

Metallicity evolution, metallicity gradients and gas fractions at $z \sim 3.4$ [★]

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ABSTRACT

We use near-infrared integral field spectroscopic observations from the AMAZE and LSD ESO programs to constrain the metallicity in a sample of 40 star forming galaxies at $3 < z < 5$ (most of which at $z \sim 3.4$). We measure metallicities by exploiting strong emission line diagnostics. We find that a significant fraction of star forming galaxies at $z \sim 3.4$ deviate from the Fundamental Metallicity Relation (FMR), by having a metallicity up to a factor of ten lower than expected by the FMR. The deviation does not correlate with the dynamical properties of the galaxy or with the presence of interactions. To further investigate the origin of the metallicity deviations, we also infer information on the gas content, by inverting the Schmidt-Kennicutt relation, assuming that the latter does not evolve significantly out to $z \sim 3.4$. In agreement with recent CO observational data, we find that, in contrast with the steeply rising trend at $0 < z < 2$, the gas fraction in massive galaxies remains constant, with indication of a marginal decline, at $2 < z < 3.5$. When combined with the metallicity information, we infer that, in order to explain both the low metallicity and gas content in $z \sim 3.4$ galaxies, both prominent outflows and massive pristine gas inflows are needed. In ten galaxies we can also spatially resolve the metallicity distribution. We find that generally the metallicity anticorrelates with the distribution of star formation and with the gas surface density. We discuss these findings, both in terms of pristine gas inflows towards the center, and outflows of metal rich gas from the center towards the external regions.

Key words. ISM: abundances – galaxies: abundances – galaxies: evolution – galaxies: high-redshift – galaxies: starburst

1. Introduction

Both observations and theory have led, during the past few years, to a new scenario where galaxy evolution is primarily regulated by the gas content in galaxies, which is, in turn, regulated by gas inflow and outflow phenomena. Millimeter observations have revealed large amount of molecular gas in high redshift galaxies (Tacconi et al. 2010; Daddi et al. 2010). Such gas rich galaxies are generally massive rotating disks, already in place at such early epochs, which obey the same Schmidt-Kennicutt (hereafter S-K law, Schmidt 1959; Kennicutt 1998) star formation law observed in the local universe and whose enhanced star formation rate is simply a consequence of their higher gas content relative to local galaxies and not driven by enhanced star formation efficiency (Genzel et al. 2004; Bouché et al. 2007; Genzel et al. 2010; Daddi et al. 2010).

Several models can account for such observed trends. The emerging scenario is that, at high redshift, gas from the in-

tergalactic medium quickly replenish galaxies through smooth cold flows (e.g. Dekel et al. 2009). As a consequence of the high pressure, such gas is mostly transformed into molecular hydrogen, which can effectively be used to feed star formation (Obreschkow & Rawlings 2009; Lagos et al. 2011). These models provide a detailed description of the evolution of the molecular gas content in galaxies as a function of redshift and as a function of galaxy (halo) mass. According to these models the evolution of the cosmic star formation rate is simply a consequence of the evolution of the molecular gas content in galaxies through the Schmidt-Kennicutt relation (Bouché et al. 2010; ?).

Gas flows are thought to also be primarily responsible for the variation of metals content in galaxies and their redshift evolution. In particular the well known mass-metallicity relation has been primarily ascribed to outflow of metal rich gas, which is preferentially expelled from low mass galaxies (Tremonti et al. 2004), although effects associated with the IMF, downsizing and gas infalls have also been invoked and several thorough theoretical models have been proposed (Köppen et al. 2007; Kobayashi et al. 2007; Brooks et al. 2007; De Rossi et al. 2007; Cescutti et

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al. 2007; Finlator & Davé 2008; Arrigoni et al. 2009; Calura et al. 2009; Calura & Menci 2009; Davé et al. 2011b; Sakstein et al. 2011; Davé et al. 2012; Dayal et al. 2013).

More recently, it has been found that the gas metallicity has also a secondary dependence on the star formation rate (SFR). At a given stellar mass the metallicity decreases with increasing SFR (Kewley et al. 2006; Ellison et al. 2008; Mannucci et al. 2010; Lara Lopez et al. 2010; Cresci et al. 2012; Yates et al. 2012; Andrews & Martini 2013; Pérez-Montero et al. 2013).

This three-dimensional relationship between stellar mass, SFR and metallicity, has been dubbed “Fundamental Metallicity Relation” (Mannucci et al. 2010, FMR). Such a relation is very tight (dispersion 0.05dex), suggesting that it reflects a smooth secular interplay between star formation and gas flows. In particular, one of the basic ideas behind the inverse correlation between SFR and metallicity is that it is primarily associated with inflow of pristine gas: the accreted gas on the one hand dilutes the gas metallicity, on the other hand boosts star formation through the Schmidt-Kennicutt relation. More detailed models and simulations have been presented by various authors to interpret the FMR (Davé et al. 2011b; Lagos et al. 2011; Davé et al. 2012; Yates et al. 2012; Dayal et al. 2013; Lilly et al. 2013; Forbes et al. 2013).

Recently, Sánchez et al. (2013) by using spatially resolved spectroscopy of nearby galaxies, have not confirmed the metallicity dependence on the SFR, in contrast to previous studies. Part of the discrepancy may be associated with the use of the metallicity at the effective radius, instead of the metallicity obtained from the integrated line emission within the same aperture used to infer the SFR. Indeed, Bothwell et al. (2013) have shown that the anticorrelation with the SFR (with small dispersion) is only found if both metallicity and SFR are extracted from the same aperture (and actually from the same spectrum integrated within the same aperture), while the scatter increases largely if the metallicity from the central region (SDSS fiber aperture) is compared with the total, integrated SFR. Bothwell et al. (2013) have also found evidence for a more fundamental relation between HI gas mass, metallicity and stellar mass (HI-FMR). They suggest that the classical FMR (SFR-FMR) is a by product of the HI-FMR. However, even if the SFR-FMR is a consequence of the HI-FMR, the former can anyhow be considered as a tool to trace galaxy evolutionary processes.

One important aspect of the FMR, is that it is found not to evolve with redshift, out to $z \sim 2.5$, suggesting that the same mechanism of galaxy formation is at work in most galaxies out to this redshift (Mannucci et al. 2010; Lara Lopez et al. 2010; Richard et al. 2011; Belli et al. 2013). Significant evolution was found at $z \sim 3$ by Mannucci et al. (2010), by using an initial subsample of the AMAZE and LSD spectroscopic surveys (Maiolino et al. 2008; Mannucci et al. 2009), finding that galaxies at $z > 3$ are anomalously metal poor, and specifically about 0.6 dex below the FMR.

If the evolution of the FMR is confirmed at $z > 3$ with higher statistics, this may suggest a change in the dominant mode of galaxy formation. One possibility is that an excess of gas inflow at early epochs causes an excess of metallicity dilution.

Evidence for such massive inflows at $z \sim 3$ has been found through the analysis of metallicity gradients. By exploiting integral field spectroscopic data of three galaxies at $z \sim 3$ from the AMAZE sample, Cresci et al. (2010) found evidence for inverted (positive) metallicity gradients. In particular, the region of lowest metallicity is found to be coincident with the region of highest star formation, suggesting that strong infall of pristine gas both dilutes the metallicity and boosts star formation in these galax-

ies at $z \sim 3$. Studies of resolved metallicities at lower redshift have obtained mixed results, with samples of galaxies showing both positive and negative gradients (Jones et al. 2010; Queyrel et al. 2012; Jones et al. 2013), possibly hinting at evolutionary trends and dependence on the dynamical status of galaxies. The inverted gradients at $z \sim 3$ are however based on only three galaxies, hence requiring a larger sample to achieve a statistically sound result.

In this paper, we present the results from the full sample of $z \sim 3-4$ galaxies from AMAZE, an ESO Large Programme exploiting the VLT integral field near-IR spectrograph SINFONI, combined with the parallel programme LSD, performed with Adaptive Optics, which are described more in detail in the next sections. While the dynamical properties of these samples were discussed in Gnerucci et al. (2011a), in this paper we focus on the distribution of the SFR (from which we infer the gas fraction) and the metallicity properties (both integrated and spatially resolved), by extending the results based on the first subsample presented in Maiolino et al. (2008), Cresci et al. (2010) and Mannucci et al. (2009).

2. The AMAZE project: sample and data

This paper is primarily based on the AMAZE project, which uses near-IR integral field spectroscopy of star forming galaxies at redshift $3 < z < 5$ with SINFONI (Eisenhauer et al. 2003) at the Very Large Telescope (VLT). A complete description of the AMAZE programs and of the methods used for data analysis and reduction are presented in Maiolino et al. (2008). Here we report a brief summary of the observing program and of the data obtained.

AMAZE is an ESO large program that was awarded 180 hours of observations with SINFONI. The sample consists of 31 Lyman Break Galaxies in the redshift range $3 < z < 5.2$ (most of which at $z \sim 3.4$), with Spitzer/IRAC photometry ($3.6 - 8 \mu\text{m}$) required to derive reliable stellar masses. LBGs hosting AGNs were discarded based on either UV (optical rest-frame) spectra, hard X-ray data and on the MIPS $24 \mu\text{m}$ flux (see discussion in Maiolino et al. 2008).

SINFONI was used in seeing-limited mode, with the $0.125'' \times 0.25''$ pixel scale and the H+K grating, yielding a spectral resolution $R \sim 1500$ over the spectral range $1.45 - 2.41 \mu\text{m}$. The typical seeing during the observations was about $0.6-0.7''$.

The main goals of the project are to obtain information on the metal enrichment and dynamics of galaxies at $z > 3$ by exploiting the optical nebular lines of [OII] $\lambda 3727$, [NeIII] $\lambda 3869$, $H\beta$ and [OIII] $\lambda 4959, 5007$ redshifted into the H and K bands.

Data were reduced by using the ESO-SINFONI pipeline (version 3.6.1). The pipeline subtracts the sky from the temporally contiguous frames, flat-fields the images, spectrally calibrates each individual slice and then reconstructs the cube. Within the pipeline the pixels are resampled to a symmetric angular size of $0.125'' \times 0.125''$. The atmospheric absorption and instrumental response were taken into account and corrected for by using a suitable standard star.

Besides SPITZER data, optical and near-IR photometry is available from the archives Steidel et al. (2003); Grazian et al. (2006) and also from new TNG observations (Sommariva in prep.) obtained with the near-IR camera NICS (Baffa et al. 2001). HST optical and near-IR archival images (WFPC3, WFPC2, ACS) are available for most of the sources located in GOODS-S as well as for a few additional AMAZE targets in the archive. Of these we have used primarily the images obtained

with the filters F606W, F775W and F814W to probe the rest-frame UV emission and, therefore, study the environment and morphology (Sommariva in prep.).

The full list of galaxies in the AMAZE sample is given in Table 1 along with some of their main observational properties. The AMAZE galaxies were extracted from the Steidel et al. (2003) and Vanzella et al. (2006) catalogues. The AMAZE sample ($\langle R \rangle \sim 24$) is globally representative of the galaxies in the parent samples (Steidel et al. 2003; Vanzella et al. 2006), which peak at $\langle R \rangle \sim 24.5$, although slightly brighter. Note that the galaxies were not pre-selected on any prior knowledge of nebular lines detectability (either in the optical or in the near-IR).

In addition, five lensed galaxies were selected (marked with an asterisk in Table 1) that allow us to probe galaxies with lower SFR than the bulk of the sample. Four of these are lensed by the cluster Abell 1689, and their magnification factor has been obtained by constructing a lens model of the cluster by using the 34 multiply imaged systems published in Limousin et al. (2007). Twenty four of these multiply imaged systems have spectroscopic redshifts, which ensures the model to be robustly calibrated. To derive the cluster magnification maps, we used the Lenstool public software (Kneib et al. 1996) and we reproduced the Limousin et al. (2007) mass model using the parameter file available at <http://www.astro.ku.dk/marceau/model.par>. Then, we sampled the magnification maps to derive the local measurements of the magnification at the galaxy positions. The data for the fifth lensed source, the ‘‘Cosmic Eye’’, were taken from the archive, and its magnification factor was taken from Smail et al. (2007).

Preliminary results on the mass-metallicity relation at $z \sim 3.4$ based on a first subset of nine galaxies are presented in Maiolino et al. (2008). As mentioned, the metallicity gradients for three bright and extended AMAZE galaxies are presented in Cresci et al. (2010). A study of the kinematics and dynamics of the whole sample is presented in Gnerucci et al. (2011a,b), who find a significant fraction (about one third) of galaxies characterized by regular disk rotation patterns. Sommariva et al. (2012) also obtained stellar metallicities from optical (UV rest-frame) spectra of a few AMAZE galaxies, finding values broadly consistent with the metallicities inferred from the optical nebular lines.

3. The LSD project

The AMAZE data are complemented with the LSD project, whose data are presented in Mannucci et al. (2009). LSD is a parallel SINFONI project consisting of observations assisted with the Adaptive Optics module of nine LBG’s at $z \sim 3$. Data analysis and reduction are presented in Mannucci et al. (2009). Thanks to the exploitation of the AO module these data achieve an angular resolution ($\sim 0.1 - 0.2''$) much higher than in the AMAZE data.

The kinematics for the LSD galaxies is presented in Gnerucci et al. (2011a). HST data of the LSD galaxies is also available through new observations (Sommariva in prep.).

The list of LSD galaxies is given in Table 1 along with their observational properties. The LSD sample is representative of the global LBG population selected by Steidel et al. (2003), as discussed in Mannucci et al. (2009).

4. Basic observational results

In this section we provide some basic observational results, such as the integrated spectra, integrated emission line fluxes, stacked spectra, as well as ancillary data and information.

4.1. Emission lines

The spectra are extracted within fixed apertures of $0.75''$ in diameter (corresponding to ~ 5.4 kpc projected on sources at $z \sim 3.4$), which in most cases encloses more than 70% of the emission line flux and generally maximizes the S/N ratio. The same procedure has been applied for the AMAZE and LSD sources previously published. There are four exceptions ‘‘SSA22aM38’’, ‘‘SSA22aC36’’, ‘‘CDF512631’’ and ‘‘DSFC21’’ for which the line emission extends significantly beyond $0.75''$. Only for these four sources an aperture of $1.25''$ has been used. Figure A.1, A.2, A.3 and A.5 in the Appendix show the spectra extracted for all sources.

For the three lensed sources at $z \sim 3$, ‘‘LnA1689-1’’, ‘‘LnA1689-4’’ and the ‘‘Cosmic eye’’ the spectra extraction was done manually by choosing the regions with high S/N. Their spectra are shown in figure A.4.

For all sources the redshift is such that [OII]3727 and [NeIII]3870 is redshifted into the H-band while $H\beta$ and [OIII]5007 are redshifted into the K-band, with the exception of galaxies at $4.1 < z < 5.2$ for which only [OII] and [NeIII] are observable in the K band. Five sources are undetected, as noted in Table 1, two of which are at $z > 4$. CDFS-13497 presents a very poor S/N spectrum (see Fig.A.2) and it is not included in the following analysis.

Fig.1 shows the stacked spectrum of all sources at $z < 4$. It is important to note that the stacked spectrum does not show any evidence for the HeII nebular line at $\lambda 4686\text{\AA}$. This line is expected if there is any contribution from AGNs. The non detection of this line further supports that our selection criteria have carefully excluded AGNs from the sample.

The emission lines fluxes have been obtained by fitting the emission lines with Gaussian functions by imposing the same *FWHM* for all the lines within the same band (hence with the same instrumental resolution, which slightly changes with wavelength). To automatically exclude noise fluctuations or bad pixels we constrained the velocity dispersion of the lines to be larger than the instrumental resolution estimated from the sky emission lines. The continuum, when detected (marginally) is subtracted with a simple linear slope, and the uncertainties in the subtraction are included in the final errors on the line fluxes. In Table 2 the measured emission line fluxes are reported. As mentioned, out of the 40 galaxies in the joint AMAZE+LSD sample, 34 have detections of all emission lines required to infer the metallicity.

As already pointed out in Gnerucci et al. (2011a) many of the sources in both the seeing-limited AMAZE data and in the AO-assisted LSD are spatially resolved. A detailed study on the morphology and size determination by using different methods of the AMAZE and LSD galaxies will be published in a companion works (see Sommariva et al. in prep.). In general the different methods used to determine the size are inconsistent with each other, with differences ranging up to a factor of four or more. This put into question the reliability of the size determination and, even more importantly, its meaning. This has implications for the determination of the surface brightness of galaxies as discussed further below (see section §6).

4.2. Physical properties from the broad band SED

For each galaxy in our sample a multiwavelength broad band SED is build with published or archival data and fitted with a set of galaxy spectral templates to obtain the stellar mass, SFR, age and dust reddening. The broad-band photometric data for the sources in the CDFS were collected from the GOODS–MUSIC

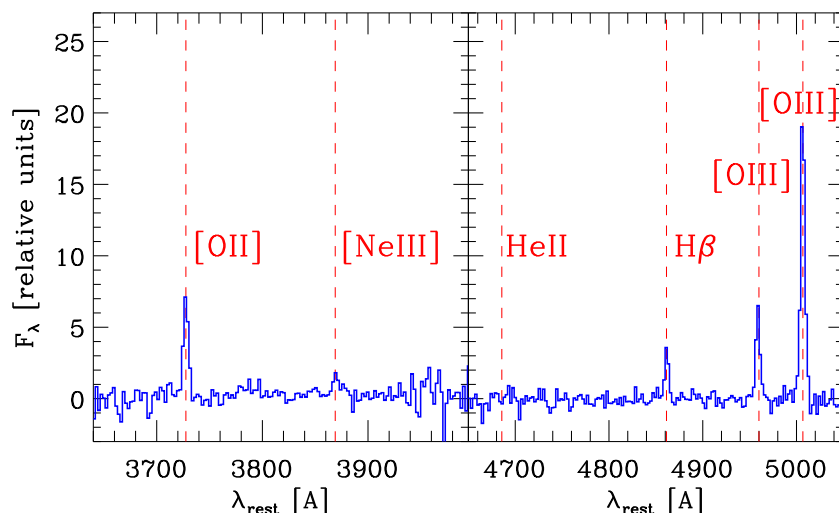


Fig. 1. Composite spectrum of the AMAZE and LSD spectra at $z \sim 3.4$ presented in this paper (34 sources).

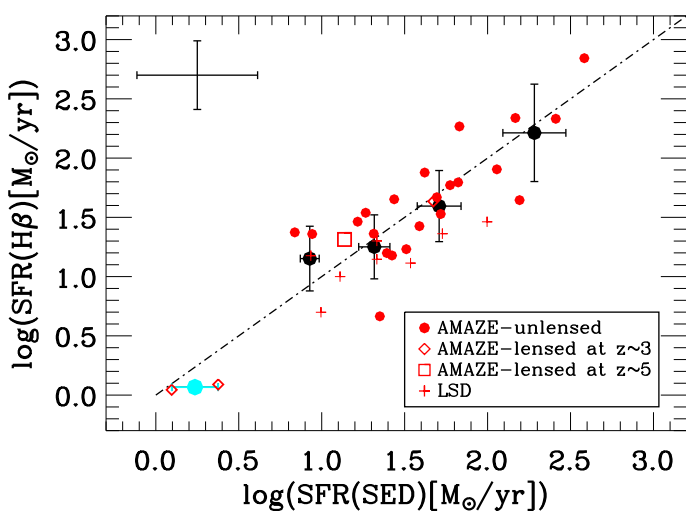


Fig. 2. Comparison between the SFRs derived from the SED fitting and the SFR based on $H\beta$. The dashed line shows the 1:1 relation along which the two estimator agree perfectly. The red circles are unlensed AMAZE galaxies at $z \sim 3.4$. The red diamonds are the three lensed sources at $z \sim 3.4$. The red square is the lensed galaxy at $z = 4.8$, for which $H\beta$ emission has been inferred from $[OII]3727$, by assuming the $[OII]/H\beta$ ratio appropriate for its metallicity (see later). The red crosses show the LSD galaxies. Black filled circles show the $SFR(H\beta)$ averaged within bins of $SFR(SED)$. The cyan bin is composed by the two lensed galaxies “LnA1689-1” and “LnA1689-4”. The error bars on the binned values correspond to the dispersion of the SFR within each bin. The error bars on the top-left corner indicated the average uncertainties on the measurements of $SFR(SED)$ and $SFR(H\beta)$ for the individual objects.

multiwavelength catalog (Grazian et al. 2006). This catalog provides photometric data in 14 spectral bands (from UV to the Spitzer-IRAC bands), and it has been recently updated to include the Spitzer-MIPS data at $24\mu\text{m}$. For the LBGs extracted from the Steidel et al. (2003) sample, optical photometric data (U,G,R,I) were extracted from the publicly available images (Steidel et al. 2003), while Spitzer IRAC and MIPS data were obtained from the Spitzer archive, or from new observations (Mannucci et al. 2009); the photometry extraction was performed following the same methods described in Grazian et al. (2006).

