star-formation. The horizontal dashed line in magenta highlights the metallicity corresponding to $\log(M_\star/M_\odot) \sim 10.2$ as derived from the MZR of Zahid et al. (2014). The red dashed line highlights the value of $Z = 8.65$ reached by the system after $\Delta t_{\text{enrich}} \sim 20 \text{ Myr}$. We note here that the metallicity scale of this figure differs from the one used in Fig. 3.9 as different calibrations are considered. In this plot we adopted the Pettini & Pagel (2004) metallicity calibration, to be consistent with the MZR of Zahid et al. (2014) used as a reference in the computation. 78
- 3.11 *Left:* $[\text{SII}]_{6717}/[\text{SII}]_{6732}$ ratio as a function of $M_\star$, from Kashino et al. (2017a), with our measurement from the average spectrum of the starburst population (red dot) overlaid. Blue filled squares are the Kashino et al. (2017a) measurements in $M_\star$ bins while the cyan square corresponds to measurement on their entire sample. The small black dots show measurements for local galaxies from the SDSS. For more details, see Kashino et al. (2017a). *Right:* Comparison of optical line ratios, as presented in Figure 2 of Dopita et al. (2016), with theoretical model grids from MAPPINGS V. The models are computed as a function of the metallicity ($Z = 12 + \log(O/H)$), ionization parameter ($U = q_{\text{ion}}/c$), and gas pressure (P). Average measurements of the FMOS sample are based on stacked spectra in five stellar mass bins (Sample-2; blue circles, labeled). The median $M_\star$ are given in the upper right corner. Shaded contours show local star-forming galaxies, with their stacked points in equally-spaced 24 mass bins ($10^{8.9} \leq M_\star/M_\odot \leq 10^{11.3}$; squares) and in the same five mass bins as the FMOS sample (green circles, labeled). We add in this plot the measurement from the average spectrum of starbursts (red dot). From Kashino et al. (2017a). In both panels, a Salpeter (1955) IMF is adopted to compute the $M_\star$ for the MS sample. The $M_\star$ of the starburst sample are thus converted to a Salpeter (1955) IMF for consistency, by diving by a factor 1.7. 79
- 3.12 Correlation between $M_\star$ derived from the SED-fitting to the optical/near-IR photometry from Ilbert et al. (2009) and from the K_s -band photometry for the *Herschel*-detected sBzk sources in COSMOS at $1.4 \leq z \leq 2.5$ 82
- 3.13 Comparison between $M_\star$ derived from the K_s -band and from the SED fitting to the optical/near-IR rest-frame photometry for the *Herschel*-FMOS sources at $z \sim 1.6$ with a sBzk counterpart. Red line is the 1:1 relation. 82
- 3.14 Same as Figure 3.12 with sources splitted in three redshift bins, as indicated in the legend. . . 83
- 3.15 *SFR* versus $M_\star$ for *Herschel*-detected galaxies with a sBzk counterpart in the COSMOS field. We report their *SFR* from the dust-corrected UV emission with green open circles, while their measurement from the FIR with red filled circles. The black solid line is the MS equation from Rodighiero et al. (2011) derived at $z \sim 2$. The dotted line corresponds to the $4 \times \text{MS}$: sources above this line are selected as starbursts. Plots on the left use $M_\star$ from the K_s -band while plots on the right use $M_\star$ from the SED-fitting. The same plot is produced for the full redshift range considered in Rodighiero et al. (2014) and splitting the sample in three different redshift bins, as indicated in each panel. The *SFR* of each source is renormalized to $z \sim 2$, i.e. the average redshift at which the MS is computed, to account for the redshift evolution of the MS normalization. In each plot we report also the starburst statistics, their average distance from the MS (i.e. the starburstiness, $SFR_{\text{FIR,SB}}/SFR_{\text{MS}}$) and the average ratio between the *SFR* as derived from the FIR and the dust corrected UV emission ($SFR_{\text{FIR,SB}}/SFR_{\text{UV}}$). Continues in the next page. 86
- 3.15 *SFR* versus $M_\star$ for *Herschel*-detected galaxies with a sBzk counterpart in the COSMOS field (continued). 87

