# A spectroscopic study of the high-redshift Universe

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# Chapter 8

# Conclusions and future outlook

## 8.1 Conclusions

Most of the results in this thesis would not have been possible five years ago, when MUSE was not available. This once again shows how crucial the development of new instruments and telescopes is for the advance of astrophysics. In addition, the progress made in understanding gravitational lensing allowed us to make use of these natural telescopes much more reliably. The increased sensitivity and spectral resolution are crucial to understand the physical properties of the gas. Information about the ionization state, gas dynamics, and column density are lost when low-resolution spectroscopy is used, as is shown in all chapters of this thesis. These physical galaxy properties are fundamental to our understanding of feedback processes at any redshift.

The increased field of view in combination with high spatial and medium spectral resolution for integral field spectrographs now allow for a blind search for line emitters in a relatively short period of time. Therefore, galaxies with strong emission lines that otherwise could not be currently discovered were revealed; see Chapters 3, 5, and 6. In addition, extended emission and spatial variations in spectra became visible which would be lost with traditional spectroscopy; see Chapters 4 and 7. Below I describe the conclusions of this thesis in more detail.

### 8.1.1 UV-spectroscopy of high-redshift galaxies

High- to medium-resolution spectroscopy in the UV restframe provides valuable information about high-redshift galaxies. In the first place the higher resolution provides secured redshifts as fewer lines are blended. In particular, the resolution used in this thesis allowed for an unambiguous spectral identification of Ly$\alpha$ and doublets like C IV, C III], and [O II]; see Chapters 2, 3, and 6.

Additionally, the increased resolution revealed narrow features that are otherwise blended or washed out. Narrow emission features of C IV, He II, and O III] became visible for LAEs at z $\sim$ 3 (see Chapters 3 and 4), which were not observed using previous low-resolution spectroscopic observations. We used the ratio of these features to demonstrate that the ionization in two of our galaxies is best explained by radiation from SF, rather than from an AGN.

Deep observations with the relatively large field of view and the high-spatial and spectral resolution of MUSE revealed a number of intrinsically faint galaxies, which had not been identified before in deep photometric *HST* observations (Chapters 3, 5, 6). This shows the potential of MUSE to blindly search for new populations of galaxies undiscovered before. In addition, the combination of gravitational lensing and MUSE was proven to be powerful, as it allowed us to simultaneously study the background high-redshift galaxies, revealing previously undetected multiple image families, and improve the corresponding lensing models (Chapters 3, 5, 6).

### 8.1.2 Gas kinematics at $z > 2.5$

The higher resolution and deep spectroscopy in this thesis allowed us to study the profiles of emission and absorption lines in detail. The resolved absorption lines are modelled using a two component fit, while the resolved Ly$\alpha$ emission lines allowed for Ly$\alpha$ line profile modelling.

In this thesis, I have shown that outflows are present in $z > 2.5$ galaxies over a large range of stellar masses. The occurence and velocity of outflows is high in massive galaxies ($\gtrsim$ 40%, Chapter 2) while outflows at low-mass galaxies appear at lower velocity with a large scatter (Chapter 5). The properties of the low mass galaxies are consistent with SF being the main driver of outflows, while there seems to be a mix of AGN and SF driving the outflows in galaxies with stellar masses $M_\star > 10^{10} M_\odot$. These results are in good agreement with model predictions that low-mass galaxies are regulated by stochastic bursts of SF, while in high-mass galaxies there is a combination of large bursts of SF and AGN, which may drive strong outflows possibly quenching the galaxy.

### 8.1.3 Stellar and gaseous properties of faint galaxies

The low mass end of the galaxy stellar mass distribution can currently only be studied through a combination of deep photometry, gravitational lensing, and relatively deep spectroscopy. Chapter 5 showed the discovery of several intrinsically faint LAEs and the spectroscopic redshifts were determined for 14 LAEs in total. These LAEs are among the intrinsically-faintest reported to date and have young ages, low dust attenuation, and low stellar masses. The SFR and sSFR of these galaxies suggest that these galaxies are in a starburst phase.

Through Ly$\alpha$ line profile modelling with shell models we found that these galaxies have low column densities, low outflow velocities, and narrow emission lines. This is to our knowledge the first time that Ly$\alpha$ lines have been modelled by using such a large number of parameters and wide parameter range. Previous studies at similar redshifts addressed much brighter and more massive galaxies and found significantly higher column densities and outflow velocities. The differences in column densities and other gas properties could be explained by the difference in sample selection and suggests a relation between gas properties and stellar mass or brightness.

The UV-continuum slope is in general very steep, in some cases approaching or exceeding the theoretically allowed values. The stellar and gaseous properties combined with the steep UV slopes are all in excellent agreement with the predicted values of low mass galaxies responsible for reionizing the Universe. Our $z \sim 3$ galaxies are therefore observable analogues for the high-redshift reionizing galaxies, and further studying their properties, occurence, and LyC leakage will be crucial to our understanding of cosmic evolution.

### 8.1.4 The driver of faint extended Ly$\alpha$ emission

We used the integral field capability of the MUSE instrument to study the extent of Ly$\alpha$ emission in several lensed galaxies. For one galaxy, we discovered Ly$\alpha$ emission which extended up to a radius of ∼17 kpc (Chapter 4). This LAB is one of the faintest observed to date, and the faintest for which also additional UV emission lines are measured. Opposed to the Ly$\alpha$ line, the C IV line is spatially compact while the He II line is too faint to determine the extent irrefutably. The total Ly$\alpha$ flux in the nebula is in agreement with the amount of Ly$\alpha$ flux emitted by the amount of SFR determined from photometry. The combination of UV line ratios with the compact C IV emission suggest that scattered photons emitted by central SF is the main driver of the extended Ly$\alpha$ emission.