The galaxy templates and best fitting technique are the same as those used in previous papers (Grazian et al. 2006, 2007), and

similar to those adopted by other groups in the literature (e.g. Dickinson et al. 2003; Drory et al. 2004; Pozzetti et al. 2007). The galaxy templates are computed with standard spectral synthesis models (Bruzual & Charlot (2003) hereafter BC03) and chosen to broadly encompass the variety of star formation histories, ages, metallicities, and extinction of real galaxies. More specifically, we considered an exponentially declining SFR with e-folding times ranging from 0.1 to 15 Gyr. We used the Salpeter IMF ($M_{min} = 0.1M_{\odot}$ and $M_{max} = 65M_{\odot}$), ranging over a set of metallicities (from $Z = 0.02Z_{\odot}$ to $Z = 2.5Z_{\odot}$) and dust extinction ($0 < E(B - V) < 1.1$), with a Calzetti et al. (2000) attenuation curve, which is generally more appropriate for the stellar component. For each model of this grid, the expected magnitudes are computed in the desired filters set (depending on the available public data). The best-fitting template is found with a standard χ^2 minimization. The stellar mass and other physical parameters of the galaxy, like SFR, age, and dust extinction, are fitted simultaneously to the actual SED of the observed galaxy. To compare our results with other studies, using the Chabrier IMF, we apply a correction factor of 1.7 (Pozzetti et al. 2007) to our masses and SFR. The SED fitting results are reported the Table 3. For the four lensed sources masses and SFR were corrected by the magnification factor obtained by us (Ln1689-1, Ln1689-2, Ln1689-4) or in the literature (Cosmic eye, Smail et al. 2007), as reported in Table 3.

4.3. Star formation rates

The star formation rate can be inferred also from the $H\beta$ line flux that, if unreddened, is proportional to the number of ionizing photons emitted by young hot stars. We have inferred the SFR from $H\beta$ by first correcting it through the reddening inferred from the continuum fitting then by applying a stellar-to-nebular differential correction factor of 1/0.44, as discussed in Calzetti et al. (2000), (although the applicability of this correction factor for high redshift galaxies is subject to some debate, as discussed in Reddy et al. (2012)), finally obtaining the $H\alpha$ luminosity by assuming the case B recombination, i.e. $H\alpha/H\beta = 2.8$, and by adopting the $H\alpha$ to SFR conversion factor given by Kennicutt (1998). The errors of the flux measurements presented in Table 2 and reddening ($\Delta(E(B - V)) = 0.1$) were taken into account to derive the final $SFR(H\beta)$ presented in Table 3. Uncertainties in $SFR(H\beta)$ are at one sigma level. We note that the correction of

the $H\beta$ flux for stellar absorption is negligible. Indeed, the continuum is not detected, or barely detected, in all of the spectra; therefore, even assuming that the $H\beta$ stellar absorption on the continuum is as deep as it can be (e.g. post-starburst A-type like spectra) this would not change the inferred $H\beta$ flux by more than a few percent.

Fig. 2 shows the comparison between the SFR inferred from the SED with the SFR inferred from $H\beta$, where, for sake of clarity, we have averaged the data in bins of SFR(SED) and where the error bars give the dispersion of the points in each bin. Each bin has on average seven galaxies, except for the cyan symbol that has two galaxies. The latter shows the average obtained from the two lensed sources “LnA1689-1” and “LnA1689-4”, which allows us to explore low star formation rates. The error bars on the top-right corner show the average measurement errors on individual objects. There is a good general agreement between the two tracers of star formation over the two orders of magnitude spanned by our data. A more extensive discussion of the reliability and comparison of the different SFR tracers for the galaxies in our sample is given in a companion paper Castellano et al. (2013). In the following we use (unless stated) the SFR inferred from $H\beta$ ($SFR_{H\beta}$), but the results are essentially unchanged if using the SFR inferred from the SED.

5. Metallicity evolution

In this section we investigate the integrated metallicity of the LBG galaxies at $z \sim 3-5$, its dependence on stellar mass and SFR, and compare them with lower redshift galaxies to infer any evolutionary effect.

To infer the metallicities we adopt the same method adopted in Maiolino et al. (2008) and in Mannucci et al. (2009). Essentially, the method consists in exploiting the R_{23} parameter (where $R_{23} = (F([OII]\lambda 3727) + F([OIII]\lambda 4959) + F([OIII]\lambda 5007))/F(H\beta)$), which depends on metallicity. The dependence of this parameter on the metallicity has been calibrated by various authors, either by using theoretical models or through empirical calibrations based on other primary indicators (such as the electronic temperature T_e inferred from auroral lines). A summary of some of the calibrations is given in Kewley & Ellison (2008). Maiolino et al. (2008) adopts a hybrid calibration method, in which at low metallicities ($12 + \log(O/H) < 8.4$, where models have problems in reproducing the observed line ratios) the R_{23} parameter is calibrated “directly” through the T_e method, while at high metallicities ($12 + \log(O/H) > 8.4$, where the electron temperature is more difficult to measure and subject to temperature fluctuations) the calibration is obtained by exploiting models. The main issue of the R_{23} parameter is that it has a double metallicity solution for each value (“upper” and “lower” branches). In Maiolino et al. (2008) the selection of the branch is made through the $[NeIII]\lambda 3869/[OII]\lambda 3727$ and $[OIII]\lambda 5007/[OII]\lambda 3727$ ratio. The latter are tracers of the ionization parameter, but also have monotonic dependence on the metallicity (although with large scatter), meaning that the ionization parameter is, on average, related with the metallicity. In practice, we simultaneously fit the three diagnostics and find the best solution. A more detailed discussion on the method adopted to infer the metallicities is given in Appendix B. Although the use of this method has some caveats, it is the same method adopted in Mannucci et al. (2010) and, therefore, it allows a direct comparison with the results in that work (FMR).

Finally, for the one lensed AMAZE galaxy at $z=4.8$ for which we can only observe $[NeIII]$ and $[OII]$ in the K-band, we infer the metallicity from the $[NeIII]/[OII]$ line ratio exploiting

the anticorrelation (though with large dispersion) between this line ratio and metallicity found in Maiolino et al. (2008). In Table 4 the integrated metallicities inferred for the AMAZE and LSD galaxies are reported.

5.1. The mass–metallicity relation at $z \sim 3.4$

Fig. 3 shows the mass-metallicity relation for the full AMAZE+LSD sample. In the left panel the red symbols show the individual measurements of the AMAZE and LSD galaxies. Red points are for the AMAZE unlensed sources. Diamonds the AMAZE lensed sources at $z \sim 3$ and the red square shows the lensed source at $z \sim 5$. Red crosses are the LSD sources. In the right panel, the full sample at $3 < z < 3.7$ is binned by stellar mass in intervals of 0.5 dex. The black points show the average metallicities in each stellar mass bin, while the red circles show the metallicity inferred from the spectra stacked in the same bins. Each bin has on average six galaxies. The overplotted curves are the best fits of the observed mass-metallicity relations at different redshifts obtained by various previous surveys (see Maiolino et al. 2008). Over the investigated mass range, the metallicity at $z \sim 3.4$ is about 0.8 dex lower than for local galaxies. Regarding the best fit to the mass-metallicity relation, we adopt the same description of the mass-metallicity relation as in Maiolino et al. (2008),

$$12 + \log(O/H) = -0.0864 (\log M_* - \log M_\odot)^2 + K_0 \quad (1)$$

where $\log M_0$ and K_0 are determined at each redshift to obtain the best fit to the observed data points. By using the complete AMAZE+LSD sample at $z \sim 3.4$, we obtain $\log M_0 = 11.35, 11.59$ and $K_0 = 8.27, 8.44$ for the stacked and average metallicities, respectively¹. The inclusion of low mass systems ($\log M_* < 9.5 M_\odot$), with respect to (Maiolino et al. 2008), results into a flatter relation relative to lower redshifts. However, such putative evolution of the mass-metallicity evolution is still convolved with the different SFR’s probed at different redshifts by the different surveys. Since the metallicity of galaxies depends also on their SFR, as discussed in Mannucci et al. (2010) the evolution of the mass-metallicity relation with redshift (both in normalization and shape) is largely apparent and mostly due to the higher SFR of galaxies observed at high redshift (both because of selection effects and because of the real intrinsic evolution of the average SFR in galaxies). Therefore, it is more meaningful to investigate the metallicity evolution relative to the 3D-relation involving both mass and SFR, as discussed in the next section.

5.2. The evolution at $z \sim 3.4$ relative to the Fundamental Metallicity Relation

As we mentioned in section §1, Mannucci et al. (2010) have observationally shown that galaxies in the redshift range $0 < z < 2.5$ are described by a tight three dimensional relation between stellar mass (M_*), star formation rate (SFR) and gas-phase metallicity, dubbed Fundamental Metallicity Relation (FMR). The homogeneity of the FMR in the redshift range $0 < z < 2.5$, suggests that the mechanisms driving galaxy evolution during this time interval are similar. A deviation of galaxies from the FMR at higher redshift (at $z \gtrsim 2.5$) would indicate different evolutionary mechanisms at such early epochs.

¹ Note that, to avoid the fit to be dominated by the mass intervals with largest number of objects, we first obtained metallicity average or stacked within mass bins and then fitted the resulting values with Eq. 1.

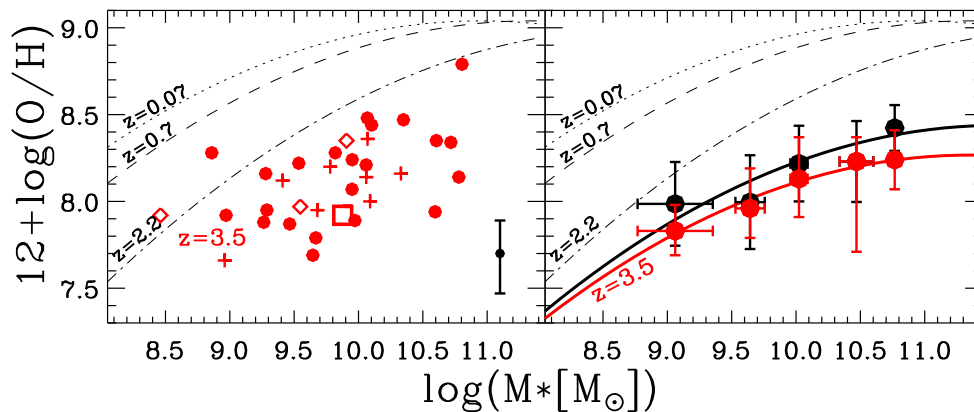


Fig. 3. Mass-metallicity relation for the galaxies in the AMAZE and LSD samples. The left panel shows the individual galaxies. Red circles are for the AMAZE unlensed sources; diamonds are the AMAZE lensed sources at $z \sim 3$; the red hollow square shows the lensed source at $z \sim 5$; while red crosses are the LSD sources. The overplotted lines (small dot, dashed, dot-dashed, long dashed) shows the mass-metallicity relation at lower redshifts from previous studies ($z \sim 0.07, 0.7, 2.2$ respectively, see Maiolino et al. (2008)). The average errorbars on the metallicity determination is shown in the lower-right corner. In the right panel the data are binned by stellar mass. The black circles show the average metallicities within each stellar mass bin, while the red circles show the metallicity inferred from the spectra stacked in the same bins. The black solid line shows the fit to the average metallicities, while the red solid line show the fit to the metallicity of the stacked spectra.

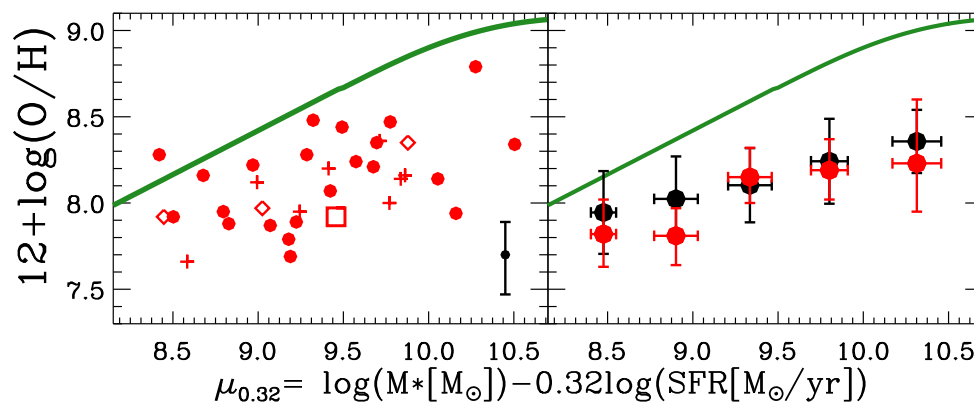


Fig. 4. Metallicity as a function of the parameter $\mu_{0.32}$. The green line is the FMR projection as a function of $\mu_{0.32}$ (Mannucci et al. 2011). The *left panel* shows the individual AMAZE and LSD galaxies at $z \sim 3-5$ (same symbol codes as in Fig. 3). The average metallicity uncertainty of the sample is shown in the lower-right corner. In the *right panel* the data are binned by $\mu_{0.32}$ parameter. The black circles show the average metallicities in each $\mu_{0.32}$ bin, while the red circles show the metallicity of the spectra stacked in the same bins. The black error bars show the dispersion of the average metallicity and $\mu_{0.32}$ at each bin. The red vertical error bars show the error of the metallicity of the stacked spectrum in each bin. The red horizontal error bars show the dispersion of the average $\mu_{0.32}$ in each bin.

At $z \sim 3$ Mannucci et al. (2010) analyzed a subsample of 17 AMAZE and LSD galaxies and found a deviation of the *average* metallicity of these galaxies from the FMR (at $0 < z < 2.5$) of about -0.6 dex.

In our sample, the metallicity of the full AMAZE+LSD composite spectrum at $z \sim 3.4$ (34 galaxies) is $8.03^{+0.16}_{-0.18}$, this is $0.43^{+0.16}_{-0.18}$ dex lower than the expected metallicity from the FMR (8.46) evaluated at the average star formation ($10^{1.5} M_{\odot} \text{yr}^{-1}$) and average stellar mass ($10^{9.8} M_{\odot}$) of the full sample. The aim of this section is to investigate the behavior of the full AMAZE+LSD sample at $z \sim 3.4$ (twice in size with respect to the one used by Mannucci et al. (2010)) relative to the FMR, by investigating the deviations as a function of SFR and mass, by exploiting the fact that the 34 galaxies of the sample span over 2 orders of magnitude in mass and star formation rate.

To further quantify the deviations of the data at $z \sim 3.4$ with respect to the local/low- z FMR, we use the parameter $\mu_{0.32} = \log(M_{*}) - 0.32 \log(\text{SFR})$, which provides a projection of the FMR that minimizes the metallicity scatter of local galaxies (Mannucci et al. 2010) and its extension to lower masses of

Mannucci et al. (2011). This projection of the FMR shows more clearly, and more globally the deviation of $z \sim 3.4$ galaxies relative to the local FMR.

In figure 4, the green line is the best fit of the metallicity distribution of local galaxies as a function of $\mu_{0.32}$ (see Mannucci et al. 2011). In the left panel, the individual measurements of the full AMAZE+LSD sample are shown (same symbol coding as in Fig.3). Galaxies at $z \sim 3.4$ have a metallicity dispersion of about 0.25 in dex, much larger than local galaxies (which have $\sigma \sim 0.05$), likely reflecting mixture of different stages of non-steady chemical evolutionary processes at this epoch, in contrast to what observed at later epochs.

In the right panel, the black circles show the average metallicities in $\mu_{0.32}$ bins, while the red symbols show the metallicity of the stacked spectra in the same bins. The plot also shows that the deviation from the FMR increases as a function of $\mu_{0.32}$. Such a trend is more clearly shown in Fig. 5, where we plot the deviation of $z \sim 3$ galaxies (averaged and stacked in bins of $\mu_{0.32}$, black and red points respectively) as a function of $\mu_{0.32}$.

The deviations (up to 0.6–1 dex) are clearly much higher than the mean scatter of local galaxies on the FMR (~ 0.05 dex). For

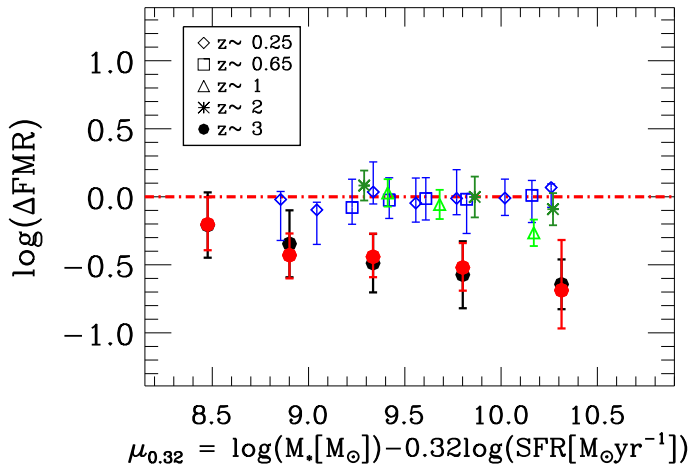


Fig. 5. Deviation of the FMR as a function of the $\mu_{0.32}$ parameter. Black and red circles show metallicity differences of the averaged and stacked spectra, respectively, within each $\mu_{0.32}$ bin, with respect to the FMR. The black error bars show the dispersion of the average metallicity within each bin. The red error bars show the error of the metallicity of the stacked spectrum in each bin. Blue diamonds, blue squares, green triangles and green asterisks show the average metallicity differences with respect to the FMR of galaxies at $z \sim 0.25$, 0.65 , 1 and 2 , respectively (Cresci et al. 2012; Vergani et al. 2012; Law et al. 2009; Lehnert et al. 2009).

comparison, in Fig. 5 we also show the location of galaxies at $z \sim 0.25$ – 0.65 (Cresci et al. 2012), at $z \sim 1$ (Vergani et al. 2012), and at $z \sim 2$ (Law et al. 2009; Lehnert et al. 2009) whose average metallicities, are derived with the Maiolino et al. (2008) calibration for consistency. Galaxies at $z \sim 0.25$ – 0.65 do not show any deviation relative to the local FMR. Galaxies at $z \sim 1$ – 2 do show some marginal deviation from the FMR at high μ_{32} , but much less significant than galaxies at $z > 3$. This result indicates that the deviation from the FMR is mostly a peculiarity of $z > 3$ galaxies, suggesting the existence of a transition epoch across $z \sim 3$ where the main mode of galaxy formation probably changes.

To further understand the physical parameters driving deviations at $z \sim 3.4$ from the FMR, we have also investigated the dependence of the deviations from FMR as a function of other galaxy physical parameters. In particular, we have investigated the deviation of $z \sim 3.4$ galaxies from the FMR as a function of stellar mass, SFR and specific SFR ($sSFR = SFR/M_*$, which is a proxy of the evolutionary stage of galaxies). None of these parameters seem to strongly correlate with the deviation from the FMR, the main driving quantity of the deviations seem to be the μ_{32} parameter that, as discussed in Mannucci et al. (2010), is linked to the star formation efficiency and to the combined effect of inflows and outflows. We will investigate these scenarios further in Sect. 7.

A possible origin of the deviation of galaxies at $z \sim 3.4$ from the FMR may be associated with an increased rate of mergers, which destabilize low metallicity gas in galaxy outskirts and drive it towards the central, active regions as suggested by some models (e.g. Rupke et al. 2010; Perez et al. 2011; Pilkington et al. 2012; Torrey et al. 2012).

The dynamical properties of the AMAZE+LSD sample has been studied by Gnerucci et al. (2011a). They found a significant fraction ($\sim 30\%$) of galaxies with regular rotation, especially among massive systems, indicating that massive rotating disk (although highly turbulent) were already in place at this early epoch. Other galaxies show irregular kinematics, suggesting recent or ongoing merging, while for other galaxies it is not pos-

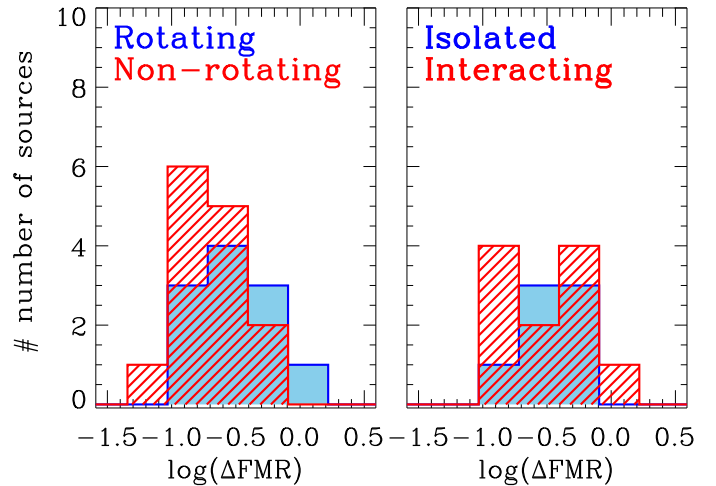


Fig. 6. Histogram of the metallicity deviations from the FMR for the AMAZE and LSD galaxies at $z \sim 3.4$. The blue histograms refer to the rotating disks and isolated galaxies. The red histograms indicate the non rotating galaxies and interacting galaxies.

sible to distinguish between rotation or irregular kinematics due to low angular resolution or low S/N.