3.16	$SFR_{\text{FIR}}/SFR_{\text{UV,corr}}$ distribution for sources above the $4 \times MS$ relation. Different colors highlight sources in three different redshift bins: $1.4 \leq z \leq 1.7$ in red; $1.7 \leq z \leq 2$ in green; $2 \leq z \leq 2.5$ in blue. Solid vertical lines highlight the median value of the distribution in each redshift bin. Off-MS galaxies are selected using $M_{\star}$ from SED-fitting (<i>up</i>) and from the K_s -band (<i>bottom</i>): note the different median ratios in the lowest redshift bin. In addition, the ratio $\langle SFR_{\text{FIR}}/SFR_{\text{UV,corr}} \rangle$ increases with redshift.	88
3.17	<i>Upper panel:</i> comparison between $M_{\star}$ derived from the SED-fitting when varying the dust attenuation. <i>Lower panel:</i> $M_{\star}$ computed via the SED fitting using photometry and photo- z from different catalogs. Continuous line is the 1:1 relation.	88
3.18	$M_{\star}$ vs SFR plane for sBzk galaxies at $z \sim 1.6$. We indicate with black dots and black contours measurements of $M_{\star}$ as derived by fitting their multi- λ SED. We report with light blue dots the pre-existing measurements of $M_{\star}$ from the K_s -band (see text for details). The black solid line is the MS obtained by fitting the black points (i.e. SED-based measurements) while the light blue solid line is the MS equation from Silverman et al. (2015a), derived by fitting the blue points (K_s -band quantities). We also show for comparison the relationship from Rodighiero et al. (2011) and Speagle et al. (2014), re-scaled at $z \sim 1.6$ (blue and dark red lines respectively).	89
4.1	BPT diagram for the <i>Herschel</i> -FMOS sources above the MS. Red labeled diamonds are the individual measurements for AGN-dominated starbursts. For sources lacking the detection of one or two key emission lines upper limits were considered. Highlighted in grey we show the two galaxies without a <i>J-long</i> spectrum, which samples the spectral range around the $H\beta$ and $[\text{OIII}]_{4959,5007}$ emission lines. The big red cross is the average measurement for the AGN-dominated starbursts derived from the stacked spectrum shown in Fig. 4.4 (see text for details about the stacking). Black symbols are the Star-forming dominated starbursts presented in Puglisi et al. (2017): small circles are individual sources, the big triangle corresponds to the stack. We report for comparison average measurements from Kashino et al. (2017a), i.e. the FMOS sources lying on the MS at $z \sim 1.6$ (blue squares).	94
4.2	SFR vs $M_{\star}$ at $z \sim 1.6$. The red labeled diamonds are the AGN-SBs, while black dots show the star-forming dominated sample discussed in Puglisi et al. (2017). I highlight in black the AGN-dominated SBs with a high-quality spectrum: only these 6 sources are included in the average spectrum shown in Fig. 4.4.	95
4.3	Distribution of the SFR inferred from the far-IR emission for the AGN (red hatched histogram) and star-forming starburst (black curve) samples. The average value of each distribution is highlighted with vertical lines.	95
4.4	Average FMOS spectra of our SB samples at $z \sim 1.6$. <i>Left:</i> spectrum of the Star-Forming dominated SBs (Puglisi et al., 2017). <i>Right:</i> spectrum of the AGN dominated SBs. Only 6 out of the 8 AGN in the starburst region were included in this spectrum. I highlight the presence of a broad blue shifted component in the AGN spectrum, undetected in the Star-Forming SB one, and a clear outflow signature. I note also the different scales on the y-axis: the AGN-starbursts spectrum extends on a wider dynamic range of L_{λ}	96
4.5	HST imaging of the AGN sources in the starburst region at $z \sim 1.6$ observed with FMOS. IDs are reported on top of each cutout.	96
4.6	HST imaging of the star-forming dominated sources in the starburst region at $z \sim 1.6$ with FMOS- $H\alpha$ detection (Puglisi et al., 2017).	97
4.7	The two main panels on the left show the integrated SINFONI spectra for the two components of source PACS-357, one of our AGN in the starburst region undergoing a merger. The integrated spectra are extracted from the SINFONI cube within pseudo-circular apertures having a radius of 4 pixels (component A, <i>lower-left</i> panel) and 2 pixels (component B, <i>upper-left</i> panels). The insets show the $H\alpha$ map created with QFitsview: light-green pixels indicate the region within which the integrated spectrum was extracted. I report on the right the HST imaging, as a comparison with the SINFONI maps.	98

4.8	<i>Left:</i> $H\alpha$ dust attenuation as a function of $M_\star$ for $z \sim 1.6$ AGN-dominated starbursts from the BD (cyan) and the IRX (red). The solid line is the $A_{H\alpha}$ versus $M_\star$ trend derived by Kashino et al. (2013) for star-forming galaxies on the MS. <i>Right:</i> Same but for star-forming dominated starbursts (same as Fig. 3.6).	99
5.1	Schematic view of the different IFU techniques. For more details see the main text. From Westmoquette et al. (2009a)	102
5.2	<i>Left:</i> Bolometric AGN luminosity versus column density of the SUPER targets. The dashed line highlight the threshold of $N_H = 10^{22} \text{ cm}^{-2}$, above which AGN are classified as Type-2. <i>Right:</i> Eddington ratio as a function of Black Hole mass for the Type-1 AGN.	104
5.3	SFR vs $M_\star$ for the SUPER targets in COSMOS, i.e. the sources with reliable estimates of stellar masses and SFRs. The solid line highlights the position of the $z \sim 2$ MS, as derived by Rodighiero et al. (2014), while the dashed and dot-dashed lines indicate the scatter and the $4\times$ MS locus respectively.	106
5.4	Integrated spectra for XN_115_23 in H and K -band (<i>left</i> and <i>right</i> panel respectively). The two spectra are extracted within a pseudo-circular aperture of 3 and 5 <i>pixels</i> radius for H and K -band. In both panels, the fit to the emission lines and the residuals are also plotted (<i>bottom panels</i>). For details about the emission line fitting see the main text.	108
5.5	From left to right: flux, velocity and velocity dispersion maps of the $[OIII]_{5007}$ emission line for the target X_N_115_23. The upper panel shows the maps for the narrow component, while in the bottom panel the maps are produced for the blue-shifted component detected in the integrated spectrum shown in left panel of Fig. 5.4.	109
5.6	From left to right: flux, velocity and velocity dispersion maps of the narrow component of the $H\alpha$ emission line for the target X_N_115_23.	110
5.7	Integrated spectrum for XN_115_23 around the $[OIII]_{5007}$ emission in the velocity space. The emission line profile derived from the Gaussian fit is shown in red. Dotted vertical lines in grey highlight the position in the velocity space where the 5, 10, 50, 90 and 95 % of the emission line flux is contained, as defined in Harrison et al. (2014). The thick black line highlight the position of the emission line peak, while the blue dashed line represent the velocity offset of the blue wing.	111
5.8	Spatially resolved maps of v_{peak} (<i>upper-left</i>), Δw_{80} (<i>upper-right</i>), v_{10} (<i>lower-left</i>) and Δv (<i>upper-left</i>) as derived from the non parametric analysis around the $[OIII]_{5007}$ emission line.	111