### 8.1.5 Heating of SN environment at $z \sim 1.5$

The discovery of the multiply-imaged SN Refsdal presented a unique opportunity to study the environment of an exploding SN in unprecedented detail at $z = 1.5$. Because of the path length difference, the multiple images represent the spiral galaxy before, during, and after the SN exploded (Chapter 6). The presence of narrow Mg II emission at every location of the SN demonstrates that the environment of the SN was already ionized before the SN exploded, either by previous SN or by the radiation of massive stars born in the same population of stars (Chapter 7). This result can have important consequences for feedback models, as SN feedback is more effective in a highly ionized surrouding.

## 8.2 Future outlook

Although this thesis has answered some questions, it also opens new questions and opportunities for future research. I conclude this thesis by presenting a few of these and discussing how they can be tackled in the near future.

### 8.2.1 Drivers and extent of outflows

In this thesis, I have presented evidence for outflowing material in galaxies of different masses. In Chapter 2, we showed that high velocity outflows are common in massive star-forming galaxies. At low masses the outflows are also present, although at significantly lower masses (Chapters 3 and 5). These outflows can enrich the CGM and IGM, but in order to determine to which extent, it is important to determine how much gas they deposit and at which distance.

Quasar-galaxy pairs are a very promising method to determine the extent of outflows and the composition of the CGM. Observations towards the galaxy trace the central CGM, while the absorption lines of the quasar provide many constraints on the density, composition, and conditions of the CGM at the projected distance of the quasar. By determining the properties of the galaxy, one can then connect the history of feedback to the properties in the CGM, and directly determine what the effects of feedback are.

Díaz et al. (2015) used this approach to demonstrate that feedback must have been very effective to explain the properties of the CGM at a distance of 213 kpc from the galaxy. However, the discovery of a galaxy at closer projected separation would decrease the needed efficiency of feedback and remove the tension between this observation and feedback models. MUSE observations are a very good way to follow up this system and have as advantage that they will simultaneously search for counterparts of all ten other absorption systems found towards this quasar.

### 8.2.2 The faint end of the Ly$\alpha$ luminosity function

With the discovery of faint LAEs behind AS1063, the question is raised if we can determine the faint end of the Ly$\alpha$ luminosity function and the galaxy stellar mass function. The effective volume that is probed by our MUSE observations is too small to reliably determine the luminosity function. An extension of MUSE observations to all FF and other gravitational lensing clusters will increase the number of intrinsically faint LAEs and low mass galaxies to a large enough number to constrain these distribution functions.

### 8.2.3 Populations of normal galaxies with extended Ly$\alpha$ emission

Because of the efficiency of MUSE to detect faint extended emission, the number of Ly$\alpha$ nebulae around L$^\star$ galaxies will increase. This will give us a direct probe of the extent and properties of the CGM of these galaxies. In addition, these sources will show the radiative impact of star formation on the CGM and ISM. This will be helped to even larger detail by the addition of the adaptive optics system to the MUSE system. Adaptive optics will provide spatial information about the shape and structure of the Ly$\alpha$ emission while simultaneously resolving the stellar population of the galaxy.

By increasing the number of deep observations or even extremely deep observations, it will be interesting to learn if there is a large variety in the gas surrounding galaxies. This will answer the questions about the occurence of ionized gas around galaxies and which stellar or nuclear properties are responsible for the ionized gas. Understanding the extent of ionized gas for a large variety of galaxies will put severe constraints on models of galaxy evolution and formation.

### 8.2.4 Galaxies that reionised the Universe

One of the recent frontiers in astronomy is understanding the EOR. Currently, the main driver of reionization is still under debate, with low mass galaxies as the main candidate. The discovery of faint Ly$\alpha$ emitting galaxies at $z \gtrsim 3$ with low column densities and narrow Ly$\alpha$ lines, presented very good analogues to the galaxies possibly responsible for reionization. A definite confirmation that these galaxies are indeed leaking a significant fraction of their Lyman continuum into the IGM is important to confirm dwarf galaxies are responsible for reionization.

Deep photometric observations in bands bluewards of restframe 912 Å are necessary to detect the Lyman continuum leakage. However, it is still very time consuming to observe these galaxies at these wavelengths, in spite of gravitational lensing. For example, to detect the LAE discussed in Vanzella et al. (2016a) and in Chapter 5 with an assumed escape fraction of $\sim 20\%$, more than 100 orbits or 80 hours of *HST* are required.

To determine the escape fraction, it is important to know the slope of the continuum to both the blue and red of 912 Å. Therefore, photometry might be insufficient to determine how much continuum photons are leaking from the galaxy. de Barros et al. (2016) reported the detection of Lyman continuum through spectroscopy, and was therefore able to derive the escape fraction directly.

Given these current observational constraints, a large observational effort is required to definitively establish low mass galaxies as main drivers of reionization. Alternatively, even stronger gravitational lenses might reduce the required time, or statistical tests can be done using a stacking of a significant number of gravitationally lensed, intrinsically faint, high-redshift LAEs.