Fig. 6 shows the distribution of the metallicity difference from the FMR of galaxies at $z \sim 3.4$. We divided the sample between rotating and non-rotating systems (according to Gnerucci et al. 2011a). There is no significant difference between rotating and non-rotating systems in terms of deviations from the FMR; the average deviation from the FMR of rotating systems is $\langle \log(\Delta FMR) \rangle = -0.39^{+0.26}_{-0.36}$ while the average deviation of non-rotating systems is $\langle \log(\Delta FMR) \rangle = -0.58^{+0.23}_{-0.09}$. We also divided the sample in interacting and isolated galaxies by visual inspection of the available HST images (including those in the H-band). There is no significant difference between interacting and isolated systems in terms of deviations from the FMR; the average deviation from the FMR of isolated systems is $\langle \log(\Delta FMR) \rangle = -0.31^{+0.10}_{-0.28}$ while the average deviation of interacting systems is $\langle \log(\Delta FMR) \rangle = -0.39^{+0.27}_{-0.36}$. These results suggests that enhanced merging cannot be the only explanation for the deviation from the FMR in galaxies at $z \sim 3.4$. Moreover, there are indications that merging galaxies in the local Universe are actually following the FMR (Cresci in prep.).

Another possibility is that the deviation from the FMR at $z > 3$ is associated with selection effects and, in particular, with the color selection criterion of LBG galaxies. The color selection tends to avoid dusty galaxies, which are presumably more metal rich. However, other samples at lower redshifts have been color-selected, but do not show similar strong deviations from the FMR, as discussed above. Moreover, some of the most deviating galaxies are also the most massive, which should also be the most dusty (according to the mass-dust relation observed locally and at high redshift), going in the opposite direction of the putative color bias. Therefore, the deviation from the FMR seems to be a peculiarity intrinsic to $z > 3$ galaxies.

While a discussion on the potential physical scenarios that could explain the deviations of galaxies at $z > 3$ will be discussed in the sections §7 and §8, here we note that gas metallicities are not the only property indicating a transition in galaxy evolution at $z \sim 3$. Indeed, the finding that galaxies at $z > 3$ deviate from the trends observed at lower redshift, has been obtained also by other studies. Moller et al. (2013) have found indication for a transition in the metal content of DLA at $z \sim 2.6$, which they interpret

as a transition from an epoch dominated by strong gas infall to the more “quiescent”, later epoch in terms of gas accretion. A transition at a similar epoch has also been observed in the reddening properties of Ly α emitters and QSO host galaxies (Fynbo et al. 2013; Nilsson & Moller 2009, 2011; Bongiovanni et al. 2010).

Even more interesting, Prochaska & Wolfe (2009) have shown that the HI content in galaxies does not evolve in the redshift range $0 < z < 2.5$, while it does evolve at higher redshifts. They associate the transition phase with the conversion of HI into H $_2$ at $z < 2.5$, which in turn regulates star formation and metal production. Although further modeling is required, it is clear that our result suggesting a transition of galaxy evolution occurring at $z \sim 2.5-3.0$ is in line with various other observational results.

We shall mention that yet another possibility to explain the deviation of our sample at $z \sim 3.4$ from the FMR is that LBGs at high- z belong to a different class of objects that, at any redshift, do not obey the FMR. Hunt et al. (2012) have shown that low mass, low metallicity galaxies follow a “fundamental plane”, whose extension to high masses fall short for accounting for star forming disks observed in the SDSS, but does reproduce the properties of the LBG at high- z . It is not simple to directly compare with the result of Hunt et al. (2012), since they use different metallicity tracers and so the comparison may be subject to significant offsets introduced by the different calibrations adopted for the different samples (see Kewley & Ellison 2008). Moreover, the sample adopted by Hunt et al. (2012) tends to preferentially select low metallicity galaxies, and also the stellar mass estimation is different from the ours. Finally, Hunt et al. (2012) use the AMAZE and LSD galaxies (the previous subsample of 17 galaxies) to construct the relationship, so claiming any consistency of the AMAZE+LSD sample with the work of Hunt et al. (2012) is somewhat circular. However, the scenario of a non-evolving population of strongly star forming galaxies, but deviating from the FMR is a scenario that should be investigated further, by including additional independent samples.

6. Gas content

As it will be discussed in the next sections, to properly interpret the metallicity evolution in galaxies it is extremely useful to have information on the gas content. This additional information allows us to partly remove degeneracies between various scenarios (e.g. closed-box, inflows, outflows). However, with the exclusion of a few powerful SMGs and QSO host galaxies, the direct measurement of the gas content in galaxies at $z > 3$ is still extremely challenging and, so far, only a few detections have been obtained (Riechers et al. 2010; Magdis et al. 2012a), only one of them (the Cosmic Eye) overlapping with our sample. An alternative method used by various authors (e.g. Conselice et al. 2013; Vergani et al. 2012; Tan et al. 2013; Erb et al. 2006b; Mannucci et al. 2009) to infer the gas content, although indirect and subject to larger uncertainties, is to invert the Schmidt-Kennicutt (S-K) law.

In the local Universe, the S-K law relates the gas surface density with the surface star formation density (Schmidt 1959; Kennicutt 1998; Bigiel et al. 2008; Schruba et al. 2011). Recently, Genzel et al. (2010), Daddi et al. (2010), Tacconi et al. (2010) and Tacconi et al. (2013) have measured large amounts of molecular gas in star forming disks at $z \sim 1-2.5$ and have found that the S-K law was already in place even at those early epochs of the Universe. Similar results have been obtained by using the dust mass as a proxy of the gas content in high- z galaxies (Magdis et al. 2012b; Santini et al. 2013).

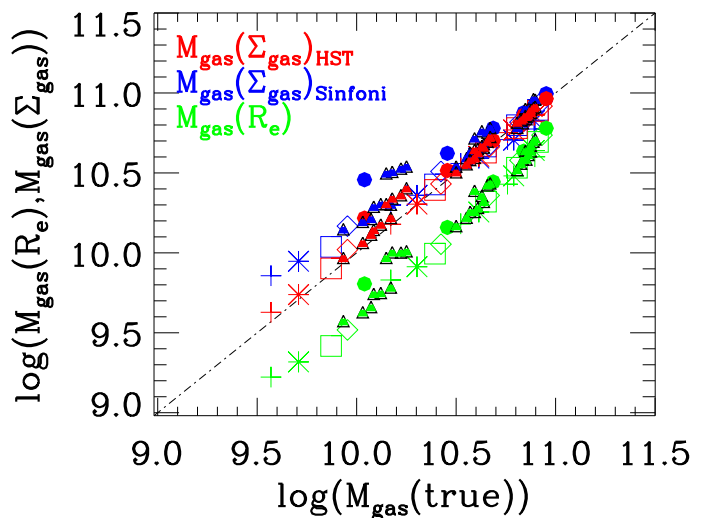


Fig. 7. Mass of gas of the simulated galaxies with different Sersic profiles ($0.5 < n < 4$) and different effective radii ($5 < R_e < 2.5$ kpc) inferred with the two different methods discussed in the text. The x-axis shows the “true” mass of gas (input in the simulated galaxy), while the y-axis shows either the mass of gas calculated with the “old” method of using the total SFR and effective radius to infer an average gas surface density ($M_{\text{gas}}(R_e)$, green symbols), or the mass of gas calculated with our “new” method measuring the Σ_{gas} pixel by pixel in the data ($M_{\text{gas}}(\Sigma_{\text{gas}})$, red and blue symbols). Red symbols show the simulations of HST data and blue symbols show the simulation of SINFONI data. The green symbols are independent of the method since they use the integrated properties of galaxies. Galaxies modelled with Sersic indices $n = 0.5, 1, 2, 3, 4$ are shown by crosses, asterisks, squares, diamonds, circles, respectively. Interacting systems are marked with black triangles.

Therefore, the currently favored scenario is that the high star formation rates measured at $z \sim 1-2.5$ are due to the presence of large amount of molecular gas and not to a more efficient mechanism converting gas to stars.

If the AMAZE galaxies are considered as typical star forming disks at $z \sim 3$ (i.e. assuming the validity of the S-K law), and assuming that the S-K relation does not evolve out to $z \sim 3$ ², we can infer the gas surface density from the surface star formation density, and finally derive the mass of gas. A similar approach was adopted by Erb et al. (2006b) and Vergani et al. (2012) for galaxies at $z \sim 1.5$, by Conselice et al. (2013) at $z \sim 1.5-3$, and by Mannucci et al. (2009) for galaxies at $z \sim 3$. Most of these previous studies do not really map the surface density of star formation, instead they measure a “size” of the galaxies and infer an average surface density of SFR, by dividing the total star formation rate by the average “size” of the galaxy, and from this they derive an average surface density of gas. By following this method, assuming an idealized galaxy with constant surface density of star formation within a radius r (by using the S-K law and adopting a Chabrier IMF) we obtain the relation

$$\Sigma_{\text{gas}}(M_{\odot}/\text{pc}^2) = 241 \left(\frac{\text{SFR}}{M_{\odot}/\text{yr}} \right)^{0.71} \left(\frac{r}{\text{kpc}} \right)^{-1.42} \quad (2)$$

and

² Note that some indications of evolution of the S-K at high- z was found by Tacconi et al. (2013) and Santini et al. (2013); however, as pointed out by Santini et al. (2013), the evolution, if any, is mild and galaxies at all redshifts can be fitted reasonably well with a single (integrated) S-K law with slope 1.5.

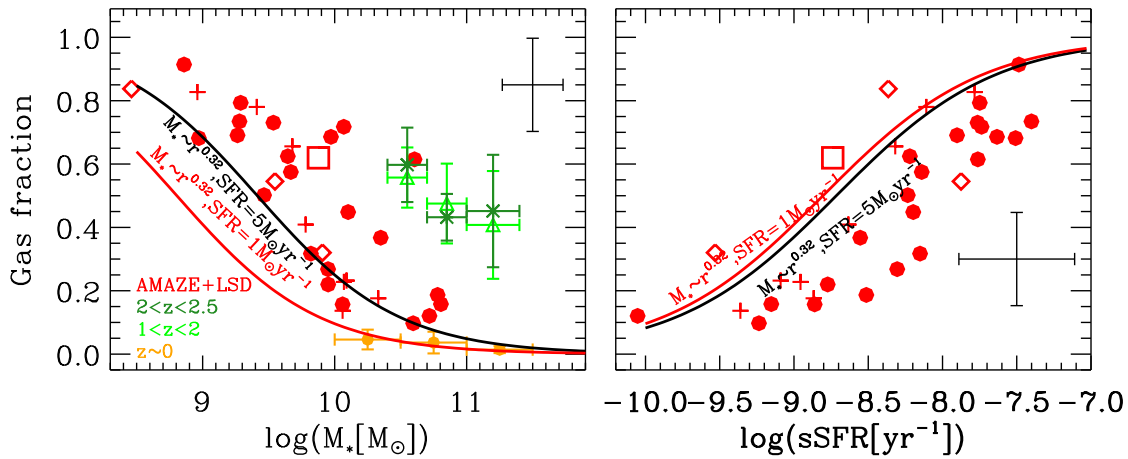


Fig. 8. Gas fraction as function of stellar mass and specific star formation rate. The red symbols show the AMAZE+LSD galaxies at $z \sim 3-5$ (same symbol coding as Fig.2). The solid lines show the incompleteness limit in the AMAZE unlensed (black) and lensed (red) galaxies. In the *left panel* the orange dots show the average gas fractions of local massive galaxies in bins of stellar mass, while green asterisks and triangles show the averages of the galaxies at $1 < z < 2$ and $2 < z < 2.5$, respectively, whose gas content has been measured through CO observations (Daddi et al. 2010; Saintonge et al. 2011; Tacconi et al. 2013). The upper-right error bars show the median error on the gas fraction and on the stellar mass in our sample. *Right panel:* Gas fraction as a function of the specific star formation rate, with the same symbols code as in the left panel.

$$M_{gas}(M_{\odot}) = 757 \times 10^6 \left(\frac{\text{SFR}}{M_{\odot}/\text{yr}} \right)^{0.71} \left(\frac{r}{\text{kpc}} \right)^{0.58} \quad (3)$$

where SFR is the total galaxy star formation rate. A factor of 1.7 between the Salpeter (adopted in Kennicutt 1998) and Chabrier IMF was applied (Pozzetti et al. 2007).

However, this method is subject to two major caveats. First, the previous equations are formally correct for a disk with a flat, constant distribution of Σ_{SFR} within a radius r . It is not obvious that, for a distribution of Σ_{SFR} typical of star forming galaxies (especially those at $z \sim 3$) these equations are appropriate, especially given that the S-K relation is not linear. Secondly, it is not clear what galaxy radius should be used to infer the average Σ_{SFR} : as we have discussed in the previous section, the galaxy radius may change by even a factor of several, depending on the method adopted to determine the radius and on the adopted definition of “galaxy radius”. In galaxies with irregular morphologies (e.g. multiple knots) or interacting/merging systems it is even more unclear what radius should be taken.

Here we have adopted a different method, which is much less affected by the issues discussed above. We measure the Σ_{SFR} within each individual pixel and, from this, we derive the Σ_{gas} locally, by applying the S-K relation, and the gas mass sampled by each pixel by simply multiplying the local Σ_{gas} by the physical area sampled by the pixel. We then infer the total gas mass by simply combining the gas masses inferred in each pixel. This method is rigorous if the galaxy is fully resolved and it totally bypasses any issue associated with the radius definition and with the problem of irregular morphologies and interacting systems affecting the previous method. Obviously, if the galaxy is not resolved, or only marginally resolved, then this method incurs in problems similar to the previous one. However, as discussed in the following, for the class of galaxies observed by us and which are resolved, we have tested that our new method provides a much more accurate determination of the gas content.

We have simulated galaxies with different Sersic profile’s, different effective radii ($R_e = 0.5, 1., 1.5, 2., 2.5$ kpc) and different Sersic indices ($n = 0.5, 1, 2, 3, 4$). We also simulate interacting/merging systems by combining two of the previous simulated galaxies, separated by 1 to 2 kpc. These simulated images

describe the “true” (intrinsic) distribution of Σ_{SFR} and, by inverting the S-K law, we can derive the “true” distribution of Σ_{gas} and therefore the “true” mass of gas. Thereafter, these images are smoothed to the PSF of SINFONI or HST and resampled to the pixel size of SINFONI or HST. We have also added noise at a level typical of our worst data, to be conservative. In such images that match the SINFONI-HST resolution, the mass of gas is estimated by using the “pixel surface brightness method” suggested by us (i.e. by adding the surface gas density inferred by the Σ_{SFR} measured in each pixel). We also applied the method adopted by previous authors, of inferring the average Σ_{gas} from the “effective radius” (Eq. 2). In the latter case we have been optimistic, in the sense that we have by-passed the measurement of “radius” in the simulated images (which introduces additional uncertainties) by directly taking the effective radius given in the simulation.

In Fig. 7, a comparison of these two methods is shown. Green symbols show the comparison between the true mass of gas “ $M_{gas}(true)$ ” and the old (“effective radius”) method “ $M_{gas}(R_e)$ ”. Red symbols show the comparison between the true mass of gas and our new method, i.e. by using the Σ_{SFR} measured in each pixel, by using HST resolution and sampling. Blue symbols show the comparison between the true mass of gas and our new method by using the SINFONI resolution. Galaxies modelled with a Sersic index $n = 0.5, 1, 2, 3, 4$ are shown in crosses, asterisks, squares, diamonds, circles, respectively. Black over-marked triangles show the simulated interacting systems. The dash-dotted line indicate the 1:1 relation, where the measurement would recover exactly the “true” mass of gas given in the simulation. Clearly, the old (R_e) method significantly underestimates the true mass of gas, by even a factor of three. Instead, our new method recover the “true” mass of gas, with an accuracy better than 20% in most cases. The resulting gas masses inferred for the AMAZE galaxies by using our method are reported in Table 4, col. 2.

The resulting mass of gas M_{gas} can be compared to the total baryonic mass $M_* + M_{gas}$ to estimate the fraction of mass in gas. The gas fraction $f_{gas} = M_{gas}/(M_{gas} + M_*)$ is an indicator of the galaxy evolutionary stage. Galaxies with a low gas fraction are systems which already used their gas to form stars and are becoming old (such as most local galaxies in Saintonge et

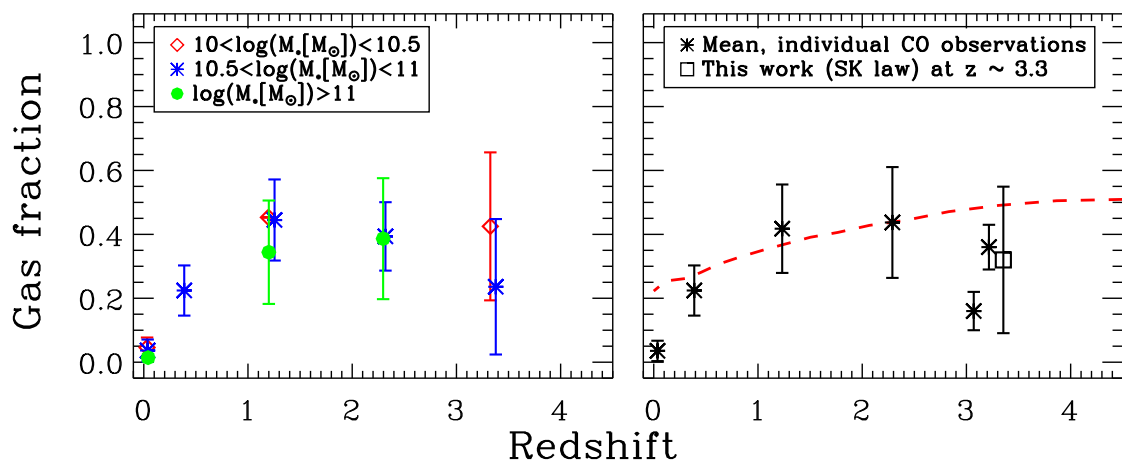


Fig. 9. Gas fraction as a function of redshift from a compilation of measurements in the redshift range $0 \leq z \leq 3.7$ (same data of Fig. 8) and including our new results. *Left panel:* Results averaged in bins of stellar mass. *Right panel:* Black asterisks show the average (over the whole mass range at $M_* > 10^{10} M_\odot$) evolution of the gas fraction up to $z \sim 3.4$. At $z \geq 3$, the asterisks show the individual values inferred from direct CO observations (Riechers et al. 2010; Magdis et al. 2012a). The hollow square is the average measurement at $z \sim 3.4$ determined in this work by inverting the SK law. The red dashed line shows the evolution of the gas fraction from the semi-analytic models of Lagos et al. (2011).

al. 2011), while galaxies with a large gas fraction have still to convert the bulk of the available gas into stars. In figure 8, left panel, the resulting gas fractions are plotted as a function of the galaxy mass. The red symbols are the AMAZE and LSD galaxies at $z \sim 3.4$ and at $z \sim 5$. For comparison, the yellow solid circles show the average gas fractions of local massive galaxies (with $M > 10^{10} M_\odot$) in bins of stellar mass, whose gas content has been measured by Saintonge et al. (2011) through direct CO observations. The green triangles and asterisks show the average gas fractions, also measured through direct CO observations, of galaxies at $z \sim 1-2.5$ in bins of stellar mass (Daddi et al. 2010; Tacconi et al. 2013).

There is an anticorrelation between gas content and galaxy stellar mass, which was already noticed in samples observed directly in CO (Tacconi et al. 2013) at lower redshifts (and high stellar masses) and also observed by using the dust mass as a proxy of the gas mass at $0 < z < 2.5$ (Santini et al. 2013). However, part of this anticorrelation may be associated with bias effects at low masses. Indeed, one should take into account that at low stellar masses our (indirect) method of deriving the gas mass is subject to incompleteness. Indeed, our sample is limited in SFR; since we estimate the gas mass through the Σ_{SFR} (by inverting the S-K law) our SFR limit indirectly translates into a lower limit on the gas mass that we can probe. Moreover, since $\Sigma_{SFR} \propto SFR/r^2$ and since the galaxy mass is known to correlate with galaxy radius ($M_* \propto r^{0.4}$), our lower limit on the gas content also depends indirectly on the galaxy mass. The solid lines in Fig. 8 show the inferred incompleteness limit for the AMAZE sample of unlensed galaxies (black line), which has a minimum SFR of $5 M_\odot \text{ yr}^{-1}$, and for the lensed galaxies in the AMAZE sample (red line), which have a minimum SFR of $1 M_\odot \text{ yr}^{-1}$. The lack of AMAZE and LSD galaxies below these lines is probably not intrinsic to the distribution of galaxies at $z \sim 3$, but is possibly due to incompleteness. However, we note that the location of the four lensed galaxies in AMAZE is significantly above the incompleteness line and they still show a clear drop of gas fraction as a function of stellar mass. Therefore, the anticorrelation between gas fraction and stellar mass may actually be real, and would be in line with the findings of direct CO observations at lower redshifts (Tacconi et al. 2013), although at higher stellar masses and lower redshifts. This result would support the downsizing scenarios, where massive galaxies at $z \sim 3$ have already consumed or

ejected a significant fraction of gas, while low mass galaxies are evolving more slowly.

The right panel of 8 shows the gas fraction as a function of $sSFR = SFR/M_{\text{star}}$ that is a tracer of the evolutionary stage of galaxies. As already found by Tacconi et al. (2013) at lower redshifts, there is a correlation between gas fraction and $sSFR$, suggesting that more evolved galaxies (lower $sSFR$) have lower gas fraction, because gas has been consumed by star formation (and expelled by the SN activity). However, also in this case, our results are affected by incompleteness at low $sSFR$, as a consequence of the SFR limit of our sample.

Either samples extending to lower SFR or direct measurements of the gas content (e.g. through CO mm observations) at $z > 3$ are required to validate these trends and verify that they are not a consequence of selection effects.