List of Tables

2.1	Filters used for the SED fitting and respective effective wavelengths λ_{eff} (μm).	44
2.2	Summary of the values obtained for the f -factor as a function of the assumed reddening curve $k(\lambda)$: the first column is the $k(\lambda)$ assumed to compute the UV attenuation at 1600 Å, the second column is the $k(\lambda)$ used to compute the H α attenuation while the last column is the f -factor, obtained from eq. 2.12.	55
2.3	Different values of f obtained from literature. In the table are also specified the redshift ranges (third column of Tab. 2.3), the types of sample and the methods implied to measure the differential extinction on nebular lines (fourth and fifth columns of Tab. 2.3, respectively).	56
2.4	List of the main parameter measured for the galaxies in the sample. The first column indicates the MUSIC-ID of the sources, the second and third columns are the coordinates, the 4 th column reports the redshift derived from the 3D-HST near-IR spectrum, the 5 th column is the observed H α luminosity (i.e. not corrected for dust attenuation), the 6 th column reports the infrared luminosity, the 7 th column is the bolometric rest-frame UV luminosity (derived from L_{1600} , as explained in Section 2.4.2) and the last column is the stellar mass. For each of the quantities listed here it is also indicated the 1σ uncertainty. The quantities L_{IR} , L_{UV} and $M_{\star}$ are derived from the SED fitting with the MAGPHYS code (see Section 2.4.1). The H α luminosity is corrected for the contamination by [NII] (cfr. Section 2.4.2) and for the aperture (see Section 2.3.2)	61
2.5	List of the main parameter computed for the galaxies in the sample (continuation).	62
3.1	Physical properties of the $z \sim 1.6$ SB sample. The 1σ error on $M_{\star}$ is 0.1 <i>dex</i> . Emission line fluxes are aperture corrected, as described in Silverman et al. (2015b). Absolute line flux values are also affected by the error on the aperture correction (0.17 <i>dex</i> , Silverman et al., 2015b) . . .	68
3.2	Statistic of starburst (off-MS) galaxies at $1.4 \leq z \leq 2.5$ and splitted in the three redshift bins defined in Figure 3.14 when varying $M_{\star}$. The first column reports the starbursts statistics when galaxies are selected using $M_{\star}$ from the K_s -band while the second column report the same quantity but for starbursts selected with $M_{\star}$ from the SED fitting.	83
5.1	Emission line parameters as derived from the Gaussian fit to the integrated spectra of XN_115_23 shown in Fig. 5.4. Column one specifies the emission line component for which I report the centroid position (column 2), the integrated flux (column 3) and the line width (column 4). . .	108
5.2	Offset in velocity space of the emission line broad components with respect to the narrow ones as measured on the integrated spectra of Fig. 5.4 through the Gaussian fit.	109
5.3	Results of the non parametric analysis on the [OIII] ₅₀₀₇ emission line. See text for more details.	112

Bibliography

- Abramson, L. E., Kelson, D. D., Dressler, A., et al. 2014, *ApJL*, 785, L36
- Aird, J., Nandra, K., Laird, E. S., et al. 2010, *MNRAS*, 401, 2531
- Alexander, D. M., & Hickox, R. C. 2012, *NewAR*, 56, 93
- Antonucci, R. 1993, *ARA&A*, 31, 473
- Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, *ARA&A*, 47, 481
- Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, *PASP*, 93, 5
- Banerji, M., McMahon, R. G., Hewett, P. C., et al. 2012, *MNRAS*, 427, 2275
- Battisti, A. J., Calzetti, D., & Chary, R.-R. 2016, *ApJ*, 818, 13
- . 2017, *ApJ*, 840, 109
- Belfiore, F., Maiolino, R., Bundy, K., et al. 2015, *MNRAS*, 449, 867
- Berta, S., Magnelli, B., Nordon, R., et al. 2011, *A&A*, 532, A49
- Berta, S., Lutz, D., Santini, P., et al. 2013, *A&A*, 551, A100
- Bertin, E., & Arnouts, S. 1996, *A & A*, 117, 393
- Bisigello, L., Caputi, K. I., Grogin, N., & Koekemoer, A. 2017, *ArXiv e-prints*, arXiv:1706.06154
- Bolzonella, M., Miralles, J.-M., & Pelló, R. 2000, *A&A*, 363, 476
- Bolzonella, M., Kovač, K., Pozzetti, L., et al. 2010, *A&A*, 524, A76
- Boselli, A., Boissier, S., Cortese, L., et al. 2009, *ApJ*, 706, 1527
- Bournaud, F., Elmegreen, B. G., & Elmegreen, D. M. 2007, *ApJ*, 670, 237
- Brammer, G., van Dokkum, P. G., Franx, M., et al. 2012, *ApJs*, 200, 13
- Brusa, M., Feruglio, C., Cresci, G., et al. 2015, *A&A*, 578, A11
- Brusa, M., Perna, M., Cresci, G., et al. 2016, *A&A*, 588, A58
- Bruzual, G., & Charlot, S. 2003, *MNRAS*, 344, 1000
- Buat, V., Noll, S., Burgarella, D., et al. 2012, *A&A*, 545, A141
- Calzetti, D. 2001a, *PASP*, 113, 1449
- . 2001b, *NewAR*, 45, 601
- Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, *ApJ*, 533, 682
- Calzetti, D., Kinney, A. L., & Storchi-Bergmann, T. 1994, *ApJ*, 429, 582