At masses higher than $10^{10} M_\odot$ the incompleteness of our sample, in terms of gas fraction, is very low. Hence our data at $M_* > 10^{10} M_\odot$ can be used, along with results at lower redshift, to constrain the evolution of the gas fraction in galaxies out to $z \sim 3.4$.

The left panel of Fig. 9 shows the evolution of the gas fraction in galaxies divided in different bins of stellar mass (to minimize the effect of variation of gas fraction with stellar mass, which is found to occur also at such high masses Santini et al. 2013). Although with large dispersion, the average gas fraction in massive galaxies shows a rapid increase, by over an order of magnitude, from $z=0$ to $z \sim 2$, which was already known by previous studies (Tacconi et al. 2010; Daddi et al. 2010; Tacconi et al. 2013). At higher redshift our data show that the evolution of the gas fraction flattens, and there is marginal indication that it may even start to turn down. This finding is in line with the result by Magdis et al. (2012a), who find indications for a flattening of the evolution of the gas fraction in galaxies at $z \sim 3$, based on CO observations of two galaxies (one of which is an upper limit). The evolution of the gas fraction in massive galaxies strongly resembles the evolution of the cosmic density of star formation rate (Hopkins & Beacom 2006) and provide further support to the scenario where the cosmic evolution of the SFR in galaxies is actually driven by the evolution of their molecular content, as suggested by Obreschkow & Rawlings (2009).

The right panel of Fig. 9 shows the inferred evolution of the gas fraction in galaxies, where we have taken the average in dif-

ferent redshift bins from the left panel. While the asterisks show the direct CO measurements (averages at $z < 3$ and individual detections at $z > 3$), the hollow square indicates the average of our measurements at $z \sim 3.4$, obtained by inverting the S-K law. The prediction of the cosmological models obtained by Lagos et al. (2011) is indicated with a red dashed line, which shows the expected average for the total population of star forming galaxies with vigorous SFR ($> 10 M_{\odot} \text{ yr}^{-1}$), i.e. a range similar to our sample. The models by Lagos et al. (2011) do indeed associate the evolution of the SFR with the evolution of the content of molecular gas in galaxies. The models expectations for strongly star forming galaxies is consistent, within the dispersion and error bars (although on the high side), with the observed evolution of the gas fraction in massive galaxies.

7. Comparison with simple models

Several models have been proposed to explain the metallicity evolution in galaxies. Here we attempt a very simple modeling to constrain the inflow and outflow in galaxies at $z > 3$. Key quantities to investigate these issues are the metallicity, the gas fraction and the “effective yield”, i.e. the amount of metals produced and retained in the ISM per unit mass of formed stars. The latter quantity deserves a few introductory words.

In a closed box model the metallicity is directly related to the gas fraction by the equation

$$Z = y \ln(1/f_{\text{gas}}) \quad (4)$$

where y is the true stellar yield, i.e. the ratio between the amount of metals produced and returned into the ISM and the mass of stars. Nevertheless, during their lifetime, galaxies experience outflows (SN explosions, winds), inflows (pristine or enriched gas) and merging events. Therefore, the resulting metallicity generally differs from Eq. 4. One can invert Eq. 4, by defining the “effective yield” as

$$y_{\text{eff}} = Z / \ln(1/f_{\text{gas}}). \quad (5)$$

The effective yield is equal to the true yield for a galaxy evolving like a close box, while it may differ substantially in the case of metal enriched outflows and in the case of inflows of metal poor gas. The effective yields computed for the AMAZE and LSD galaxies are given in Table 4.

In order to constrain inflow and outflow properties of $z > 3$ galaxies, we compare our results with the simple model described in Erb (2008). This model considers pristine gas accretion at a rate that is a constant fraction f_i of the star formation rate (i.e. as a continuous process or average of many minor events) and also an outflow rate f_o (of gas with the same metallicity as the current galaxy average) at a constant fraction of the SFR (i.e. the so called mass loading factor of the outflow).

In Figure 10, the metallicity and effective yields are plotted as a function of the gas fraction. Red symbols show the metallicity and effective yields for the AMAZE and LSD galaxies.

For comparison, the bulk of the local disk galaxies (e.g. those in the SDSS sample), especially those with $M > 10^{10} M_{\odot}$ have low gas fraction (< 0.2), metallicities around solar and high effective yields, while massive galaxies at $z > 3$ with similar gas fractions have much lower metallicities and much lower effective yields.

The Erb (2008) models are overplotted with various inflow and outflow rates. The black dotted line is the closed box model

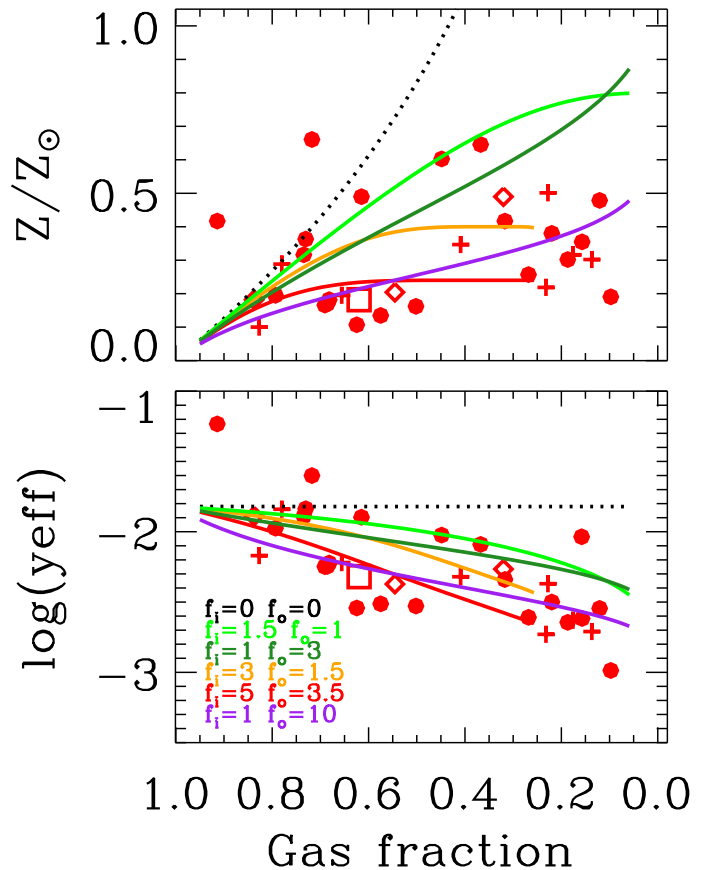


Fig. 10. Metallicities and effective yields as a function of gas fraction, for the galaxies in our sample at $z \sim 3$, with the same symbols as in the previous figures. In both panels the Erb (2008) models for various inflows “ f_i ”, outflows “ f_o ” rates (relative to the SFR) are shown. The black dotted line is the closed box model ($f_i = f_o = 0$). In the bottom panel (lower-right corner), the inflows and outflows rates in units of the SFR are shown for every model (with different color-coding).

(i.e. $f_i = f_o = 0$), which is far from reproducing the bulk behavior of the AMAZE and LSD galaxies. The most suitable models for the bulk of the sample are the ones with both massive inflow rates $f_i = 1 - 5 \times SFR$ and massive outflow rates $f_o = 1.5 - 3.5 \times SFR$.

Massive cool inflows are indeed expected in the early universe by recent cosmological models (e.g. Dekel et al. 2009; van de Voort et al. 2012, and references therein), although direct observational evidence is still marginal. In particular, no direct measurement of the inflow rate is available, which could be compared with the high values inferred by us in this paper. Outflows are ubiquitously observed, both locally and at high redshift. However, in high- z star forming galaxies the typical “load factor” (f_o) measured by observations is generally about one, or a few (Steidel et al. 2010; Genzel et al. 2011; Newman et al. 2012). Our data seem to require a load factor of at least a few, and even $f_o \geq 3$ for the most extreme galaxies at $z > 3$.

Achieving such high outflow rate in models of star forming galaxies is difficult. However, a possibility is that such high outflow rate could be associated with AGN/quasar activity. Very high quasar-driven outflow rates have been observed both locally (Feruglio et al. 2010; Sturm et al. 2011; Rupke & Veilleux et al. 2011; Ciccone et al. 2012) and at high redshift (Cano-diaz et al. 2012; Maiolino et al. 2012). Although, the galaxies in the AMAZE sample do not show evidence for any AGN activity, black hole feedback may have occurred in cyclic episodes and

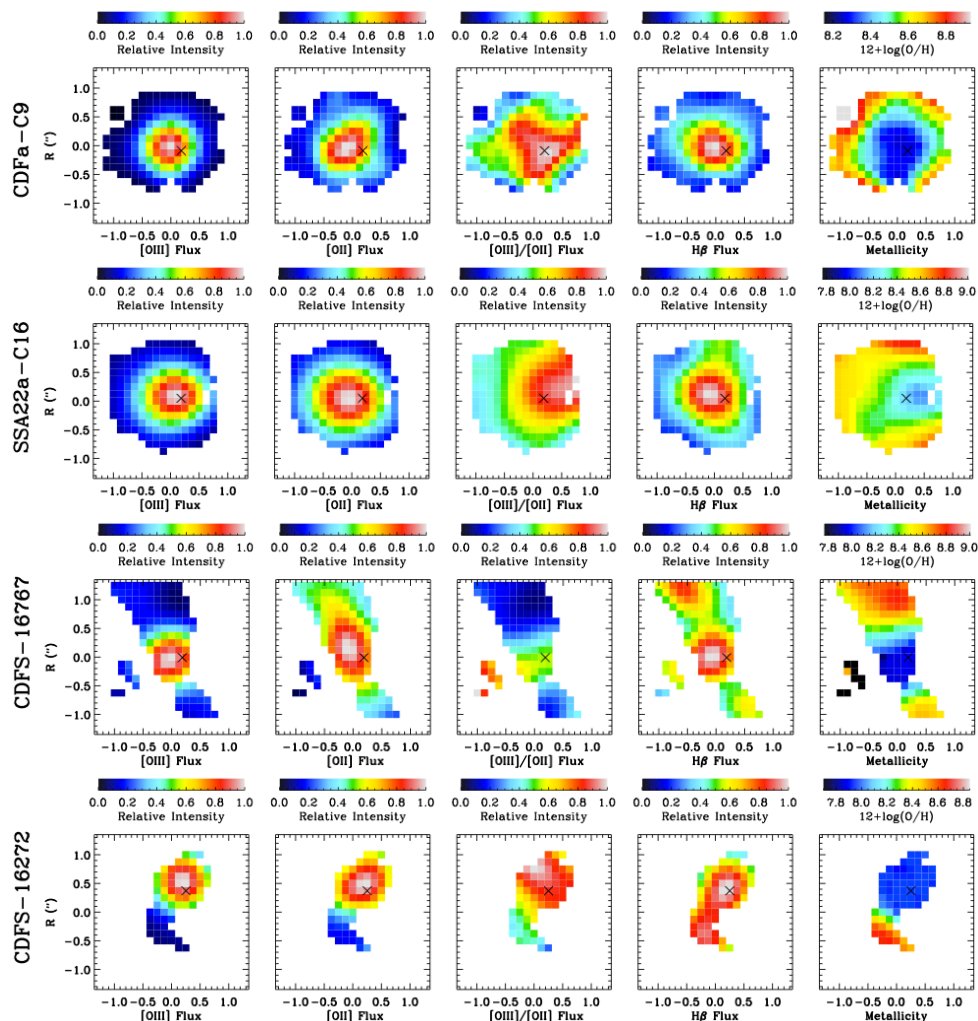


Fig. 11. [OIII] λ 5007, [OII] λ 3727, $H\beta$ flux maps, [OIII] λ 5007/[OIII] λ 3727 ratio, and metallicity maps for the galaxies CDFa-C9, SSA22a-C16, CDFS-11991 and CDFS-16272.

driven enriched gas out of the galaxy. Such massive inflows and outflows may likely be responsible for bringing the early galaxies out of the “equilibrium” characterizing galaxies at lower redshifts and making them deviate from the FMR.

8. Metallicity gradients at $z \sim 3$

As mentioned in the introduction, metallicity gradients provide important information on the formation mechanism of galaxies. Mapping the gas metallicity in high- z galaxies is extremely challenging, both because the surface brightness of the emission lines in galaxies is low and because the emission is often unresolved in seeing limited images. Cresci et al. (2010) presented the first metallicity maps at $z > 3$ by exploiting data of three bright and resolved AMAZE galaxies, out of the first subsample observed initially (Maiolino et al. 2008). Here we present resolved metallicity maps for a total of eleven galaxies in the AMAZE sample, for which both the S/N on the lines and the spatial extension allow us to resolve information on their metal content.

As for the integrated metallicities, the metallicity maps are determined by means of a combination of strong line diagnostics based on $H\beta$ and [OIII] λ 5007 shifted into the K band, as well as [OII] λ 3727 shifted into the H-band for sources at $3 < z < 3.7$, as mentioned at the beginning of section §5 and as detailed in Appendix B. The derived metallicity maps and flux maps are shown

in figures 11, 12 and 13. In the same figures we also show the [OIII]/[OII] line ratio, which is a proxy of the ionization parameter, but which also correlates with the metallicity, although with a large dispersion, and therefore useful to remove the degeneracy in the R_{23} parameter. Regions with an error on the metallicity larger than about 0.15-0.2 dex are masked out (in case of strongly asymmetric error bars the points were retained if the shortest error bar provide evidence of clear metallicity variation with respect to other points in the galaxy). The black cross in each map indicates the peak of the continuum flux. As found by Cresci et al. (2010) for the initial subsample of three galaxies, the peak of the star formation activity, as traced by $H\beta$ and [OIII] λ 5007 emission, is spatially correlated with the region of the galaxy with the lowest metallicity. A clear exception is “CDFS4414” where the metallicity tends to be flat.

In order to increase the S/N on the outer region we have also obtained the radial metallicity variation by integrating the line fluxes within a central aperture (a few kpc in radius) and in an outer ring (with outer radius typically extending to about 8-10 kpc). The resulting metallicity radial profiles are shown in Fig. 14 and Fig. 15. For “DSFc21” it was not possible to determine the metallicity of the outer region due to the low S/N even in the spectrum integrated in the annulus. The resulting radial metallicity gradients are reported in Table 9. Most of the gradients are flat or inverted (positive).

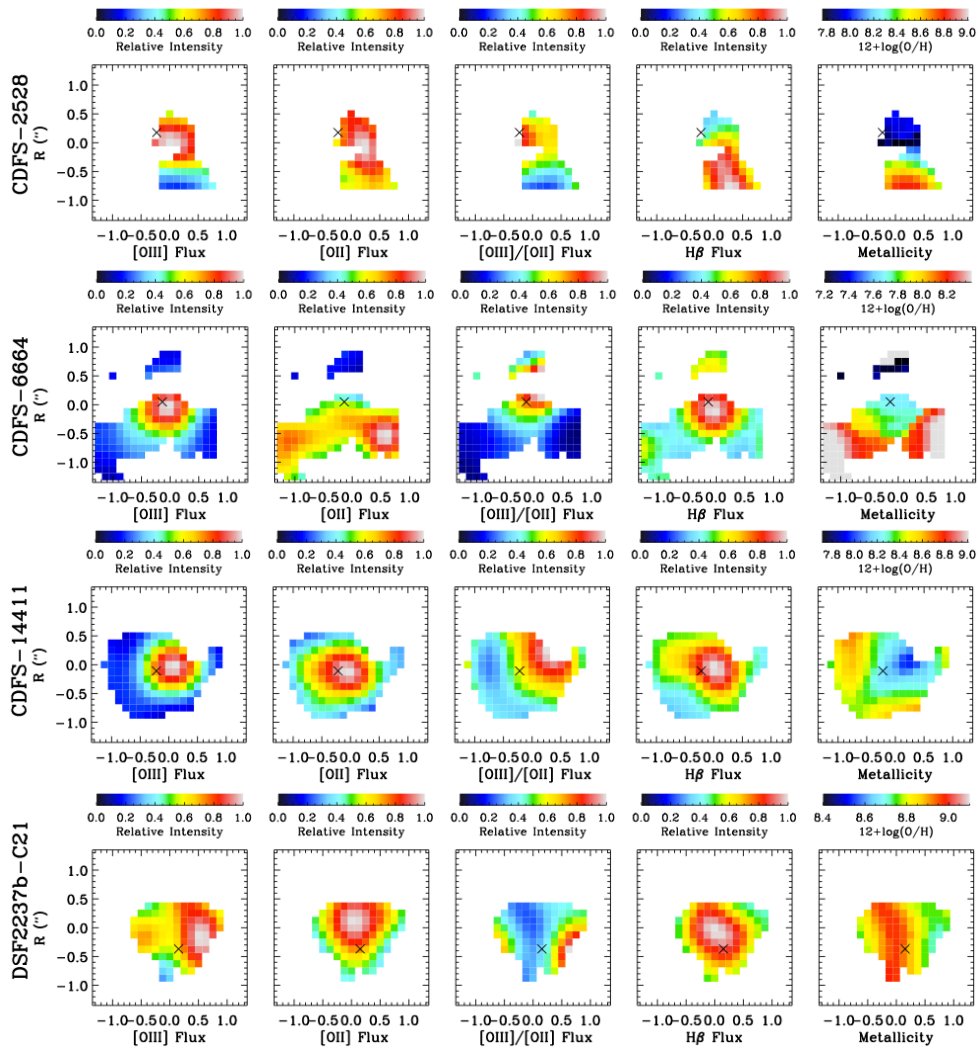


Fig. 12. [OIII]5007, [OII]3727, $H\beta$ flux maps, [OIII]5007/[OIII]3727 ratio, and metallicity maps for the galaxies CDFS-2528, CDFS-6664, CDFS-14411 and DSF2237b-C21.

Regarding the “flat” gradients one should keep in mind that, as pointed out by Yuan et al. (2013) these shallow gradients may be partially due to the low angular resolution. However, we also note that the two-dimensional metallicity maps show complex, non-radially symmetric patterns, which are averaged out when obtaining averages in radial annuli.

We do not find significant dependence of the metallicity gradients as a function of stellar mass, SFR and sSFR.

We have also investigated the metallicity gradients as a function of morphology and as function of the dynamical status. Fig. 14 gathers all galaxies that, according to the HST images, are isolated, while Fig. 15 include all galaxies which are in close interaction (a companion within 30 kpc) or with strongly irregular morphology (in the H band), presumably associated with late mergers. There is no relation between the morphological properties (isolated versus interacting) and the trend of the metallicity gradient. The dynamical status (rotating disk versus non-rotating), as inferred by Gnerucci et al. (2011a), is also reported in each panel, when available. It is interesting to note that most of the systems with inverted gradients are associated with rotating disks, as already suggested by Cresci et al. (2010) in the first subsample of three galaxies. These results do not fully support, at least at $z > 3$, the scenario in which inverted gradients are preferentially associated with galaxy interactions/mergers that,

according to some models (e.g. Rupke et al. 2010; Perez et al. 2011; Pilkington et al. 2012; Torrey et al. 2012), are supposed to drive pristine gas from the outskirts to the inner region. Instead, smooth inflows of pristine gas towards the central region, both diluting the gas metallicity and enhancing star formation, may be responsible for the gradients observed at $z > 3$.

However, it is clear from figures 11 to 13, that the metallicity gradients are generally not radially symmetric, hence the radial averages shown obtained in Figs. 14-15 and in Table 9 can be deceiving, and anyhow, as already mentioned, tend to wash away more pronounced gradients observed in the metallicity maps of galaxies.

To avoid the radial average approach, and to further investigate the scenario in which lower metallicity regions are associated with star forming regions due to an excess of (pristine) gas which both dilutes and boost star formation, we have compared the spatially resolved metallicity with the surface gas density (obtained by inverting the Schmidt-Kennicutt law). This comparison is shown for each galaxy in Fig. 16 and Fig.17, where each point shows the metallicity and Σ_{gas} at each pixel. Note that we have verified that the correlated errors on both axis (due to the fact that the $H\beta$ flux is used on both axes) does not introduce any significant, artificial correlation. Also, one should be aware that not all of the plotted points are fully independent of each other,

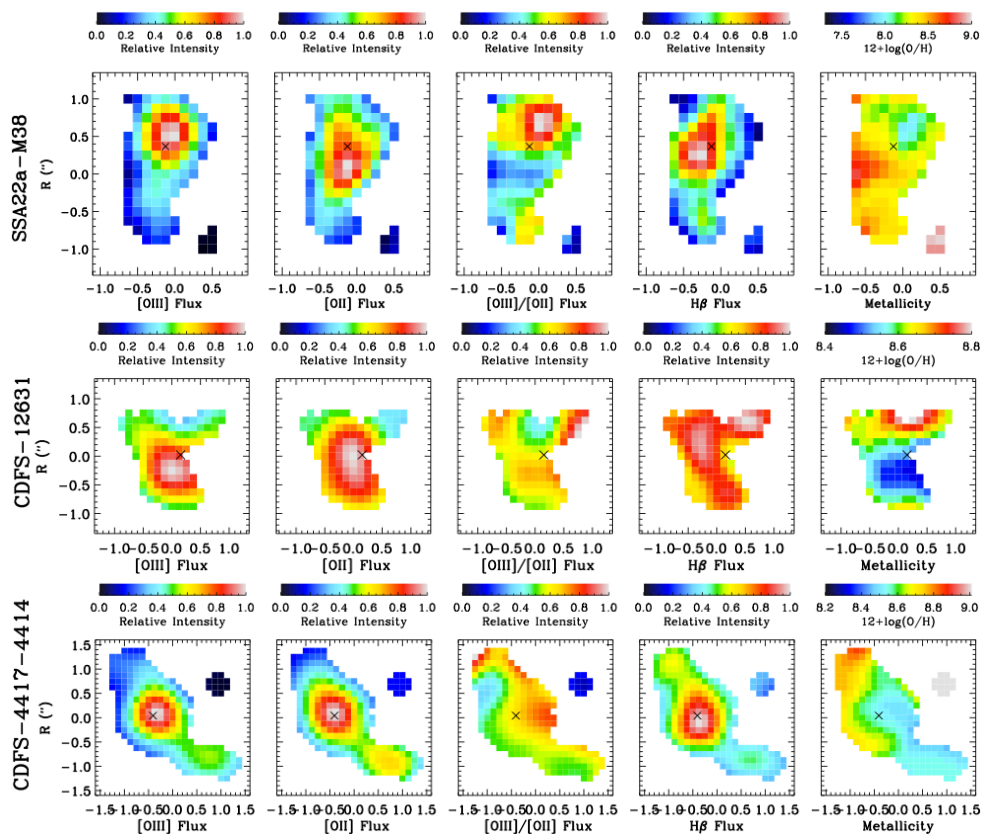


Fig. 13. [OIII]5007, [OII]3727, H β flux maps, [OIII]5007/[OII]3727 ratio, and metallicity maps for the galaxies SSA22a-M38, CDFS-12631 and the interacting galaxies CDFS-4417/CDFS-4414.

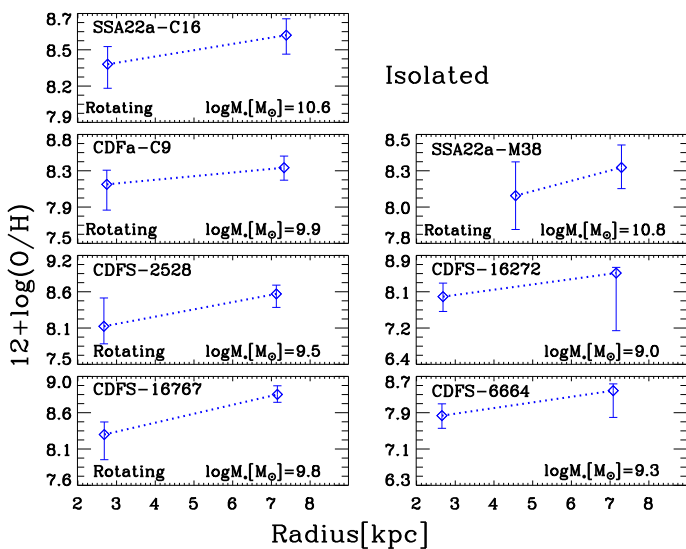


Fig. 14. Azimuthally averaged metallicity as a function of the galaxy radius for galaxies classified as “isolated” by visual inspection of F160W-band (H-band) HST images. The galaxies are dynamically classified according to Gnerucci et al. (2011a). Note however that the azimuthal averages tends to wash out the non-axisymmetric metallicity variations characterizing these objects.

because of the seeing. However, in most galaxies there is a clear anticorrelation between metallicity and Σ_{gas} , further supporting the inflow/dilution scenario.

However, Σ_{gas} is not necessarily illustrative of the evolutionary stage of individual regions of each galaxy. The gas fraction is

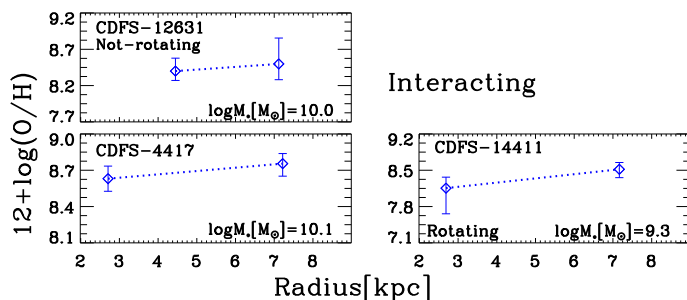


Fig. 15. Azimuthally averaged metallicity as a function of the galaxy radius for galaxies classified as “interacting” by visual inspection of F160W-band (H-band) HST images. The galaxies are dynamically classified according to Gnerucci et al. (2011a). Note however that the azimuthal averages tends to wash out the non-axisymmetric metallicity variations characterizing these objects.

more useful to constrain the local evolutionary processes. However, obtaining resolved information on the gas fraction is difficult, since it is not easy to determine the stellar mass surface density. However, for a few galaxies for which we resolve the distribution of the nebular lines (hence for which we have spatially resolved information on Σ_{gas} by inverting the S-K relation) we also have deep HST-WFC3 images in the H-band, sampling the V-band rest frame. To a first approximation, we can assume that the Σ_{star} scales proportionally to the rest-frame V-band surface brightness (the normalization factor is given by the constraint that the total V-band light should be associated with the total stellar mass inferred by the detailed multi-band SED modeling). We could therefore estimate the gas fraction in the same inner and outer regions for which the metallicity could be inferred.

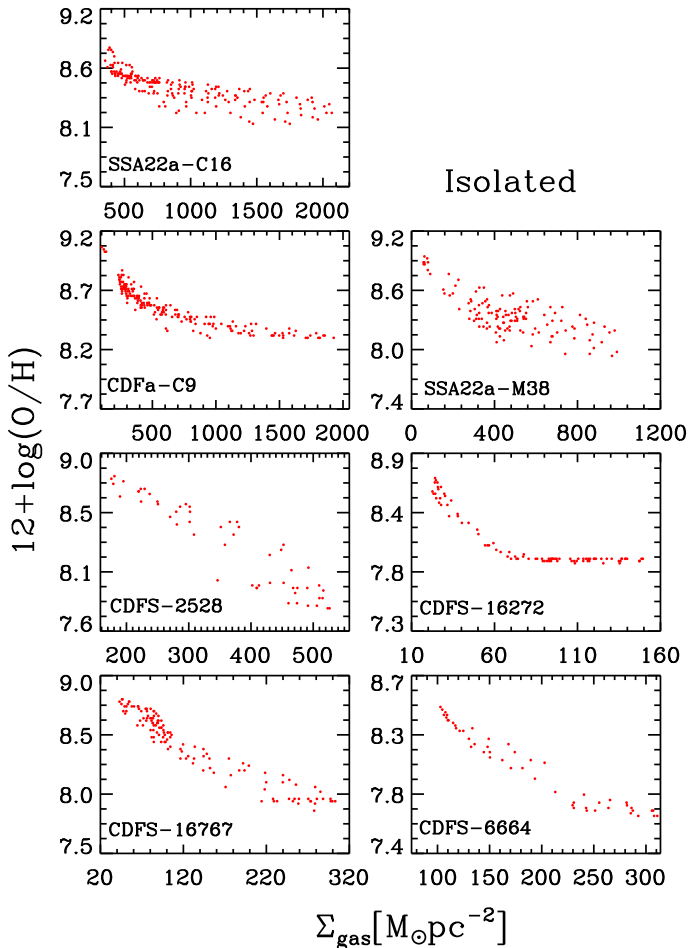


Fig. 16. Spatially resolved metallicities as a function of the gas surface density of isolated galaxies.

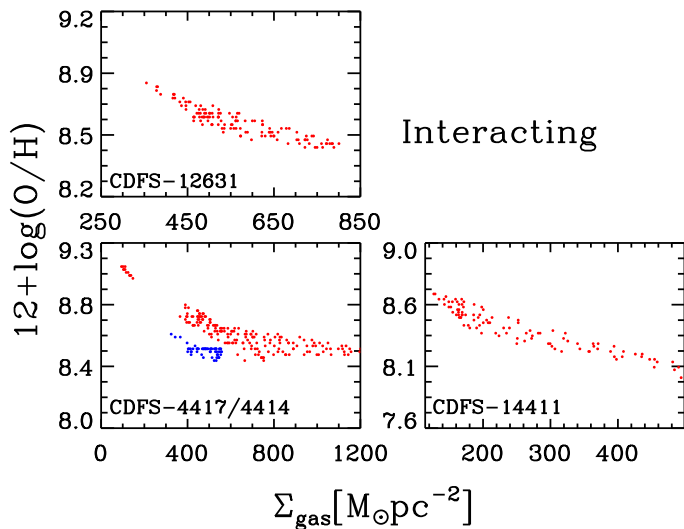


Fig. 17. Spatially resolved metallicities as a function of the gas surface density of interacting galaxies. Blue dots show the distribution of the galaxy CDFS-4414 interacting with CDFS-4417.

Fig. 18 shows the metallicity as a function of the gas fraction for the four galaxies for which we can resolve both the metallicity and the gas fraction. Blue symbols indicate the inner regions, while red symbols indicate the outer regions. In all these galaxies the inner region has a lower metallicity and higher gas fraction

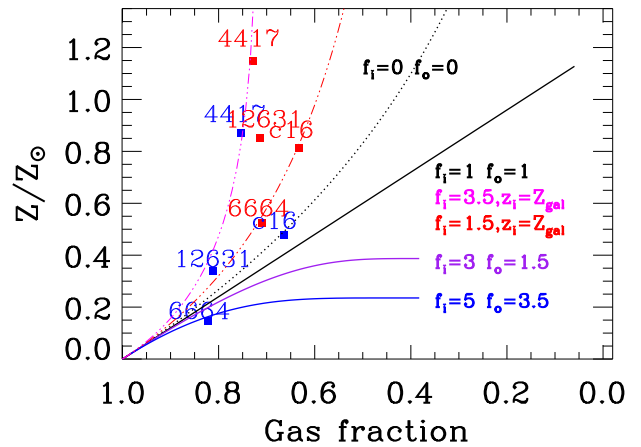


Fig. 18. Metallicity as a function of the gas fraction for the inner/outer galaxy regions. Blue squares show the inner regions, while red squares show the outer regions. Blue and purple solid lines show models with outflows and inflows of pristine gas. The black dotted line shows the closed box model. Red and magenta dashed-dotted lines show models with enriched inflows (with the same metallicity as the galaxy) and no outflows.

than the outer region. This finding is in line with the result of Cresci et al. (2010) suggesting that the inner regions suffer from metallicity dilution from inflow of pristine gas, which centrally both increases the gas fraction and dilutes the metallicity.

However, we note that several points, especially those in the outer regions, have metallicities higher than the closed box model. This may indicate that our metallicity calibration is biased high or, alternatively, that in these regions the stellar yields are higher than the average of a normal stellar population (e.g. through recent injection of metals by massive stars, which have yields higher than average). An additional, alternative explanation for the high metallicity in these regions, especially in the outer ones, is inflow of metal enriched gas, which can give a metal content higher than expected by the closed box model. Indeed, in several recent models of galactic fountains, a significant fraction of the metals ejected from the central winds fall back onto the outer parts of the galaxy.

We explore the latter scenario by using the model of Erb (2008). We construct additional models in which the gas inflow is not pristine, but actually has a metallicity equal to the metallicity of the bulk of the galaxy. These models are shown with red and magenta lines in Fig. 18 and can reproduce nicely the observed values in the outer regions of several of these galaxies. Therefore, enhanced metallicity transport from the inner to the outer regions through galactic fountains may be an additional mechanism responsible for the inverted gradients in these young systems.

9. Conclusions

We have reported the results of a program aimed at measuring optical nebular emission lines in a sample of 35 star-forming galaxies at $z \sim 3.4$ by using SINFONI, the near infrared integral field spectrograph at VLT. The integrated and spatially resolved spectral information allows us to constrain the metallicity and, indirectly, the amount of gas hosted in these galaxies. The main results are summarized as follows:

- On average the galaxies in our sample at $z \sim 3.4$ are metal poorer, by $-0.43^{+0.16}_{-0.18}$ dex, relative to the fundamental relation between metallicity, stellar mass and star formation

rate (FMR) characterizing local and lower redshift galaxies ($0 < z < 2.5$). Galaxies at $z \sim 3.4$ have a metallicity dispersion of about 0.25 dex in the FMR, much larger than local galaxies (which have $\sigma \sim 0.05$), likely reflecting a mixture of different stages of non-steady chemical evolutionary processes at this epoch, in contrast to what observed at later epochs.

- There is no significant correlation between the dynamical state of these galaxies and the deviations from the FMR. More specifically, galaxies characterized by regular rotation patterns have, on average, the same metallicity deviations from the FMR as galaxies with irregular kinematics (indicative of recent/ongoing merging). These results suggest that the enhanced merging rate at $z > 3$ is unlikely to be the main reason for the deviations from the FMR at $z > 3$.
- We find that the deviations from the FMR at $z \sim 3.4$ correlate with $\mu_{32} = \log(M_*) - 0.32 \log(\text{SFR})$, which is the parameter giving the projection of the FMR that minimizes the dispersion, and which is associated with the star formation efficiency as well as with the presence of outflows and inflows.
- By mapping the optical nebular emission lines and by inverting the Schmidt-Kennicutt relation we inferred the amount of molecular gas hosted in these galaxies. At $z \sim 3$, the average gas fraction of massive galaxies ($M_* > 10^{10} M_\odot$) does not follow the steep increasing evolution observed from $z=0$ to $z \sim 2$. Between $z \sim 2$ and $z \sim 3$ the average gas fraction in galaxies remains constant or, possibly, even decreases. Our results support the scenario in which the evolution of cosmic star formation in galaxies is primarily driven by the evolution of the amount of gas in galaxies, and not by an evolution in the efficiency of star formation.
- The observed anticorrelation between gas fraction and stellar mass, as well as the correlation between gas fraction and $s\text{SFR}$, may support downsizing already in place at $z \sim 3$. However, new observations are required to verify this trend and validate that it is not a consequence of selection effects.
- Models with both high inflows and outflows rates ($\sim 2 - 5 \times \text{SFR}$) are necessary to reproduce the measured galaxy properties, and in particular the metallicities, gas fraction and effective yields. Such massive flows in the early universe are likely responsible for the different properties and deviations of galaxies at $z \sim 3$ relative to local and lower redshift galaxies.
- By mapping the distribution of the star formation and metallicity in 10 out of 34 galaxies at $z \sim 3$, we found an spatial anticorrelation between the peak of the star formation rate and the lowest metallicity region. We further find, within each galaxy, an anti-correlation between metallicity and gas surface density. This result supports the models of smooth gas inflows feeding galaxies at high redshift. In this scenario the pristine infall both boosts star formation (through the Schmidt-Kennicutt law) and dilutes the metallicity, generating the observed anticorrelation.
- For four AMAZE galaxies, it was possible to determine both metallicity and gas fraction in the inner ($r < 3$ kpc) and in the outer ($3 < r < 8$ kpc) galaxy regions. In all these galaxies, the inner region has a lower metallicity and higher gas fraction with respect to the outer region. This finding suggests that the inner regions suffer from metallicity dilution from inflows of pristine gas, which centrally both increases the gas fraction and dilutes the metallicity. However, nuclear enriched outflows are likely contributing to lower the metallicity in the central region. Further modeling, supports the

galactic fountain scenario in which outflows of enriched material are expelled from the inner region and fall back, as inflows of enriched material, onto the galaxy outskirts.

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Table 1. Galaxy sample.

Object	sample	R.A. ⁽¹⁾	Dec. ⁽¹⁾	z ⁽²⁾	Texp(min)	R-band(mag)
CDFa-C9	AMAZE	00:53:13.7	+12:32:11.1	3.2119	250	23.99
CDFS-4414	AMAZE	03:32:23.2	-27:51:57.9	3.4714	350	24.18
CDFS-4417 ⁽³⁾	AMAZE	03:32:23.3	-27:51:56.8	3.4733	350	23.42
CDFS-6664	AMAZE	03:32:33.3	-27:50:7.4	3.7967	500	24.80
CDFS-16767	AMAZE	03:32:35.9	-27:41:49.9	3.6239	300	24.13
CDFS-13497	AMAZE	03:32:36.3	-27:44:34.6	3.4138	150	24.21
CDFS-11991	AMAZE	03:32:42.4	-27:45:51.6	3.6110	450	24.23
CDFS-2528	AMAZE	03:32:45.5	-27:53:33.3	3.6872	350	24.64
CDFS-16272	AMAZE	03:32:17.1	-27:42:17.8	3.6195	350	25.08
CDFS-9313	AMAZE	03:32:17.2	-27:47:54.4	3.6545	250	24.82
CDFS-9340 ⁽³⁾	AMAZE	03:32:17.2	-27:47:53.4	3.6578	250	25.85
CDFS-12631	AMAZE	03:32:18.1	-27:45:19.0	3.7090	250	24.72
CDFS-14411	AMAZE	03:32:20.9	-27:43:46.3	3.5989	200	24.57
CDFS-5161	AMAZE	03:32:22.6	-27:51:18.0	3.6610	300	24.96
LnA1689-2 ⁽⁴⁾	AMAZE	13:11:25.5	-01:20:51.9	4.8740	400	23.31
LnA1689-4 ⁽⁴⁾	AMAZE	13:11:26.5	-01:19:56.8	3.0428	240	22.40
LnA1689-1 ⁽⁴⁾	AMAZE	13:11:30.0	-01:19:15.3	3.7760	300	24.20
LnA1689-3 ^(4,5)	AMAZE	13:11:35.0	-01:19:51.6	5.120	225	25.0
Q1422-D88	AMAZE	14:24:37.9	+23:00:22.3	3.7520	250	24.44
3C324-C3	AMAZE	15:49:47.1	+21:27:05.0	3.2890	150	24.14
Cosmic eye ^(4*)	AMAZE	21:35:12.7	-01:01:42.9	3.0755 ⁽⁵⁾	200	20.54
SSA22a-M38	AMAZE	22:17:17.7	+00:19:00.7	3.2928	400	24.11
SSA22a-C48 ⁽⁵⁾	AMAZE	22:17:18.6	+00:18:16.2	3.079	250	24.71
SSA22a-D17 ⁽³⁾	AMAZE	22:17:18.9	+00:18:16.8	3.0870	250	24.27
SSA22a-aug96M16	AMAZE	22:17:30.9	+00:13:10.7	3.2920	250	23.83
SSA22a-G03 ⁽⁵⁾	AMAZE	22:17:30.8	+00:12:51.0	4.527	225	25.03
SSA22a-C16	AMAZE	22:17:32.0	+00:13:16.1	3.0675	350	23.64
SSA22a-C36	AMAZE	22:17:46.1	+00:16:43.0	3.0630	100	24.06
DFS2237b-C21	AMAZE	22:39:29.0	+11:50:58.0	3.4029	200	23.50
DFS2237b-D29	AMAZE	22:39:32.7	+11:55:51.7	3.3709	250	23.70
Q0302-C131	LSD	03:04:35.0	-00:11:18.3	3.2350	240	24.5
Q0302-C171	LSD	03:04:44.3	-00:08:23.2	3.3280	240	24.6
Q0302-M80	LSD	03:04:45.7	-00:13:40.6	3.4160	240	24.1
Q0302-MD287 ⁽⁵⁾	LSD	03:04:52.8	-00:09:54.6	2.395	160	24.8
SSA22a-C30	LSD	22:17:19.3	+00:15:44.7	3.1025	240	24.2
SSA22a-C6	LSD	22:17:40.9	+00:11:26.0	3.0970	280	23.4
SSA22a-M4 ⁽³⁾	LSD	22:17:40.9	+00:11:27.9	3.0972	280	24.8
SSA22b-C5	LSD	22:17:47.1	+00:04:25.7	3.1120	240	22.0
DSF2237b-D28	LSD	22:39:20.2	+11:55:11.3	2.9323	240	24.5
DSF2237b-MD19 ⁽⁵⁾	LSD	22:39:21.1	+11:48:27.7	2.6160	200	24.5

(1) J2000.

(2) Redshifts are measured from the observed OIII (5007Å) line wavelength.

(3) The object is in the same field of view as the object on the previous line.

(4) Lensed objects. (*) Data was taken from the archive.

(5) Undetected sources. Redshift from literature.