BIBLIOGRAPHY

- Cano-Díaz, M., Maiolino, R., Marconi, A., et al. 2012, *A&A*, 537, L8
- Capak, P. L., Carilli, C., Jones, G., et al. 2015, *Nature*, 522, 455
- Cappellari, M., di Serego Alighieri, S., Cimatti, A., et al. 2009, *ApJL*, 704, L34
- Caputi, K. I., Deshmukh, S., Ashby, M. L. N., et al. 2017, *ArXiv e-prints*, arXiv:1705.06179
- Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, *ApJ*, 345, 245
- Carniani, S., Marconi, A., Maiolino, R., et al. 2017, *A&A*, 605, A105
- Casey, C. M., Narayanan, D., & Cooray, A. 2014a, *PhR*, 541, 45
- Casey, C. M., Scoville, N. Z., Sanders, D. B., et al. 2014b, *ApJ*, 796, 95
- Casey, C. M., Cooray, A., Killi, M., et al. 2017, *ApJ*, 840, 101
- Chabrier, G. 2003, *PASP*, 115, 763
- Chapman, S. C., Blain, A. W., Smail, I., & Ivison, R. J. 2005, *ApJ*, 622, 772
- Charlot, S., & Fall, S. M. 2000, *ApJ*, 539, 718
- Cicone, C., Maiolino, R., & Marconi, A. 2016, *A&A*, 588, A41
- Cicone, C., Maiolino, R., Sturm, E., et al. 2014, *A&A*, 562, A21
- Cid Fernandes, R., Mateus, A., Sodré, L., Stasińska, G., & Gomes, J. M. 2005, *MNRAS*, 358, 363
- Ciesla, L., Elbaz, D., & Fensch, J. 2017, *ArXiv e-prints*, arXiv:1706.08531
- Cimatti, A., Cassata, P., Pozzetti, L., et al. 2008, *A&A*, 482, 21
- Comastri, A. 2004, in *Astrophysics and Space Science Library*, Vol. 308, *Supermassive Black Holes in the Distant Universe*, ed. A. J. Barger, 245
- Concas, A., Popesso, P., Brusa, M., et al. 2017, *ArXiv e-prints*, arXiv:1701.06569
- Conroy, C. 2013, *ARA&A*, 51, 393
- Courteau, S., Cappellari, M., de Jong, R. S., et al. 2014, *Reviews of Modern Physics*, 86, 47
- Cresci, G., Mannucci, F., Maiolino, R., et al. 2010, *Nature*, 467, 811
- Cresci, G., Mainieri, V., Brusa, M., et al. 2015a, *ApJ*, 799, 82
- Cresci, G., Marconi, A., Zibetti, S., et al. 2015b, *A&A*, 582, A63
- da Cunha, E., Charlot, S., & Elbaz, D. 2008, *MNRAS*, 388, 1595
- Daddi, E., Cimatti, A., Renzini, A., et al. 2004, *ApJ*, 617, 746
- Daddi, E., Dickinson, M., Morrison, G., et al. 2007, *ApJ*, 670, 156
- Daddi, E., Elbaz, D., Walter, F., et al. 2010a, *ApJL*, 714, L118
- Daddi, E., Bournaud, F., Walter, F., et al. 2010b, *ApJ*, 713, 686
- Danielson, A. L. R., Swinbank, A. M., Smail, I., et al. 2011, *MNRAS*, 410, 1687
- . 2017, *ApJ*, 840, 78
- Davies, R. I. 2007, *MNRAS*, 375, 1099
- Dekel, A., & Burkert, A. 2014, *MNRAS*, 438, 1870

- Di Matteo, T., Springel, V., & Hernquist, L. 2005, *Nature*, 433, 604
- Domínguez, A., Siana, B., Henry, A. L., et al. 2013, *ApJ*, 763, 145
- Domínguez Sánchez, H., Bongiovanni, A., Lara-López, M. A., et al. 2014, *MNRAS*, 441, 2
- Dopita, M. A., Kewley, L. J., Sutherland, R. S., & Nicholls, D. C. 2016, *Ap&SS*, 361, 61
- Draine, B. T., & Li, A. 2007, *ApJ*, 657, 810
- Draine, B. T., Dale, D. A., Bendo, G., et al. 2007, *ApJ*, 663, 866
- Eisenhauer, F., Abuter, R., Bickert, K., et al. 2003, in *Proc. SPIE*, Vol. 4841, *Instrument Design and Performance for Optical/Infrared Ground-based Telescopes*, ed. M. Iye & A. F. M. Moorwood, 1548–1561
- Elbaz, D., Daddi, E., Le Borgne, D., et al. 2007, *A&A*, 468, 33
- Elbaz, D., Dickinson, M., Hwang, H. S., et al. 2011, *A&A*, 533, A119
- Ellison, S. L., Patton, D. R., Simard, L., & McConnachie, A. W. 2008, *AJ*, 135, 1877
- Elvis, M., Civano, F., Vignali, C., et al. 2009, *ApJS*, 184, 158
- Erb, D. K., Steidel, C. C., Shapley, A. E., et al. 2006, *ApJ*, 647, 128
- Fabian, A. C. 1994, *ARA&A*, 32, 277
- . 2012, *ARA&A*, 50, 455
- Fadda, D., & Rodighiero, G. 2014, *MNRAS*, 444, L95
- Fanelli, M. N., O’Connell, R. W., & Thuan, T. X. 1988, *ApJ*, 334, 665
- Farrah, D., Urrutia, T., Lacy, M., et al. 2012, *ApJ*, 745, 178
- Farrah, D., Lebouteiller, V., Spoon, H. W. W., et al. 2013, *ApJ*, 776, 38
- Farrah, D., Petty, S., Connolly, B., et al. 2017, *ArXiv e-prints*, arXiv:1705.02649
- Fensch, J., Renaud, F., Bournaud, F., et al. 2017, *MNRAS*, 465, 1934
- Feruglio, C., Maiolino, R., Piconcelli, E., et al. 2010, *A&A*, 518, L155
- Fioc, M., & Rocca-Volmerange, B. 1997, *A&A*, 326, 950
- Fiore, F., Feruglio, C., Shankar, F., et al. 2017, *ArXiv e-prints*, arXiv:1702.04507
- Fitzpatrick, E. L. 1999, *PASP*, 111, 63
- Förster Schreiber, N. M., Genzel, R., Bouché, N., et al. 2009, *ApJ*, 706, 1364
- Förster Schreiber, N. M., Genzel, R., Lehnert, M. D., et al. 2006, *ApJ*, 645, 1062
- Fritz, J., Franceschini, A., & Hatziminaoglou, E. 2006, *MNRAS*, 366, 767
- Fudamoto, Y., Oesch, P. A., Schinnerer, E., et al. 2017, *ArXiv e-prints*, arXiv:1705.01559
- Gabor, J. M., & Bournaud, F. 2014, *MNRAS*, 441, 1615
- Gao, Y., Lo, K. Y., Lee, S.-W., & Lee, T.-H. 2001, *ApJ*, 548, 172
- Garn, T., & Best, P. N. 2010, *MNRAS*, 409, 421
- Gavazzi, G., Consolandi, G., Dotti, M., et al. 2015, *A&A*, 580, A116
- Genzel, R., Tacconi, L. J., Gracia-Carpio, J., et al. 2010, *MNRAS*, 407, 2091