Table 2. Line fluxes inferred from the near-IR spectra

Name	F([OIII]5007)	F(H β)	F([OII]3727)	F([NeIII]3870)
		10 ⁻¹⁷ erg s ⁻¹ cm ⁻²		
CDFa-C9	7.23 ^{+0.09}	1.49 ^{+0.09}	2.36 ^{+0.11}	0.60 ^{+0.09}
CDFS-4414	1.06 ^{+0.08}	0.42 ^{+0.06}	0.89 ^{+0.08}	0.12 ^{+0.04}
CDFS-4417	1.77 ^{+0.08}	0.88 ^{+0.09}	1.39 ^{+0.09}	0.31 ^{+0.07}
CDFS-6664	3.38 ^{+0.15}	0.34 ^{+0.09}	0.29 ^{+0.04}	–
CDFS-16767	1.99 ^{+0.08}	0.46 ^{+0.09}	0.60 ^{+0.05}	–
CDFS-11991	3.02 ^{+0.10}	0.28 ^{+0.09}	0.52 ^{+0.05}	0.22 ^{+0.07}
CDFS-2528	1.61 ^{+0.11}	0.35 ^{+0.10}	0.61 ^{+0.07}	–
CDFS-16272	3.62 ^{+0.09}	0.48 ^{+0.13}	0.66 ^{+0.05}	0.23 ^{+0.09}
CDFS-9313	4.45 ^{+0.13}	0.54 ^{+0.12}	0.72 ^{+0.06}	–
CDFS-9340	1.64 ^{+0.10}	0.37 ^{+0.09}	0.40 ^{+0.06}	–
CDFS-12631	2.98 ^{+0.25}	0.49 ^{+0.12}	2.09 ^{+0.19}	1.13 ^{+0.13}
CDFS-14411	3.88 ^{+0.13}	0.75 ^{+0.11}	1.02 ^{+0.07}	0.20 ^{+0.06}
CDFS-5161	1.23 ^{+0.17}	0.17 ^{+0.09}	0.17 ^{+0.04}	0.11 ^{+0.05}
LnA1689-2 ^a	–	–	0.16 ^{+0.03}	0.05 ^{+0.03}
LnA1689-4 ^a	0.45 ^{+0.01}	0.05 ^{+0.00}	0.06 ^{+0.01}	0.02 ^{+0.00}
LnA1689-1 ^a	0.15 ^{+0.02}	0.04 ^{+0.01}	0.06 ^{+0.01}	–
Q1422-D88	4.31 ^{+0.21}	0.55 ^{+0.17}	0.55 ^{+0.08}	–
3C324-C3	1.15 ^{+0.08}	0.26 ^{+0.06}	0.46 ^{+0.12}	0.31 ^{+0.11}
Cosmic eye ^a	0.78 ^{+0.02}	0.09 ^{+0.03}	0.24 ^{+0.03}	–
SSA22a-M38	5.56 ^{+0.14}	1.40 ^{+0.18}	3.12 ^{+0.18}	1.03 ^{+0.16}
SSA22a-D17	1.73 ^{+0.11}	0.36 ^{+0.09}	1.04 ^{+0.10}	–
SSA22a-aug96M16	1.82 ^{+0.08}	0.38 ^{+0.06}	0.47 ^{+0.08}	–
SSA22a-C16	5.45 ^{+0.09}	1.47 ^{+0.12}	2.59 ^{+0.09}	–
SSA22a-C36	1.81 ^{+0.24}	0.48 ^{+0.21}	2.12 ^{+0.32}	0.34 ^{+0.17}
DSF2237b-C21	0.70 ^{+0.12}	1.00 ^{+0.17}	1.85 ^{+0.14}	0.35 ^{+0.13}
DSF2237b-D29	0.93 ^{+0.09}	0.14 ^{+0.07}	0.76 ^{+0.09}	–
Q0302-C131	2.62 ^{+0.52}	0.46 ^{+0.16}	0.80 ^{+0.32}	–
Q0302-C171	1.10 ^{+0.12}	0.18 ^{+0.08}	0.56 ^{+0.24}	–
Q0302-M80	1.32 ^{+0.26}	0.40 ^{+0.12}	0.56 ^{+0.18}	–
SSA22a-C30	1.28 ^{+0.22}	0.26 ^{+0.10}	0.30 ^{+0.12}	–
SSA22a-C6	5.50 ^{+0.62}	0.76 ^{+0.45}	1.21 ^{+0.38}	–
SSA22a-M4	3.66 ^{+0.49}	0.69 ^{+0.25}	1.46 ^{+0.23}	–
SSA22b-C5	3.28 ^{+0.24}	0.50 ^{+0.14}	0.27 ^{+0.09}	0.38 ^{+0.14}
DSF2237b-D28	1.86 ^{+0.36}	0.16 ^{+0.08}	0.74 ^{+0.16}	–
<i>Composite</i> ^b	6.13 \pm 0.14	1.00 \pm 0.10	1.70 \pm 0.12	0.39 \pm 0.08

The following quantities are reported in each column: col. 1, object name; col. 2-5, emission line fluxes.

Notes:^a values corrected for a magnification factor of 43.5 ± 4.1 , 6.7 ± 2.1 , 5.9 ± 1.9 (see text) and 28 ± 3 (Smail et al. 2007), respectively. ^b In the case of the composite spectrum fluxes are normalized to the H β flux (which is also subject to an error as listed in the corresponding column).

Table 3. Physical properties of the sample inferred from their SED and metallicity.

Name	$\log M_*$ (BC03) [M_\odot]	$\log M_*$ (M05) [M_\odot]	$E(B-V)_*$ [mag]	$\log \text{SFR}$ (SED) [$M_\odot \text{yr}^{-1}$]	$\log \text{SFR}$ ($H\beta$) [$M_\odot \text{yr}^{-1}$]
CDFa-C9	$9.95^{+0.40}_{-0.08}$	$9.90^{+0.30}_{-0.05}$	0.00	$2.19^{+0.18}_{-0.30}$	$1.65^{+0.14}_{-0.30}$
CDFS-4414	$10.35^{+0.19}_{-0.23}$	$10.25^{+0.07}_{-1.24}$	0.20	$1.82^{+0.25}_{-0.62}$	$1.80^{+0.31}_{-0.62}$
CDFS-4417	$10.07^{+0.38}_{-0.11}$	$10.09^{+0.12}_{-0.05}$	0.25	$2.41^{+0.01}_{-0.63}$	$2.33^{+0.31}_{-0.63}$
CDFS-6664	$9.26^{+0.11}_{-0.23}$	$9.07^{+0.22}_{-0.08}$	0.10	$1.31^{+0.27}_{-0.31}$	$1.36^{+0.33}_{-0.31}$
CDFS-16767	$9.82^{+0.10}_{-0.16}$	$9.67^{+0.13}_{-0.13}$	0.15	$1.69^{+0.31}_{-0.05}$	$1.67^{+0.31}_{-0.05}$
CDFS-11991	$9.47^{+0.13}_{-0.16}$	$9.42^{+0.18}_{-0.08}$	0.10	$1.51^{+0.26}_{-0.24}$	$1.23^{+0.34}_{-0.24}$
CDFS-2528	$9.54^{+0.09}_{-0.08}$	$9.48^{+0.16}_{-0.09}$	0.20	$1.77^{+0.02}_{-0.02}$	$1.77^{+0.33}_{-0.02}$
CDFS-16272	$8.97^{+0.08}_{-0.28}$	$9.00^{+0.09}_{-0.25}$	0.10	$1.22^{+0.30}_{-0.29}$	$1.46^{+0.33}_{-0.29}$
CDFS-9313	$9.29^{+0.28}_{-0.39}$	$9.29^{+0.27}_{-0.32}$	0.10	$1.27^{+0.53}_{-0.53}$	$1.54^{+0.32}_{-0.53}$
CDFS-9340	$8.86^{+0.28}_{-0.45}$	$8.85^{+0.26}_{-0.10}$	0.10	$0.84^{+0.65}_{-0.65}$	$1.37^{+0.32}_{-0.65}$
CDFS-12631	$9.97^{+0.10}_{-0.10}$	$10.18^{+0.29}_{-0.29}$	0.30	$2.17^{+0.86}_{-0.86}$	$2.34^{+0.32}_{-0.86}$
CDFS-14411	$9.28^{+0.08}_{-0.03}$	$9.30^{+0.05}_{-0.05}$	0.15	$1.62^{+0.02}_{-0.02}$	$1.88^{+0.31}_{-0.02}$
CDFS-5161	$9.65^{+0.58}_{-0.24}$	$9.67^{+0.29}_{-0.24}$	0.20	$1.59^{+0.27}_{-1.21}$	$1.43^{+0.40}_{-1.21}$
LnA1689-2 ^a	$9.88^{+0.21}_{-0.36}$	$9.79^{+0.10}_{-0.32}$	0.06	$1.14^{+0.18}_{-0.30}$	$1.31^{+0.34}_{-0.30}$
LnA1689-4 ^a	$8.46^{+0.26}_{-0.39}$	$8.12^{+0.33}_{-0.03}$	0.06	$0.10^{+0.18}_{-0.30}$	$0.04^{+0.24}_{-0.30}$
LnA1689-1 ^a	$9.91^{+0.06}_{-0.10}$	$9.63^{+0.21}_{-0.09}$	0.00	$0.38^{+0.18}_{-0.30}$	$0.09^{+0.19}_{-0.30}$
Q1422-D88	$10.60^{+0.02}_{-0.23}$	$10.43^{+0.11}_{-0.10}$	0.00	$0.94^{+0.30}_{-0.05}$	$1.36^{+0.19}_{-0.05}$
3C324-C3	$9.67^{+0.33}_{-0.23}$	$9.62^{+0.28}_{-0.16}$	0.20	$1.72^{+0.25}_{-0.95}$	$1.53^{+0.32}_{-0.95}$
Cosmic eye ^a	$9.55^{+0.48}_{-0.48}$	$9.55^{+0.48}_{-0.48}$	0.40	$1.67^{+0.40}_{-0.40}$	$1.63^{+0.36}_{-0.40}$
SSA22a-M38	$10.78^{+0.18}_{-0.41}$	$10.48^{+0.19}_{-0.40}$	0.20	$1.83^{+0.18}_{-0.30}$	$2.27^{+0.31}_{-0.30}$
SSA22a-D17	$9.95^{+0.50}_{-0.61}$	$9.67^{+0.50}_{-0.27}$	0.10	$1.42^{+0.18}_{-0.30}$	$1.18^{+0.32}_{-0.30}$
SSA22a-aug96M16	$10.06^{+0.20}_{-0.21}$	$9.92^{+0.11}_{-0.28}$	0.06	$1.39^{+0.18}_{-0.30}$	$1.20^{+0.24}_{-0.30}$
SSA22a-C16	$10.61^{+0.13}_{-0.55}$	$10.46^{+0.11}_{-0.37}$	0.35	$2.58^{+0.18}_{-0.30}$	$2.84^{+0.31}_{-0.30}$
SSA22a-C36	$10.10^{+0.30}_{-0.20}$	$10.08^{+0.21}_{-0.17}$	0.25	$2.06^{+0.27}_{-1.46}$	$1.91^{+0.38}_{-1.46}$
DSF2237b-C21	$10.80^{+0.14}_{-0.31}$	$10.55^{+0.06}_{-0.11}$	0.06	$1.44^{+0.74}_{-0.56}$	$1.65^{+0.24}_{-0.56}$
DSF2237b-D29	$10.72^{+0.15}_{-0.22}$	$10.55^{+0.14}_{-0.11}$	0.00	$1.35^{+0.50}_{-0.56}$	$0.66^{+0.26}_{-0.56}$
Q0302-C131 (*)	$10.09^{+0.10}_{-0.33}$	–	0.15	$1.11^{+0.16}_{-0.26}$	$1.00^{+0.22}_{-0.40}$
Q0302-C171 (*)	$10.06^{+0.10}_{-0.28}$	–	0.10	$1.00^{+0.13}_{-0.18}$	$0.70^{+0.40}_{-0.40}$
Q0302-M80 (*)	$10.07^{+0.23}_{-0.19}$	–	0.30	$1.54^{+0.26}_{-0.70}$	$1.11^{+0.12}_{-0.21}$
SSA22a-C30 (*)	$10.33^{+0.31}_{-0.38}$	–	0.40	$2.00^{+0.29}_{-1.35}$	$1.46^{+0.14}_{-0.45}$
SSA22a-C6 (*)	$9.68^{+0.15}_{-0.06}$	–	0.40	$1.73^{+0.16}_{-0.24}$	$1.36^{+0.32}_{-0.46}$
SSA22a-M4 (*)	$9.41^{+0.34}_{-0.13}$	–	0.40	$1.33^{+0.27}_{-0.89}$	$1.30^{+0.30}_{-0.19}$
SSA22b-C5 (*)	$8.96^{+0.38}_{-0.22}$	–	0.25	$0.93^{+0.23}_{-0.52}$	$1.18^{+0.00}_{-0.27}$
DSF2237b-D28 (*)	$9.78^{+0.28}_{-0.29}$	–	0.30	$1.33^{+0.25}_{-0.66}$	$1.15^{+0.11}_{-0.24}$

The following quantities are reported in each column: col. 1, object name; col. 2, stellar mass inferred by using the galaxy templates of BC03; col. 3, stellar mass inferred by using the galaxy templates of M05; col. 4, dust reddening affecting the stellar light, by using the attenuation curve of Calzetti et al. (2000); col. 5, star formation rate (by using BC03); col. 6, star formation rate (by using $H\beta$ flux). In order to compare our results with other studies using the Chabrier IMF, the masses and the star formation rates were calculated by using the Salpeter IMF and corrected by a factor of 1.7. The stellar mass, reddening and star formation rate of the Cosmic-eye correspond to the best SED fitting values reported in Coppin et al. (2007), the $SFR(H\beta)$ was derived with the measured $H\beta$ flux and the reported extinction considering an error of $\pm 0.15 \text{ mag}$. ^a values corrected for a magnification factor of 43.5 ± 4.1 , 6.7 ± 2.1 , 5.9 ± 1.9 (see text), 28 ± 3 (Smail et al. 2007), respectively. * LSD galaxies, all values have been taken from Mannucci et al. (2009).

Table 4. Galaxy mass estimated using OIII images. Derived quantities yields and metallicities.

Name	$\log M_{\text{gas}}(\Sigma SFR) M_{\odot}$	Gas fraction	$12+\log(\text{O}/\text{H})$	log Yields
CDFa-C9	9.51±0.29	0.27±0.17	8.07 ^{+0.17} _{-0.17}	-2.61±0.54
CDFS-4414	10.11±0.30	0.37±0.20	8.47 ^{+0.11} _{-0.10}	-2.09±0.50
CDFS-4417	10.47±0.30	0.72±0.18	8.48 ^{+0.09} _{-0.09}	-1.60±0.62
CDFS-6664	9.61±0.30	0.69±0.17	7.88 ^{+0.17} _{-0.20}	-2.25±0.72
CDFS-16767	9.49±0.30	0.32±0.16	8.28 ^{+0.16} _{-0.32}	-2.34±0.69
CDFS-11991	9.47±0.30	0.50±0.19	7.87 ^{+0.20} _{-0.20}	-2.53±0.68
CDFS-2528	9.97±0.30	0.73±0.14	8.22 ^{+0.24} _{-0.31}	-1.84±0.87
CDFS-16272	9.30±0.30	0.68±0.16	7.92 ^{+0.23} _{-0.22}	-2.22±0.77
CDFS-9313	9.87±0.30	0.79±0.16	7.95 ^{+0.23} _{-0.25}	-1.97±0.83
CDFS-9340	9.89±0.30	0.91±0.08	8.28 ^{+0.14} _{-0.71}	-1.23±1.18
CDFS-12631	10.31±0.30	0.69±0.20	7.89 ^{+0.16} _{-0.17}	-2.25±0.69
CDFS-14411	9.72±0.30	0.73±0.14	8.16 ^{+0.16} _{-0.23}	-1.89±0.74
CDFS-5161	9.87±0.30	0.62±0.27	7.69 ^{+0.37} _{-0.28}	-2.54±0.93
LnA1689-2	10.09±0.31	0.62±0.23	7.92^{+0.74}_{-0.39}	-2.32±1.42
LnA1689-4	9.17±0.29	0.84±0.14	7.92 ^{+0.11} _{-0.11}	-1.89±0.66
LnA1689-1	9.58±0.30	0.32±0.16	8.35 ^{+0.19} _{-0.26}	-2.27±0.66
Q1422-D88	9.63±0.30	0.10±0.07	7.94 ^{+0.24} _{-0.33}	-2.99±0.71
3C324-C3	9.80±0.30	0.57±0.23	7.79 ^{+0.35} _{-0.29}	-2.51±0.91
Cosmic eye	9.63±0.29	0.55±0.32	7.97 ^{+0.32} _{-0.23}	-2.37±0.81
SSA22a-M38	10.14±0.30	0.19±0.15	8.14 ^{+0.11} _{-0.15}	-2.64±0.45
SSA22a-D17	9.40±0.30	0.22±0.25	8.24 ^{+0.18} _{-0.17}	-2.50±0.54
SSA22a-aug96M16	9.33±0.30	0.16±0.11	8.21 ^{+0.18} _{-0.60}	-2.62±0.95
SSA22a-C16	10.81±0.29	0.61±0.24	8.35 ^{+0.13} _{-0.15}	-1.90±0.62
SSA22a-C36	10.01±0.30	0.45±0.22	8.44 ^{+0.13} _{-0.15}	-2.02±0.57
DSF2237b-C21	10.08±0.30	0.16±0.11	8.79 ^{+0.08} _{-0.07}	-2.04±0.36
DSF2237b-D29	9.85±0.30	0.12±0.09	8.34 ^{+0.19} _{-0.19}	-2.55±0.52

The following quantities are reported in each column: col. 1, object name; col. 2, mass of gas in [M_{\odot}] obtained by inverting the Schmidt-Kennicutt law and adding the surface star formation rate at every galaxy pixel overall the galaxy extension, col. 3 gas fraction col. 4 metallicity at 0.375arcs using the Maiolino et al. (2008) metallicity calibration, col. 5 effective yields.

Table 5. Metallicities differences between inner and outer galaxy regions inferred from the near-IR spectra .

Name	$12+\log(\text{O}/\text{H})_{\text{inner}}$	$12+\log(\text{O}/\text{H})_{\text{outer}}$	$\Delta 12+\log(\text{O}/\text{H})$
CDFa-C9	$8.18^{+0.17}_{-0.31}$	$8.38^{+0.14}_{-0.15}$	$0.20^{+0.22}_{-0.34}$
CDFS-4417	$8.60^{+0.10}_{-0.10}$	$8.72^{+0.08}_{-0.10}$	$0.12^{+0.13}_{-0.14}$
CDFS-6664	$7.83^{+0.26}_{-0.28}$	$8.38^{+0.15}_{-0.59}$	$0.55^{+0.30}_{-0.65}$
CDFS-16767	$8.28^{+0.16}_{-0.32}$	$8.79^{+0.11}_{-0.10}$	$0.51^{+0.19}_{-0.34}$
CDFS-2528	$8.10^{+0.42}_{-0.26}$	$8.58^{+0.13}_{-0.20}$	$0.48^{+0.44}_{-0.33}$
CDFS-16272	$7.95^{+0.31}_{-0.34}$	$8.49^{+0.13}_{-1.32}$	$0.54^{+0.34}_{-1.36}$
CDFS-12631	$8.41^{+0.18}_{-0.13}$	$8.51^{+0.36}_{-0.22}$	$0.10^{+0.40}_{-0.26}$
CDFS-14411	$8.13^{+0.21}_{-0.49}$	$8.49^{+0.13}_{-0.16}$	$0.36^{+0.25}_{-0.52}$
SSA22a-M38	$8.10^{+0.24}_{-0.24}$	$8.30^{+0.16}_{-0.15}$	$0.20^{+0.29}_{-0.28}$
SSA22a-C16	$8.34^{+0.14}_{-0.19}$	$8.57^{+0.13}_{-0.15}$	$0.23^{+0.19}_{-0.24}$
<i>Composite</i> ^a	$8.13^{+0.23}_{-0.18}$	$8.56^{+0.44}_{-0.29}$	$0.43^{+0.50}_{-0.34}$

The following quantities are reported in each column: col. 1, object name; col. 2, gas metallicity of the inner aperture within a radius of $0.375''$; col. 3, gas metallicity of the outer region within a radius of $0.375'' < r < 1''$; col. 4, metallicity difference between inner and outer regions. ^a In each column the same values described above are reported for the composite spectra of the ten galaxies presented in this table.

Appendix A: Integrated near-IR spectra of the AMAZE and LSD galaxies

Figs.A.1–A.4 show the integrated spectra of all galaxies in the AMAZE and LSD samples, restricted to the spectral regions covering the nebular lines used to measure the metallicities.

Appendix B: Metallicity measurements

In this appendix we provide some additional details on the measurements of the gas metallicity. As mentioned in sect.5 the metallicities are inferred following the calibrations and the method described in detail in Maiolino et al. (2008). Here we briefly summarize the method and show the application to our full sample of galaxies. Maiolino et al. (2008) inferred relationship between metallicity and various nebular line ratios, by exploiting a combination of “direct” measurements (based on the T_e method, mostly at low metallicities) and photoionization modeling (mostly at high metallicities). It has been recently argued that the excitation conditions in high- z galaxies are different from the local ones and that, therefore, the local calibrations may not apply to high redshift (Kewley et al. 2013). However, we have found in a parallel work (Maiolino et al. 2013) that local calibrations are actually appropriate for high- z galaxies, once selection effects are properly taken in to account. These relations are shown in Fig B.1, where solid black lines show the average of the galaxy distribution and the dashed black lines show the dispersion. Each of these diagnostics has advantages and disadvantages. Some of them are practically unaffected by extinction (e.g. $[\text{OIII}]/\text{H}\beta$), but have a double-degenerate metallicity solution; others, have a monotonic dependence on metallicity (e.g. $[\text{OIII}]/[\text{OII}]$, $[\text{NeIII}]/[\text{OII}]$), but have large dispersion and are affected by reddening. However, if these diagnostics are used simultaneously, then only some combinations of metallicity and reddening are allowed by the data. Obviously, not all of the diagnostics shown in Figs. B.1 – B.5 are independent. We have decided to use the following independent metallicity diagnostics: R_{23} (which has the tightest relationship with metallicity, although with double solution), $[\text{OIII}]/[\text{OII}]$ (which has a monotonic dependence on metallicity, although with large scatter, which allows us to remove the degeneracy on R_{23}) and, when available, $[\text{NeIII}]/[\text{OII}]$ (which has also a monotonic dependence on metallicity). In practice, we determined the χ^2 for each combination of metallicity and dust extinction for each of these relations, and found the best combination as the minimum of χ^2 . The result of this method is shown, for each object in our sample, in Figs. B.1 B.2, B.3, B.4 and B.5. The upper-left panel of the figure associated with each object shows, in the metallicity-extinction plane, the best fitting value (blue cross) and the 1σ confidence level. Clearly the metallicity is generally well constrained. The extinction is instead poorly constrained by this method; but this figure is telling us that the uncertainties on extinction do not affect significantly the metallicity determination. In the other panels the vertical green errorbar indicate the measured ratio with the associated uncertainties, while the blue cross gives the best-fitted value of the metallicity and the dereddened ratio assuming the best-fit reddening value; the red lines show the projection of the 1σ confidence levels. The horizontal green errorbar shows the resulting uncertainty on the metallicity.