BIBLIOGRAPHY

- Genzel, R., Tacconi, L. J., Lutz, D., et al. 2015, *ApJ*, 800, 20
- Genzel, R., Schreiber, N. M. F., Übler, H., et al. 2017, *Nature*, 543, 397
- Georgantopoulos, I., Rovilos, E., Akylas, A., et al. 2011, *A&A*, 534, A23
- Glazebrook, K., Schreiber, C., Labbé, I., et al. 2017, *Nature*, 544, 71
- Gnerucci, A., Marconi, A., Cresci, G., et al. 2011, *A&A*, 528, A88
- Goldader, J. D., Meurer, G., Heckman, T. M., et al. 2002, *ApJ*, 568, 651
- Grazian, A., Fontana, A., de Santis, C., et al. 2006, *A & A*, 449, 951
- Greggio, L., & Renzini, A. 2011, *Stellar Populations. A User Guide from Low to High Redshift*
- Grogin, N. A., Kocevski, D. D., Faber, S. M., et al. 2011, *ApJs*, 197, 35
- Grupponi, C., Pozzi, F., Rodighiero, G., et al. 2013, *MNRAS*, 432, 23
- Harrison, C. M. 2017, *Nature Astronomy*, 1, 0165
- Harrison, C. M., Alexander, D. M., Mullaney, J. R., & Swinbank, A. M. 2014, *MNRAS*, 441, 3306
- Harrison, C. M., Alexander, D. M., Mullaney, J. R., et al. 2012, *ApJL*, 760, L15
- Harrison, C. M., Johnson, H. L., Swinbank, A. M., et al. 2017, *MNRAS*, 467, 1965
- Hirschmann, M., Charlot, S., Feltre, A., et al. 2017, *ArXiv e-prints*, arXiv:1706.00010
- Hoekstra, H., Bartelmann, M., Dahle, H., et al. 2013, *SSRv*, 177, 75
- Hopkins, P. F., Hernquist, L., Cox, T. J., & Kereš, D. 2008, *ApJS*, 175, 356
- Howell, J. H., Armus, L., Mazzarella, J. M., et al. 2010, *ApJ*, 715, 572
- Husemann, B., Scharwächter, J., Bennert, V. N., et al. 2016, *A&A*, 594, A44
- Ibar, E., Sobral, D., Best, P. N., et al. 2013, *MNRAS*, 434, 3218
- Ilbert, O., Arnouts, S., McCracken, H. J., et al. 2006, *A&A*, 457, 841
- Ilbert, O., Capak, P., Salvato, M., et al. 2009, *ApJ*, 690, 1236
- Ilbert, O., Salvato, M., Le Floc’h, E., et al. 2010, *ApJ*, 709, 644
- Ilbert, O., Arnouts, S., Le Floc’h, E., et al. 2015, *A&A*, 579, A2
- Ishibashi, W., & Fabian, A. C. 2016, *MNRAS*, 463, 1291
- Iwamuro, F., Moritani, Y., Yabe, K., et al. 2011, *FIBRE-pac: FMOS Image-based Reduction Package, Astrophysics Source Code Library*, , ascl:1111.013
- Johnson, B. D., Schiminovich, D., Seibert, M., et al. 2007, *ApJS*, 173, 392
- Juneau, S., Narayanan, D. T., Moustakas, J., et al. 2009, *ApJ*, 707, 1217
- Kakkad, D., Mainieri, V., Padovani, P., et al. 2016, *A&A*, 592, A148
- Kakkad, D., Mainieri, V., Brusa, M., et al. 2017, *MNRAS*, 468, 4205
- Kannappan, S. J., & Gawiser, E. 2007, *ApJL*, 657, L5
- Karim, A., Schinnerer, E., Martínez-Sansigre, A., et al. 2011, *ApJ*, 730, 61
- Kashino, D., Renzini, A., Silverman, J. D., & Daddi, E. 2016, *ApJL*, 823, L24

- Kashino, D., Silverman, J. D., Rodighiero, G., et al. 2013, *ApJL*, 777, L8
- Kashino, D., Silverman, J. D., Sanders, D., et al. 2017a, *ApJ*, 835, 88
- Kashino, D., More, S., Silverman, J. D., et al. 2017b, *ArXiv e-prints*, arXiv:1703.08326
- Kennicutt, R. C., & Evans, N. J. 2012, *ARA&A*, 50, 531
- Kennicutt, Jr., R. C. 1998a, *ARAA*, 36, 189
- . 1998b, *ApJ*, 498, 541
- Kennicutt, Jr., R. C., Hao, C.-N., Calzetti, D., et al. 2009, *ApJ*, 703, 1672
- Kewley, L. J., & Dopita, M. A. 2002, *ApJS*, 142, 35
- Kewley, L. J., Dopita, M. A., Leitherer, C., et al. 2013, *ApJ*, 774, 100
- Kimura, M., Maihara, T., Iwamuro, F., et al. 2010, *PASJ*, 62, 1135
- King, A., & Pounds, K. 2015, *ARA&A*, 53, 115
- Koekemoer, A. M., Faber, S. M., Ferguson, H. C., et al. 2011, *ApJs*, 197, 36
- Kong, X., Charlot, S., Brinchmann, J., & Fall, S. M. 2004, *MNRAS*, 349, 769
- Kormendy, J., & Ho, L. C. 2013, *ARA&A*, 51, 511
- Kriek, M., Shapley, A. E., Reddy, N. A., et al. 2015, *ApJS*, 218, 15
- Laigle, C., McCracken, H. J., Ilbert, O., et al. 2016, *ApJS*, 224, 24
- Lanzuisi, G., Delvecchio, I., Berta, S., et al. 2017, *ArXiv e-prints*, arXiv:1702.07357
- Levenson, L., Marsden, G., Zemcov, M., et al. 2010, *MNRAS*, 409, 83
- Lilly, S. J., Carollo, C. M., Pipino, A., Renzini, A., & Peng, Y. 2013, *ApJ*, 772, 119
- Liu, G., Zakamska, N. L., & Greene, J. E. 2014, *MNRAS*, 442, 1303
- Liu, G., Calzetti, D., Hong, S., et al. 2013, *ApJL*, 778, L41
- Lo Faro, B., Franceschini, A., Vaccari, M., et al. 2013, *ApJ*, 762, 108
- Lutz, D., Poglitsch, A., Altieri, B., et al. 2011, *A & A*, 532, A90
- Ma, X., Hopkins, P. F., Feldmann, R., et al. 2017, *MNRAS*, 466, 4780
- Madau, P., & Dickinson, M. 2014, *ArXiv e-prints*, arXiv:1403.0007
- Magdis, G. E., Daddi, E., Béthermin, M., et al. 2012, *ApJ*, 760, 6
- Magnelli, B., Elbaz, D., Chary, R. R., et al. 2009, *A & A*, 496, 57
- Magnelli, B., Lutz, D., Saintonge, A., et al. 2014, *A&A*, 561, A86
- Maier, C., Kuchner, U., Ziegler, B. L., et al. 2016, *A&A*, 590, A108
- Maiolino, R., Marconi, A., Salvati, M., et al. 2001, *A&A*, 365, 28
- Maiolino, R., Cox, P., Caselli, P., et al. 2005, *A&A*, 440, L51
- Maiolino, R., Nagao, T., Grazian, A., et al. 2008, *A&A*, 488, 463
- Maiolino, R., Gallerani, S., Neri, R., et al. 2012, *MNRAS*, 425, L66
- Maiolino, R., Russell, H. R., Fabian, A. C., et al. 2017, *Nature*, 544, 202