While Figs. B.1 B.2, B.3, B.4 and B.5 show the results only for the line ratios obtained from the integrated fluxes in each galaxy, the same method has been applied pixel-to-pixel for resolved galaxies, to infer the metallicity maps shown in Figs. 11, 12 and 13 .

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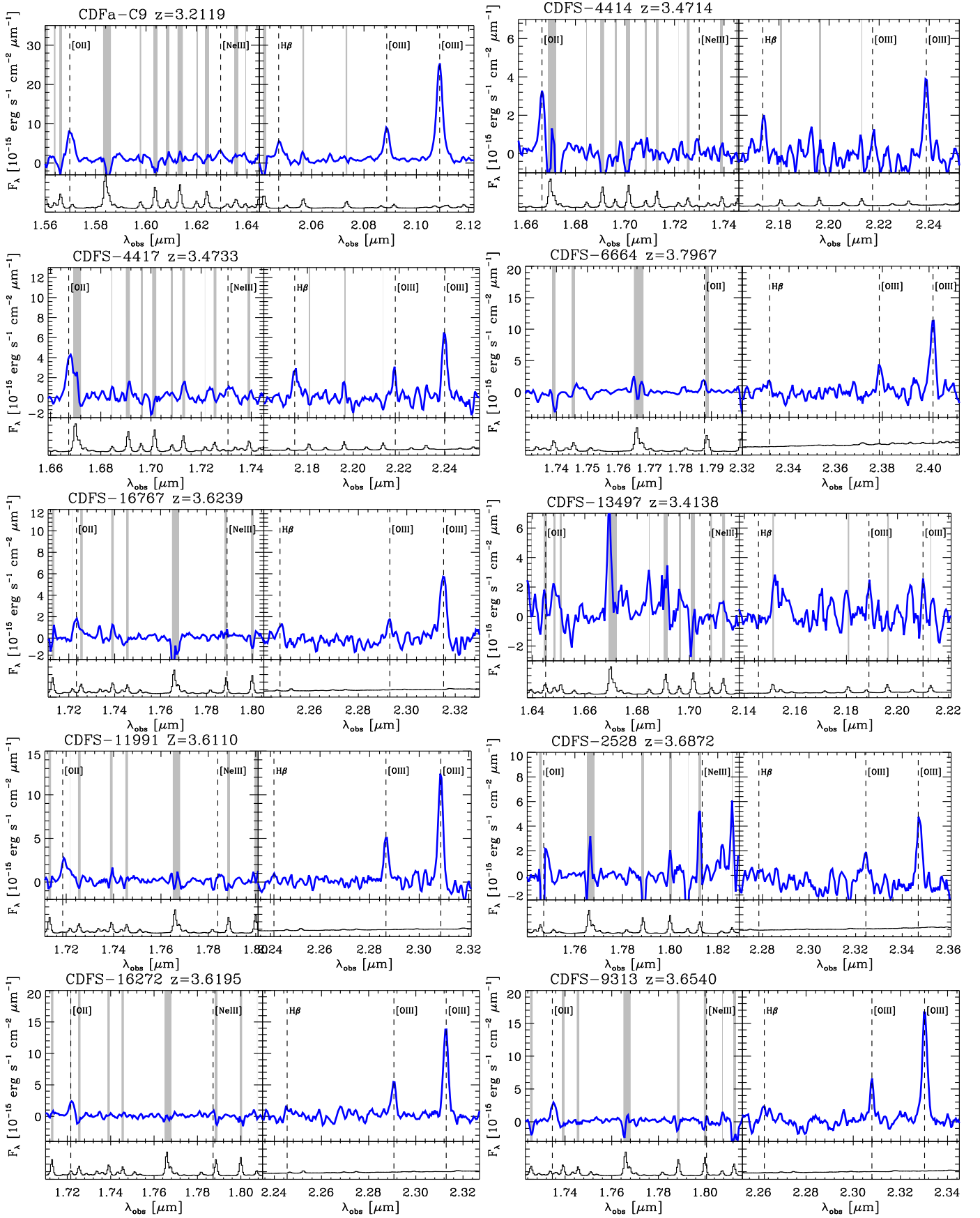


Fig. A.1. Near-IR spectra of the galaxies in the AMAZE sample. The vertical dotted lines indicate the expected location of nebular emission lines. The shaded vertical regions overlaid on each spectrum highlight spectral regions affected by strong sky emission lines.

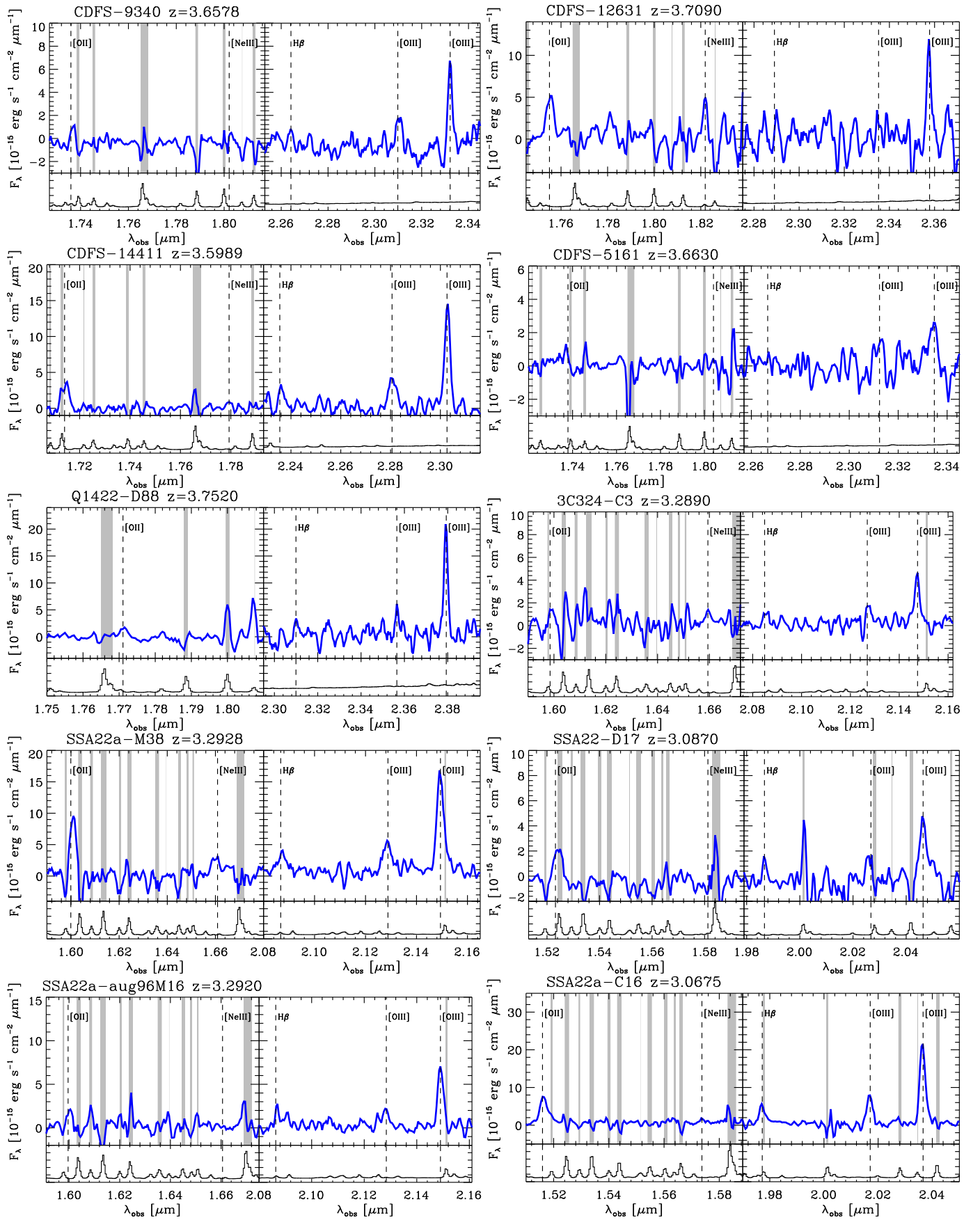


Fig. A.2. Near-IR spectra of the galaxies in the AMAZE sample. The vertical dotted lines indicate the expected location of nebular emission lines. The shaded vertical regions overlaid on each spectrum highlight spectral regions affected by strong sky emission lines.

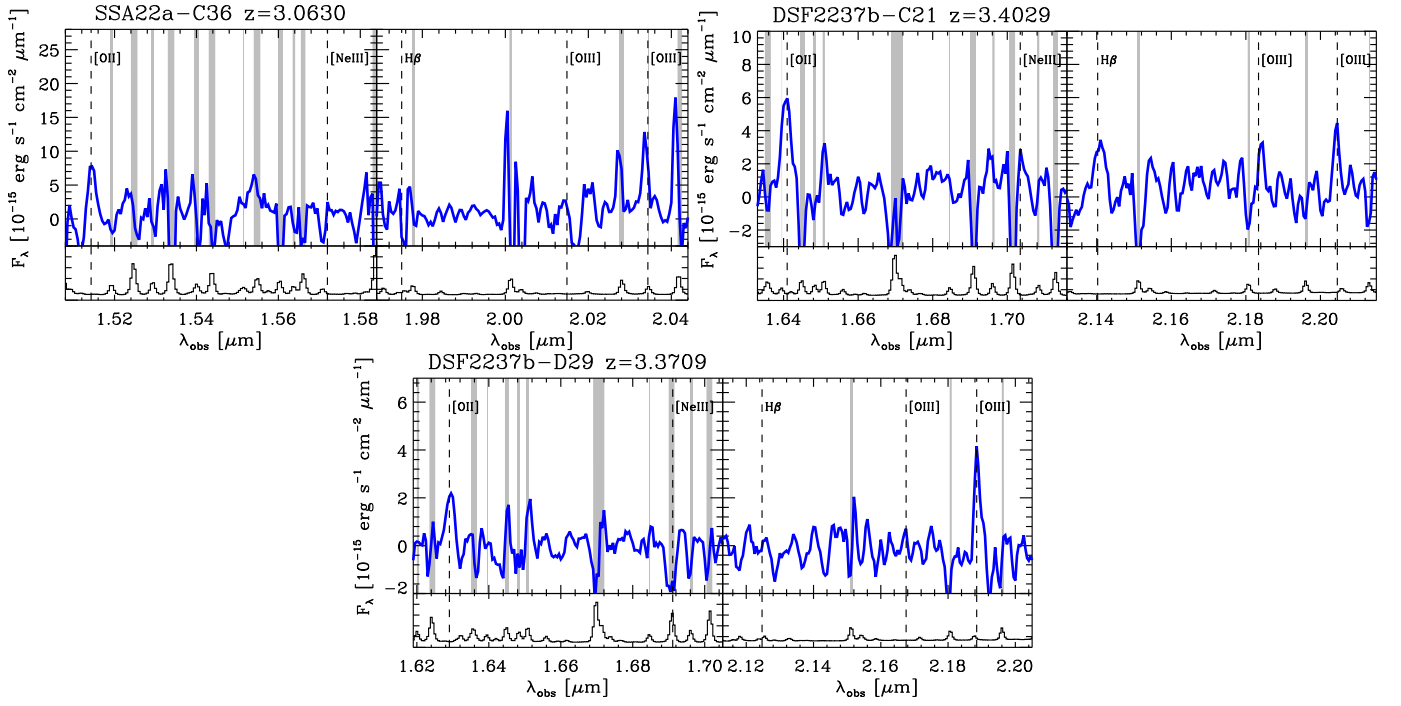


Fig. A.3. Near-IR spectra of the galaxies in the AMAZE sample. The vertical dotted lines indicate the expected location of nebular emission lines. The shaded vertical regions overlaid on each spectrum highlight spectral regions affected by strong sky emission lines.

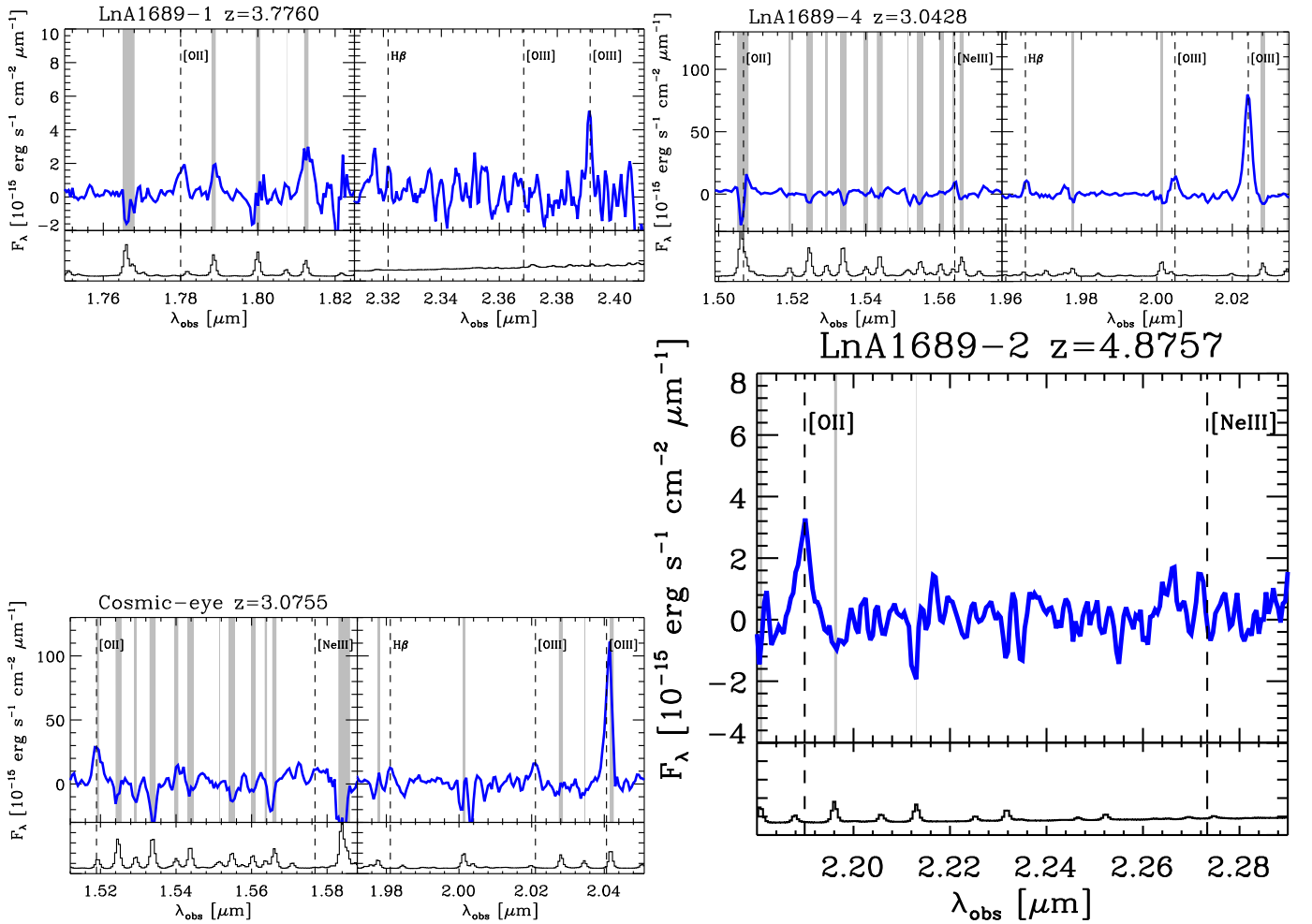


Fig. A.4. Near-IR spectra of the lensed galaxies in the AMAZE sample. The vertical dotted lines indicate the expected location of nebular emission lines. The shaded vertical regions overlaid on each spectrum highlight spectral regions affected by strong sky emission lines.

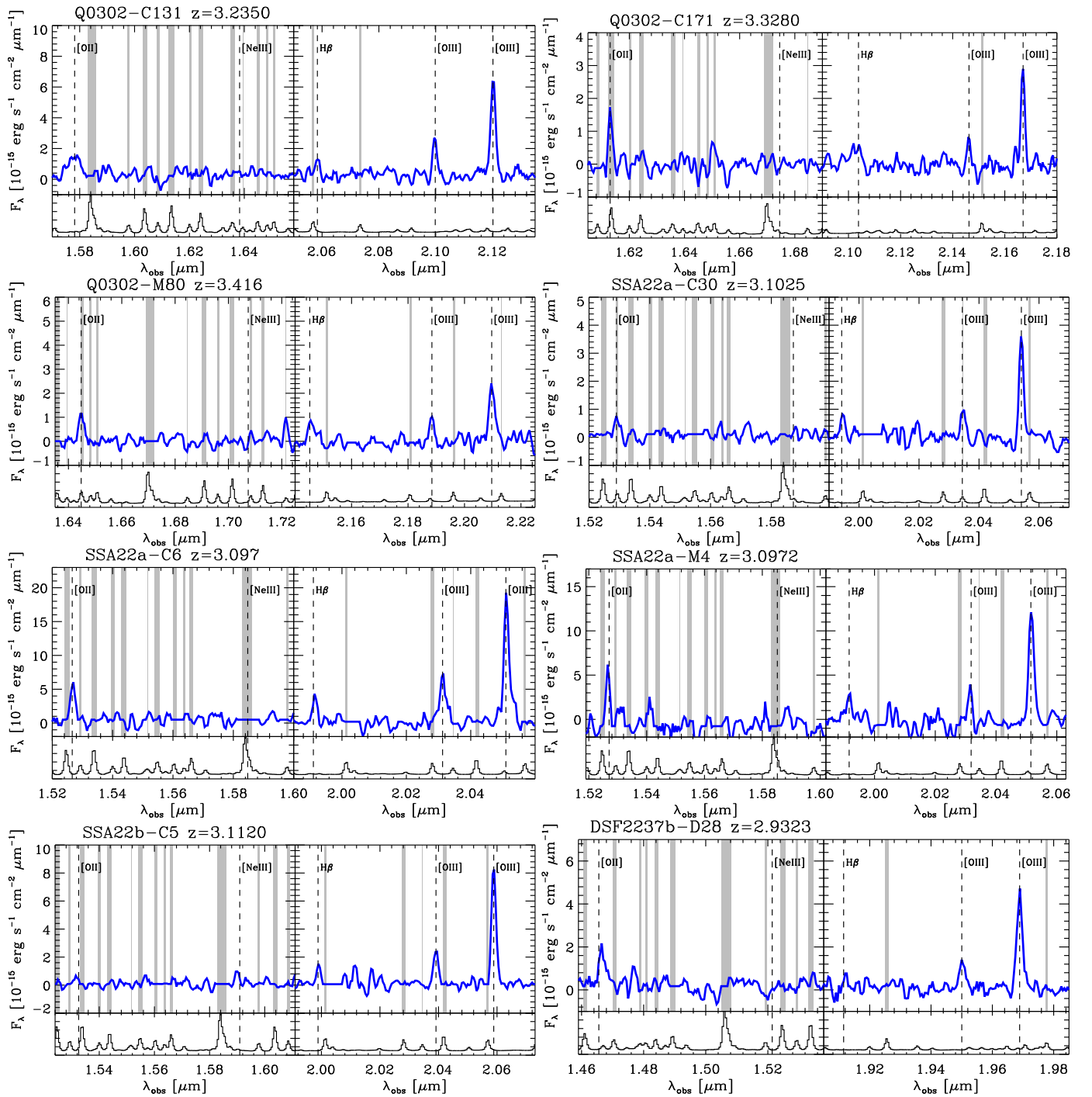


Fig. A.5. Near-IR spectra of the galaxies in the LSD sample. The vertical dotted lines indicate the expected location of nebular emission lines. The shaded vertical regions overlaid on each spectrum highlight spectral regions affected by strong sky emission lines.