BIBLIOGRAPHY

- Mancini, C., Förster Schreiber, N. M., Renzini, A., et al. 2011, *ApJ*, 743, 86
- Mancuso, C., Lapi, A., Shi, J., et al. 2016, *ApJ*, 833, 152
- Mannucci, F., Cresci, G., Maiolino, R., Marconi, A., & Gnerucci, A. 2010, *MNRAS*, 408, 2115
- Maraston, C., Pforr, J., Renzini, A., et al. 2010, *MNRAS*, 407, 830
- Marchesi, S., Civano, F., Elvis, M., et al. 2016, *ApJ*, 817, 34
- Marconi, A., Risaliti, G., Gilli, R., et al. 2004, *MNRAS*, 351, 169
- Markwardt, C. B. 2009, in *Astronomical Society of the Pacific Conference Series*, Vol. 411, *Astronomical Data Analysis Software and Systems XVIII*, ed. D. A. Bohlender, D. Durand, & P. Dowler, 251
- Martig, M., Bournaud, F., Teyssier, R., & Dekel, A. 2009, *ApJ*, 707, 250
- Mas-Hesse, J. M., & Kunth, D. 1999, *A&A*, 349, 765
- Masters, D., & Capak, P. 2014, *SpecPro: Astronomical spectra viewer and analyzer*, *Astrophysics Source Code Library*, , , ascl:1404.014
- Mayya, Y. D., Bressan, A., Rodríguez, M., Valdes, J. R., & Chavez, M. 2004, *ApJ*, 600, 188
- McCracken, H. J., Capak, P., Salvato, M., et al. 2010, *ApJ*, 708, 202
- Meurer, G. R., Heckman, T. M., & Calzetti, D. 1999, *ApJ*, 521, 64
- Meurer, G. R., Heckman, T. M., Seibert, M., et al. 2002, *Highlights of Astronomy*, 12, 489
- Miettinen, O., Delvecchio, I., Smolčić, V., et al. 2017, *ArXiv e-prints*, arXiv:1707.00637
- Mobasher, B., Dahlen, T., Ferguson, H. C., et al. 2015, *ApJ*, 808, 101
- Modigliani, A., Hummel, W., Abuter, R., et al. 2007, *ArXiv Astrophysics e-prints*, astro-ph/0701297
- Monreal-Ibero, A., Vílchez, J. M., Walsh, J. R., & Muñoz-Tuñón, C. 2010, *A&A*, 517, A27
- Mor, R., & Netzer, H. 2012, *MNRAS*, 420, 526
- Morris, A. M., Kocevski, D. D., Trump, J. R., et al. 2015, *ArXiv e-prints*, arXiv:1502.02659
- Morselli, L., Popesso, P., Erfanianfar, G., & Concas, A. 2017, *A&A*, 597, A97
- Müller-Sánchez, F., Prieto, M. A., Hicks, E. K. S., et al. 2011, *ApJ*, 739, 69
- Muzzin, A., van Dokkum, P., Kriek, M., et al. 2010, *ApJ*, 725, 742
- Muzzin, A., Marchesini, D., Stefanon, M., et al. 2013, *ApJS*, 206, 8
- Narayanan, D., Dave, R., Johnson, B., et al. 2017, *ArXiv e-prints*, arXiv:1705.05858
- Narayanan, D., Krumholz, M. R., Ostriker, E. C., & Hernquist, L. 2012, *MNRAS*, 421, 3127
- Narayanan, D., Turk, M., Feldmann, R., et al. 2015, *Nature*, 525, 496
- Negrello, M., Amber, S., Amvrosiadis, A., et al. 2017, *MNRAS*, 465, 3558
- Nelson, E. J., van Dokkum, P. G., Förster Schreiber, N. M., et al. 2016, *ApJ*, 828, 27
- Netzer, H. 2013, *The Physics and Evolution of Active Galactic Nuclei*
- Noeske, K. G., Weiner, B. J., Faber, S. M., et al. 2007, *ApJL*, 660, L43
- Noll, S., Burgarella, D., Giovannoli, E., et al. 2009, *A&A*, 507, 1793

- Nordon, R., Lutz, D., Saintonge, A., et al. 2013, *ApJ*, 762, 125
- Nordon, R., Lutz, D., Genzel, R., et al. 2012, *ApJ*, 745, 182
- Oliver, S. J., Bock, J., Altieri, B., et al. 2012, *MNRAS*, 424, 1614
- Onodera, M., Arimoto, N., Daddi, E., et al. 2010a, *ApJ*, 715, 385
- Onodera, M., Daddi, E., Gobat, R., et al. 2010b, *ApJL*, 715, L6
- Osterbrock, D. E., & Ferland, G. J. 2006, *Astrophysics of gaseous nebulae and active galactic nuclei*
- Oteo, I., Bongiovanni, Á., Magdis, G., et al. 2014, *MNRAS*, 439, 1337
- Padovani, P., Alexander, D. M., Assef, R. J., et al. 2017, *A&A Rv*, 25, 2
- Pannella, M., Carilli, C. L., Daddi, E., et al. 2009, *ApJL*, 698, L116
- Pannella, M., Elbaz, D., Daddi, E., et al. 2014, *ArXiv e-prints*, arXiv:1407.5072
- Panter, B., Jimenez, R., Heavens, A. F., & Charlot, S. 2008, *MNRAS*, 391, 1117
- Papovich, C., Rudnick, G., Le Floch, E., et al. 2007, *ApJ*, 668, 45
- Peng, C. Y. 2007, *ApJ*, 671, 1098
- Perna, M., Lanzuisi, G., Brusa, M., Cresci, G., & Mignoli, M. 2017, *ArXiv e-prints*, arXiv:1705.08388
- Perna, M., Brusa, M., Cresci, G., et al. 2015, *A&A*, 574, A82
- Pettini, M., & Pagel, B. E. J. 2004, *MNRAS*, 348, L59
- Pforr, J., Maraston, C., & Tonini, C. 2012, *MNRAS*, 422, 3285
- Poggianti, B. M., Bressan, A., & Franceschini, A. 2001, *ApJ*, 550, 195
- Pope, A., Scott, D., Dickinson, M., et al. 2006, *MNRAS*, 370, 1185
- Popping, G., Puglisi, A., & Norman, C. A. 2017, *ArXiv e-prints*, arXiv:1706.06587
- Price, S. H., Kriek, M., Brammer, G. B., et al. 2014, *ApJ*, 788, 86
- Price, S. H., Kriek, M., Shapley, A. E., et al. 2016, *ApJ*, 819, 80
- Puglisi, A., Rodighiero, G., Franceschini, A., et al. 2016, *A&A*, 586, A83
- Puglisi, A., Daddi, E., Renzini, A., et al. 2017, *ApJL*, 838, L18
- Reddy, N., Dickinson, M., Elbaz, D., et al. 2012, *ApJ*, 744, 154
- Reddy, N. A., Erb, D. K., Pettini, M., et al. 2010, *ApJ*, 712, 1070
- Reddy, N. A., Kriek, M., Shapley, A. E., et al. 2015, *ArXiv e-prints*, arXiv:1504.02782
- Reddy, N. A., Oesch, P. A., Bouwens, R. J., et al. 2017, *ArXiv e-prints*, arXiv:1705.09302
- Renzini, A. 2016, *MNRAS*, 460, L45
- Renzini, A., & Peng, Y.-j. 2015, *ApJL*, 801, L29
- Rich, J. A., Kewley, L. J., & Dopita, M. A. 2015, *ApJS*, 221, 28
- Rodighiero, G., Renzini, A., Daddi, E., et al. 2014, *MNRAS*, 443, 19
- Rodighiero, G., Daddi, E., Baronchelli, I., et al. 2011, *ApJL*, 739, L40
- Rodighiero, G., Brusa, M., Daddi, E., et al. 2015, *ApJL*, 800, L10

BIBLIOGRAPHY

- Roseboom, I. G., Oliver, S. J., Kunz, M., et al. 2010, *MNRAS*, 409, 48
- Roseboom, I. G., Dunlop, J. S., Cirasuolo, M., et al. 2013, *MNRAS*, 436, 430
- Rousselot, P., Lidman, C., Cuby, J.-G., Moreels, G., & Monnet, G. 2000, *A&A*, 354, 1134
- Rupke, D. S. N., Kewley, L. J., & Barnes, J. E. 2010, *ApJL*, 710, L156
- Salpeter, E. E. 1955, *ApJ*, 121, 161
- Sanders, D. B., & Mirabel, I. F. 1996, *ARA&A*, 34, 749
- Sanders, D. B., Soifer, B. T., Elias, J. H., et al. 1988, *ApJ*, 325, 74
- Sanders, R. L., Shapley, A. E., Kriek, M., et al. 2016, *ApJ*, 816, 23
- Santini, P., Fontana, A., Grazian, A., et al. 2009, *VizieR Online Data Catalog*, 350, 40751
- Santini, P., Maiolino, R., Magnelli, B., et al. 2014, *A&A*, 562, A30
- Sargent, M. T., Béthermin, M., Daddi, E., & Elbaz, D. 2012, *ApJL*, 747, L31
- Sargent, M. T., Daddi, E., Béthermin, M., et al. 2014, *ApJ*, 793, 19
- Schawinski, K., Thomas, D., Sarzi, M., et al. 2007, *MNRAS*, 382, 1415
- Schmidt, K. B., Rix, H.-W., da Cunha, E., et al. 2013, *MNRAS*, 432, 285
- Schreiber, C., Elbaz, D., Pannella, M., et al. 2016, *A&A*, 589, A35
- Schreiber, C., Pannella, M., Elbaz, D., et al. 2015, *A&A*, 575, A74
- Scoville, N., Sheth, K., Aussel, H., et al. 2015, *ArXiv e-prints*, arXiv:1505.02159
- . 2016, *ApJ*, 820, 83
- Scoville, N. Z., Sanders, D. B., & Clemens, D. P. 1986, *ApJL*, 310, L77
- Seibert, M., Heckman, T., Charlot, S., & GALEX Science Team. 2003, in *Bulletin of the American Astronomical Society*, Vol. 35, American Astronomical Society Meeting Abstracts, 1372
- Shankar, F., Weinberg, D. H., & Miralda-Escudé, J. 2009, *ApJ*, 690, 20
- Shapley, A. E., Steidel, C. C., Erb, D. K., et al. 2005, *ApJ*, 626, 698
- Shivaei, I., Kriek, M., Reddy, N. A., et al. 2016, *ApJL*, 820, L23
- Silk, J., & Mamon, G. A. 2012, *Research in Astronomy and Astrophysics*, 12, 917
- Silverman, J. D., Kampczyk, P., Jahnke, K., et al. 2011, *ApJ*, 743, 2
- Silverman, J. D., Daddi, E., Rodighiero, G., et al. 2015a, *ApJL*, 812, L23
- Silverman, J. D., Kashino, D., Sanders, D., et al. 2015b, *ApJS*, 220, 12
- Simpson, J. M., Smail, I., Swinbank, A. M., et al. 2016, *ArXiv e-prints*, arXiv:1611.03084
- Skelton, R. E., Whitaker, K. E., Momcheva, I. G., et al. 2014, *ArXiv e-prints*, arXiv:1403.3689
- Sobral, D., Swinbank, A. M., Stott, J. P., et al. 2013, *ApJ*, 779, 139
- Speagle, J. S., Steinhardt, C. L., Capak, P. L., & Silverman, J. D. 2014, *ApJS*, 214, 15
- Steidel, C. C., Rudie, G. C., Strom, A. L., et al. 2014, *ApJ*, 795, 165
- Stott, J. P., Sobral, D., Swinbank, A. M., et al. 2014, *MNRAS*, 443, 2695