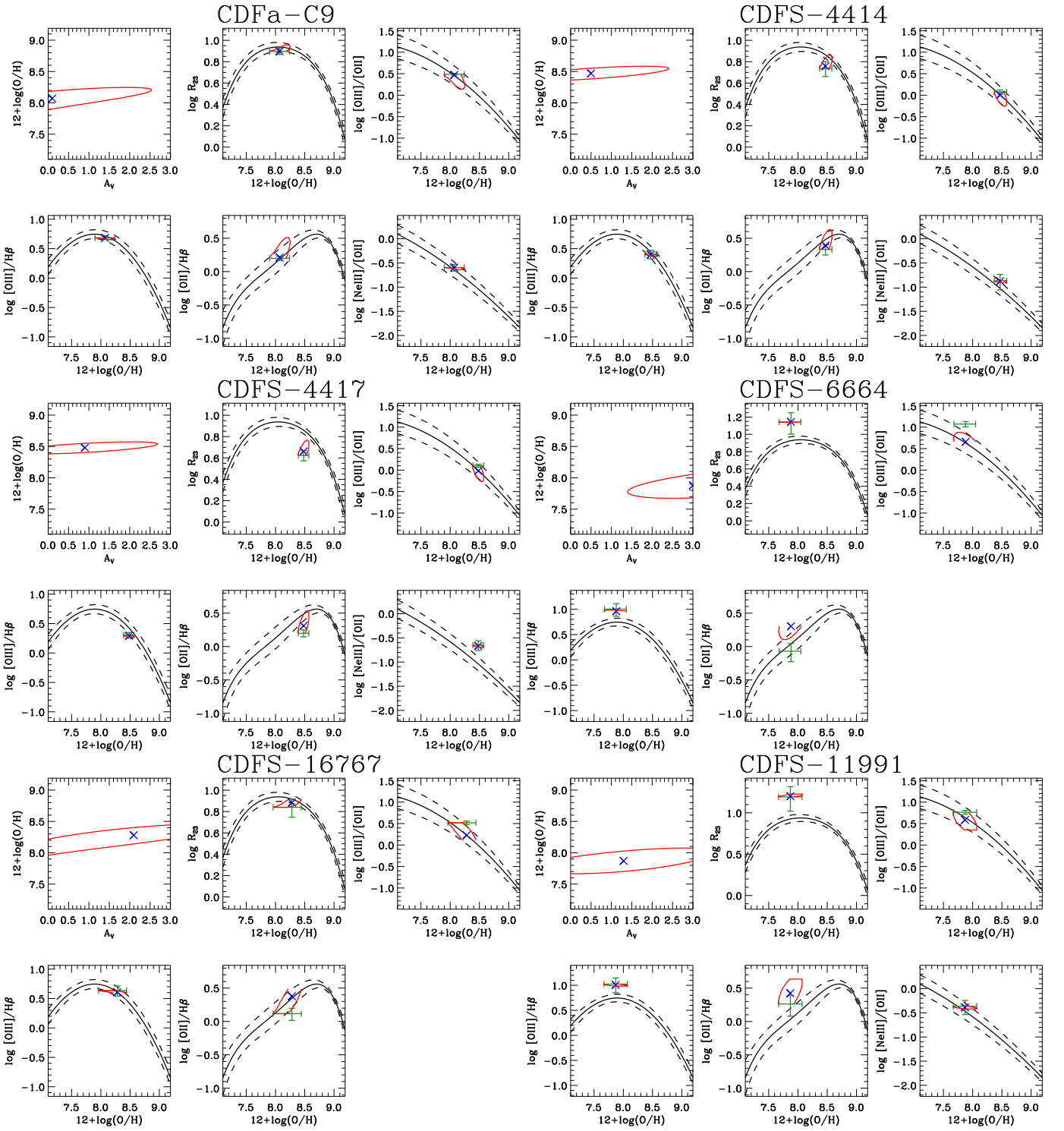


Fig. B.1. Diagnostic tools used to determine the metallicity of galaxies in the AMAZE sample. In each plot, the upper left panel shows the best solution (blue cross) and the 1σ confidence level in the A_V -metallicity plane. In the other panels the black solid line (best fit) and the dashed lines (dispersion) show the empirical relations between various line ratios and the gas metallicity. The green errorbars show the observed ratios (along the Y-axis) and the best-fit metallicity with uncertainty (along the X-axis); the blue cross shows the de-reddened ratios, by adopting the best-fit extinction; the red line shows the projection of the 1σ uncertainty of the fit in the top-left panel.

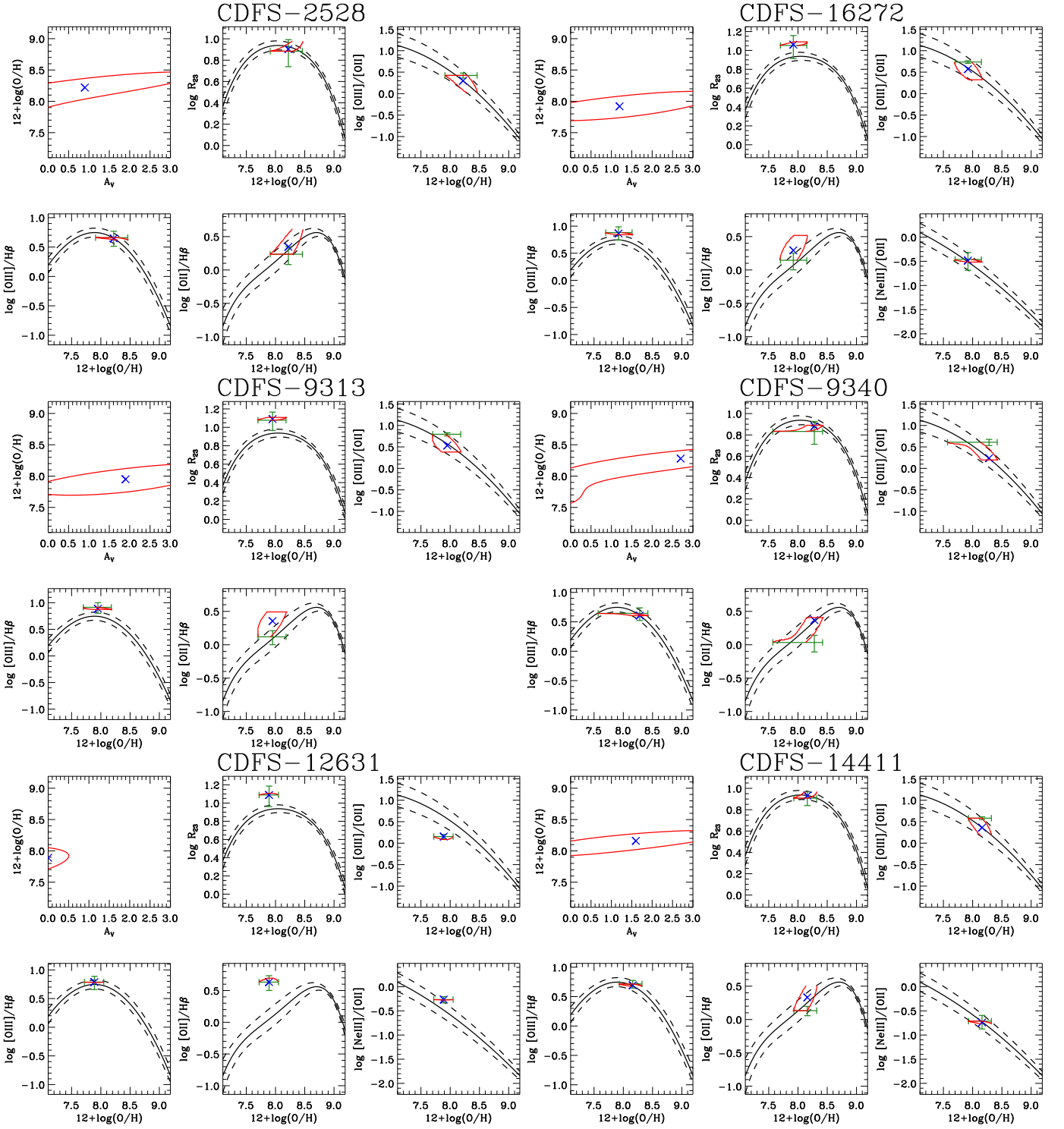


Fig. B.2. Diagnostic tools used to determine the metallicity of the galaxies in the AMAZE sample. In each plot, the upper left panel shows the best solution (blue cross) and the 1σ confidence level in the A_V -metallicity plane. In the other panels the black solid line (best fit) and the dashed lines (dispersion) show the empirical relations between various line ratios and the gas metallicity. The green errorbars show the observed ratios (along the Y-axis) and the best-fit metallicity with uncertainty (along the X-axis); the blue cross shows the de-reddened ratios, by adopting the best-fit extinction; the red line shows the projection of the 1σ uncertainty of the fit in the top-left panel.

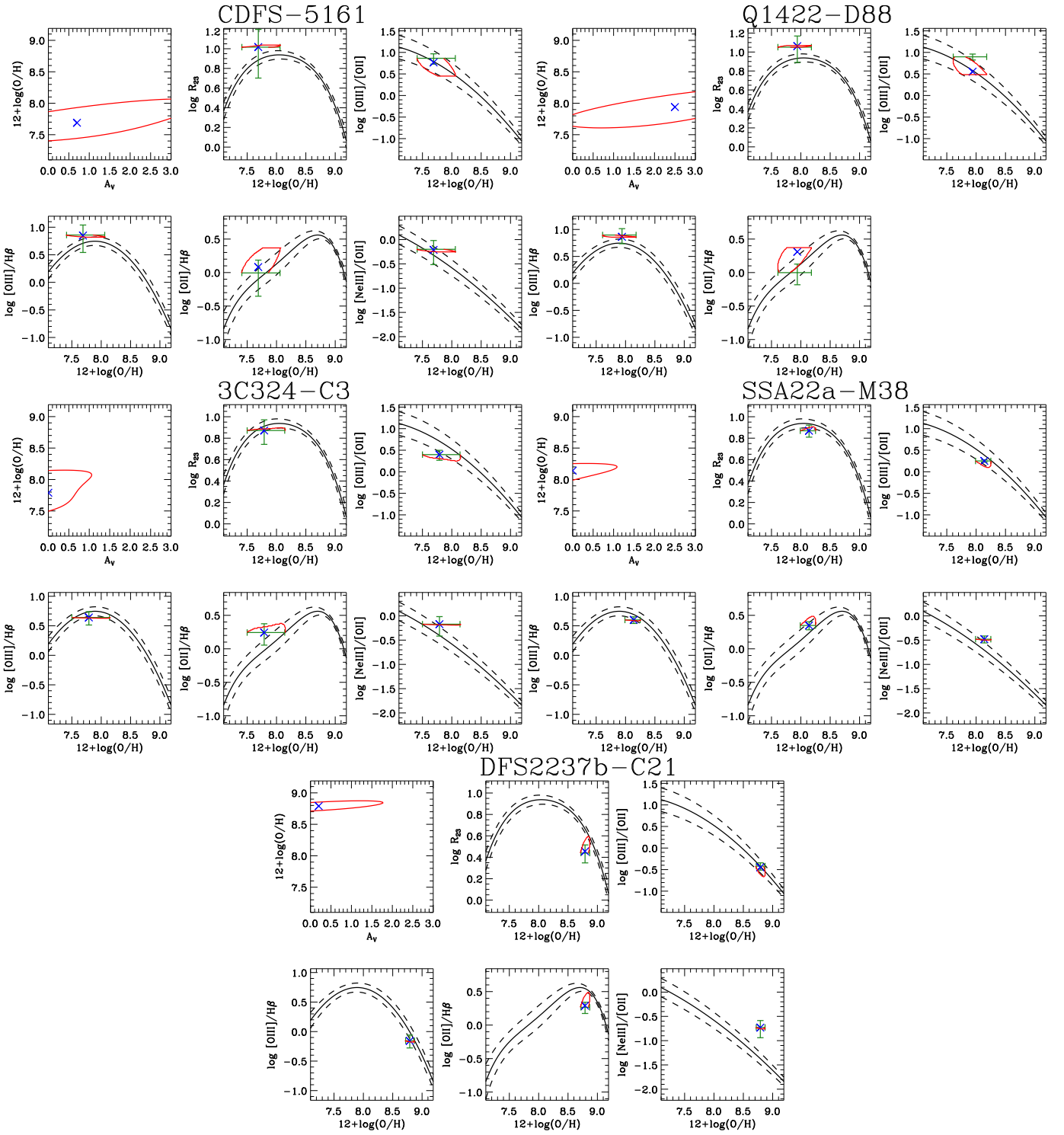


Fig. B.3. Diagnostic tools used to determine the metallicity of the galaxies in the AMAZE sample. In each plot, the upper left panel shows the best solution (blue cross) and the 1σ confidence level in the A_V -metallicity plane. In the other panels the black solid line (best fit) and the dashed lines (dispersion) show the empirical relations between various line ratios and the gas metallicity. The green errorbars show the observed ratios (along the Y-axis) and the best-fit metallicity with uncertainty (along the X-axis); the blue cross shows the de-reddened ratios, by adopting the best-fit extinction; the red line shows the projection of the 1σ uncertainty of the fit in the top-left panel.

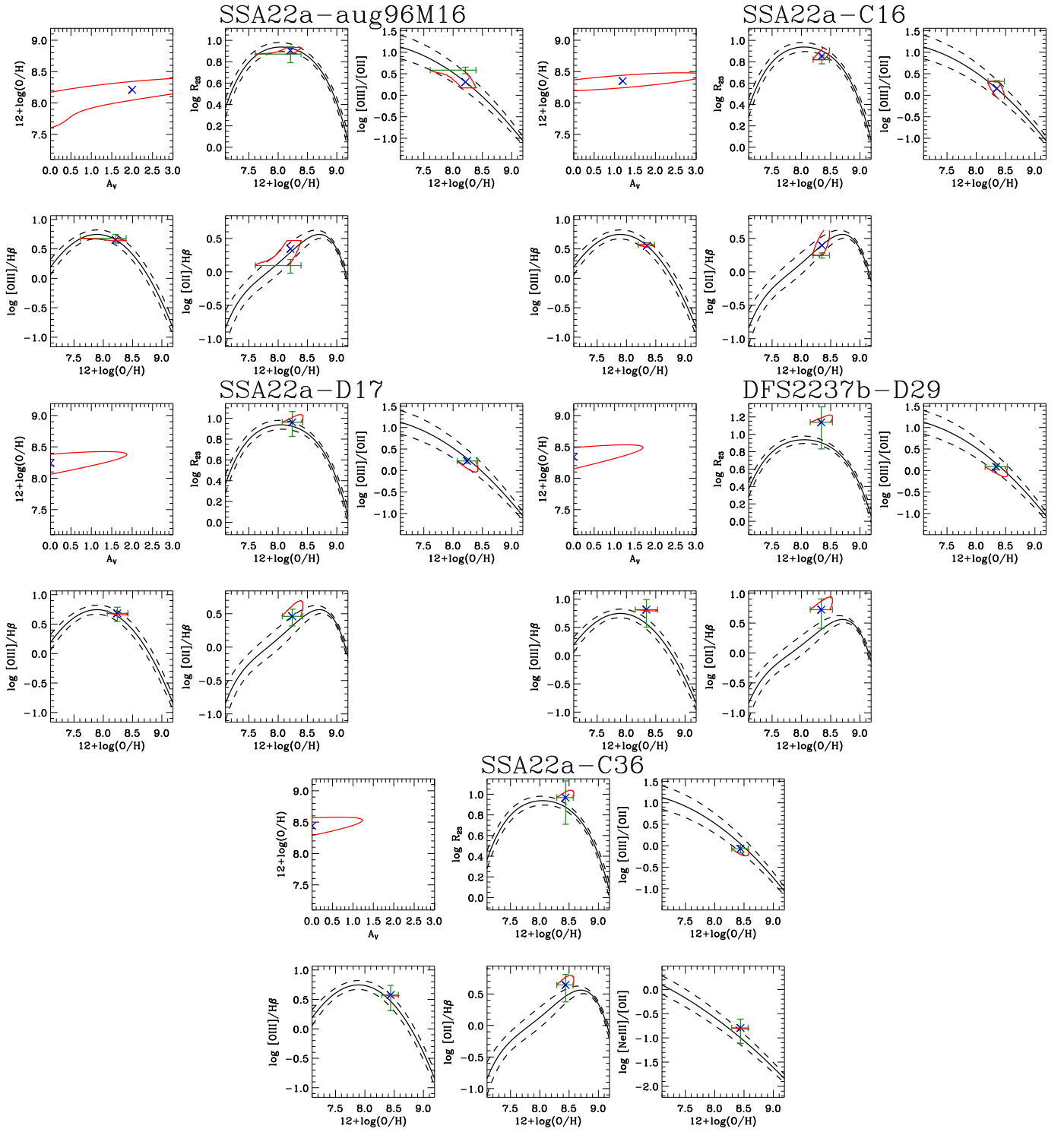


Fig. B.4. Diagnostic tools used to determine the metallicity of the galaxies in the AMAZE sample. In each plot, the upper left panel shows the best solution (blue cross) and the 1σ confidence level in the A_V -metallicity plane. In the other panels the black solid line (best fit) and the dashed lines (dispersion) show the empirical relations between various line ratios and the gas metallicity. The green errorbars show the observed ratios (along the Y-axis) and the best-fit metallicity with uncertainty (along the X-axis); the blue cross shows the de-reddened ratios, by adopting the best-fit extinction; the red line shows the projection of the 1σ uncertainty of the fit in the top-left panel.

LnA1689-2

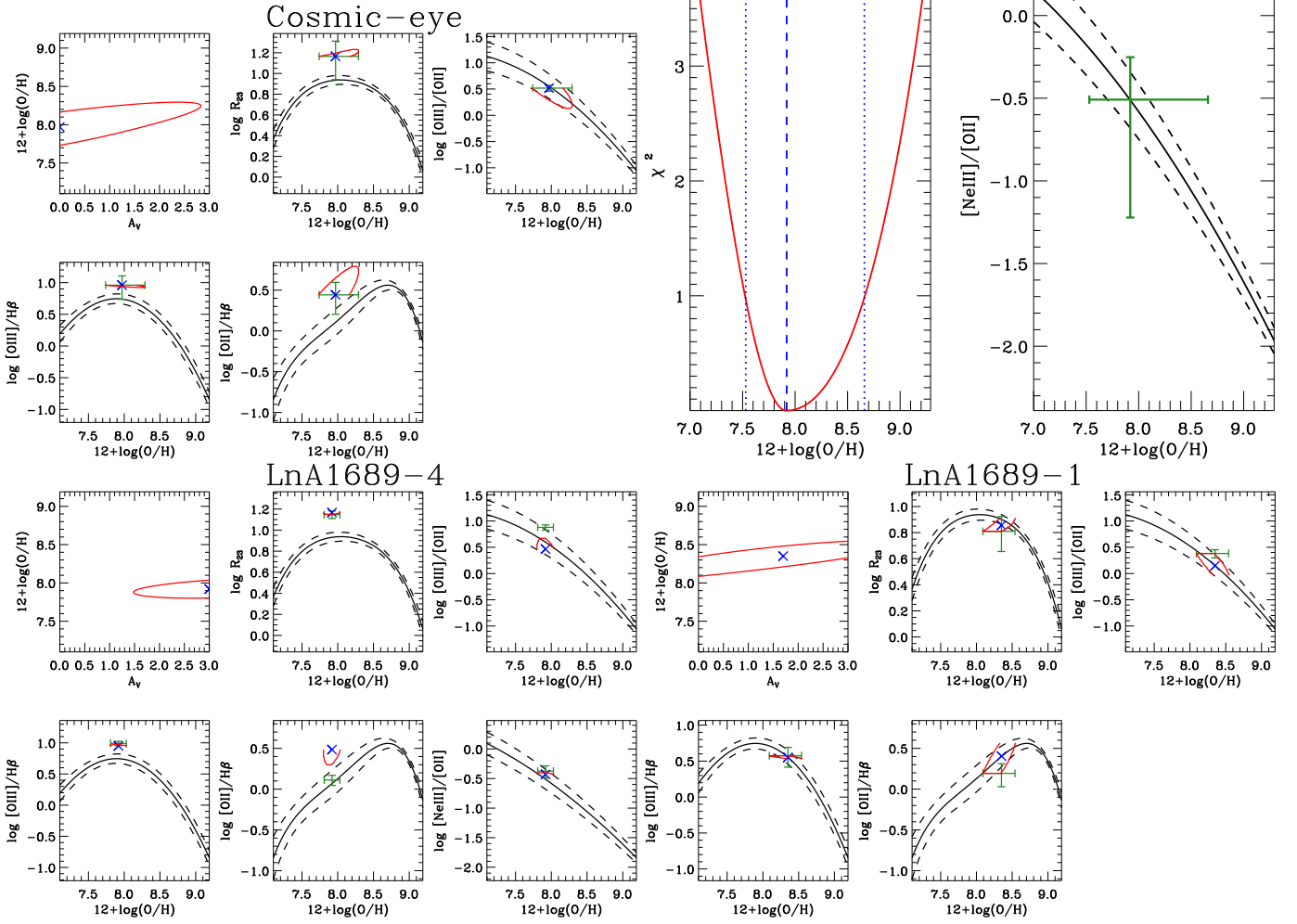


Fig. B.5. Diagnostic tools used to determine the metallicity of lensed galaxies in the AMAZE sample. In each plot, the upper left panel shows the best solution (blue cross) and the 1σ confidence level in the A_V -metallicity plane. In the other panels the black solid line show the average relations between various line ratios and the gas metallicity as inferred by Maiolino et al. (2008). The dashed lines show the associated dispersions. The green errorbars show the observed ratios (along the y-axis) and the best-fit metallicity with uncertainty (along the x-axis); the blue cross shows the best fit metallicity and the de-reddened ratios, by adopting the best-fit extinction; the red line shows the projection of the 1σ uncertainty of the fit in the top-left panel. For the lensed AMAZE galaxy "LnA1689-2" the metallicity is inferred from the $[\text{NeIII}]/[\text{OII}]$ line ratio exploiting the anticorrelation (though with large dispersion) between this line ratio and metallicity found in Maiolino et al. (2008).