- Sturm, E., Verma, A., Graciá-Carpio, J., et al. 2010, *A&A*, 518, L36
- Su, S., Kong, X., Li, J., & Fang, G. 2013, *ApJ*, 778, 10
- Swinbank, A. M., Sobral, D., Smail, I., et al. 2012, *MNRAS*, 426, 935
- Swinbank, A. M., Dye, S., Nightingale, J. W., et al. 2015, *ApJL*, 806, L17
- Swinbank, A. M., Harrison, C. M., Trayford, J., et al. 2017, *MNRAS*, 467, 3140
- Tacchella, S., Dekel, A., Carollo, C. M., et al. 2016, *MNRAS*, 457, 2790
- Tacchella, S., Carollo, C. M., Renzini, A., et al. 2015, *Science*, 348, 314
- Tacchella, S., Carollo, C. M., Forster Schreiber, N. M., et al. 2017, *ArXiv e-prints*, arXiv:1704.00733
- Tacconi, L. J., Neri, R., Genzel, R., et al. 2013, *ApJ*, 768, 74
- Tacconi, L. J., Genzel, R., Saintonge, A., et al. 2017, *ArXiv e-prints*, arXiv:1702.01140
- Takata, T., Sekiguchi, K., Smail, I., et al. 2006, *ApJ*, 651, 713
- Talia, M., Cimatti, A., Pozzetti, L., et al. 2015, *A&A*, 582, A80
- Talia, M., Cimatti, A., Brusa, M., et al. 2016, *ArXiv e-prints*, arXiv:1611.05884
- Tan, Q., Daddi, E., Magdis, G., et al. 2014, *A&A*, 569, A98
- Teplitz, H. I., Charmandaris, V., Chary, R., et al. 2005, *ApJ*, 634, 128
- Thomas, D., Maraston, C., Bender, R., & Mendes de Oliveira, C. 2005, *ApJ*, 621, 673
- Toft, S., Smolčić, V., Magnelli, B., et al. 2014, *ApJ*, 782, 68
- Tombesi, F., Cappi, M., Reeves, J. N., & Braitto, V. 2012, *MNRAS*, 422, L1
- Tremonti, C. A., Heckman, T. M., Kauffmann, G., et al. 2004, *ApJ*, 613, 898
- Treu, T., & Marshall, P. J. 2016, *A&A Rv*, 24, 11
- Troncoso, P., Maiolino, R., Sommariva, V., et al. 2014, *A&A*, 563, A58
- Turner, O. J., Cirasuolo, M., Harrison, C. M., et al. 2017, *ArXiv e-prints*, arXiv:1704.06263
- Urry, C. M., & Padovani, P. 1995, *PASP*, 107, 803
- Väisänen, P., Reunanen, J., Kotilainen, J., et al. 2017, *ArXiv e-prints*, arXiv:1701.00890
- Väisänen, P., Mattila, S., Kniazev, A., et al. 2008, *MNRAS*, 384, 886
- Valentino, F., Daddi, E., Strazzullo, V., et al. 2015, *ApJ*, 801, 132
- Valentino, F., Daddi, E., Silverman, J. D., et al. 2017, *MNRAS*, 472, 4878
- van de Sande, J., Kriek, M., Franx, M., et al. 2013, *ApJ*, 771, 85
- Veilleux, S., Rupke, D. S. N., Kim, D.-C., et al. 2009, *ApJS*, 182, 628
- Viero, M. P., Wang, L., Zemcov, M., et al. 2013, *ApJ*, 772, 77
- Wardlow, J. L., Cooray, A., Osage, W., et al. 2017, *ApJ*, 837, 12
- Westmoquette, M. S., Clements, D. L., Bendo, G. J., & Khan, S. A. 2012, *MNRAS*, 424, 416
- Westmoquette, M. S., Exter, K. M., Christensen, L., et al. 2009a, *ArXiv e-prints*, arXiv:0905.3054
- Westmoquette, M. S., Gallagher, J. S., Smith, L. J., et al. 2009b, *ApJ*, 706, 1571

BIBLIOGRAPHY

- Whitaker, K. E., Franx, M., Leja, J., et al. 2014, ArXiv e-prints, arXiv:1407.1843
- Whitaker, K. E., van Dokkum, P. G., Brammer, G., & Franx, M. 2012, ApJL, 754, L29
- Wild, V., Charlot, S., Brinchmann, J., et al. 2011, MNRAS, 417, 1760
- Wisnioski, E., Förster Schreiber, N. M., Wuyts, S., et al. 2015, ApJ, 799, 209
- Wuyts, E., Wisnioski, E., Fossati, M., et al. 2016a, ApJ, 827, 74
- Wuyts, S., Cox, T. J., Hayward, C. C., et al. 2010, ApJ, 722, 1666
- Wuyts, S., Förster Schreiber, N. M., Lutz, D., et al. 2011, ApJ, 738, 106
- Wuyts, S., Förster Schreiber, N. M., Nelson, E. J., et al. 2013, ApJ, 779, 135
- Wuyts, S., Förster Schreiber, N. M., Wisnioski, E., et al. 2016b, ApJ, 831, 149
- Xue, Y. Q., Luo, B., Brandt, W. N., et al. 2011, ApJS, 195, 10
- Yoshikawa, T., Akiyama, M., Kajisawa, M., et al. 2010, ApJ, 718, 112
- Zahid, H. J., Geller, M. J., Kewley, L. J., et al. 2013, ApJL, 771, L19
- Zahid, H. J., Kashino, D., Silverman, J. D., et al. 2014, ApJ, 792, 75
- Zakamska, N. L., & Greene, J. E. 2014, MNRAS, 442, 784
- Zolotov, A., Dekel, A., Mandelker, N., et al. 2015, MNRAS, 450, 2327