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The MUSE view of the Frontier Field clusters

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Abstract. Strong gravitational magnification in the core of lensing clusters allows to probe the faint-end of the galaxy luminosity function up to very high redshift. In particular, the Frontier Fields have allowed us to identify a large number of faint dropouts and constrain the Lyman-break luminosity function at $z \sim 5-7$. I present here the results of an ongoing program with MUSE, a new integral field spectrograph on the Very Large Telescope having a large field of view (1 arcmin^2), to confirm these candidate high redshift dropouts through Lyman-α emission and identify additional emitters with high equivalent width, fainter than the depth of the Frontier Fields Hubble images. Combined with similar deep exposures taken with MUSE in blank fields, this gives us the best opportunity to probe the Lyman-α luminosity function over a wide range in luminosity.

Keywords. gravitational lensing, galaxies: clusters: general, techniques: spectroscopic

1. Introduction

The Frontier Field initiative (http://www.stsci.edu/hst/campaigns/frontier-fields/) has extended the use of massive galaxy clusters as gravitational telescopes by providing us with the deepest Hubble view of cluster cores. The main science applications of these deep data concern the accurate mass modelling of these clusters from the identification of multiple images appearing through strong lensing (e.g. Diego *et al.* 2014,Grillo *et al.* 2015, Jauzac *et al.* 2014, Johnson *et al.* 2014, Richard *et al.* 2014) as well as the characterisation of very high redshift dropouts from WFC3 (e.g. Atek *et al.* 2014, Ishigaki *et al.* 2015, Oesch *et al.* 2015, Zheng *et al.* 2014).

However, for both of these applications a lot of additional science can be achieved by combining the high quality of the Frontier Fields data with spectroscopic follow-up on ground based telescopes. In particular, having the spectroscopic redshifts allows us to confirm the identification of multiple images and improve the accuracy of mass modelling, or measure the physical properties of high redshift dropouts (such as the equivalent width of Lyman-α or other UV lines).

We have thus started to observe some massive galaxy clusters, including the southern Frontier Fields, with MUSE (Multi Unit Spectroscopic Explorer), a new integral-field spectrograph which has recently been commissioned on the Very Large Telescope (VLT) (Bacon *et al.* 2014). With a 1×1 arcmin^2 field-of-view MUSE is ideally suited to measure the spectroscopic redshifts of many multiple images and high redshift galaxies. Also, MUSE's very high throughput (up to 37% at 700 nm, including telescope and atmosphere) makes it the most sensitive spectrograph on VLT in the optical domain.

Cluster	Exposure Time	Seeing
SMACS2031	10.4 hours	0.72”
Abell 1689	2 hours	1.0”
Abell 2744 (FF)	2x2 mosaic 18 hours	0.55-1.05”
Abell 2390	2 hours	0.56-0.68”
Abell 2667	2 hours	0.60-0.73”
Abell 370 (FF)	2 hours	0.57-0.79”
MACS0416 (FF)	4 hours	0.64-0.76”
BULLET	2 hours	0.60-0.68”
MACS1206	4 hours	0.52-0.80”

Table 1. Summary of MUSE observations. We provide for each cluster the total exposure time and the range of seeing in the observations. Frontier field clusters are marked as (FF).

2. MUSE observations and data analysis

The MUSE observations focused on the strong lensing region of the clusters, which we covered by 1 to 4 pointings (see Table 1) in nominal mode (wavelength range 4750-9350 Angstroms). The main goals of these observations is to confirm $z > 3$ dropouts through Lyman-α emission, as well as identify additional multiple images for high precision mass modelling.

Each dataset has been reduced using the latest version of the MUSE data reduction pipeline (v. 1.2) and further processed using ZAP (the Zurich Atmosphere Purge, Soto *et al.* in prep.) to remove the strongest sky residuals using a principal component analysis method. The final datacube was combined and aligned to the astrometry of the Hubble Frontier Field images using bright sources identified in the MUSE white light image.

We then extracted the spectra of all HST sources within the MUSE datacube using a SExtractor photometric catalog with a very low detection threshold. This catalog was optimised to detect very faint and compact sources which are likely to be multiple images, for this purpose we filtered the large-scale intracluster light using a running spatial median filter across the Hubble images (see contribution by Guillaume Mahler, this volume). The SExtractor segmentation map is then convolved by the MUSE seeing to define a weighting image to optimally extract the spectra from the MUSE datacubes. Each spectrum is then visually inspected for emission and absorption lines to derive the redshifts.

In addition, we make use of MUSELET, a SExtractor-based line detector tool to search for pure (i.e., not associated with HST continuum) line emitters in the MUSE datacube. These sources have strong line equivalent widths, generally associated with $z > 3$ Lyman-α emission. We combine both continuum sources and line emitters into the final redshift catalog.

3. Results

MUSE commissioning data were SMACS2031, which was observed during the MUSE commissioning, were presented in Richard *et al.* (2015). In total we securely measured the redshift for 113 sources in this cluster, including 11 new multiple images, which allowed us to significantly improve our model of the mass distribution in the cluster core. One of the multiple images is a highly magnified extended Lyman-α emitter at $z = 3.5$ for which it is possible to derive many important physical properties (see contribution by Vera Patrício, this volume).

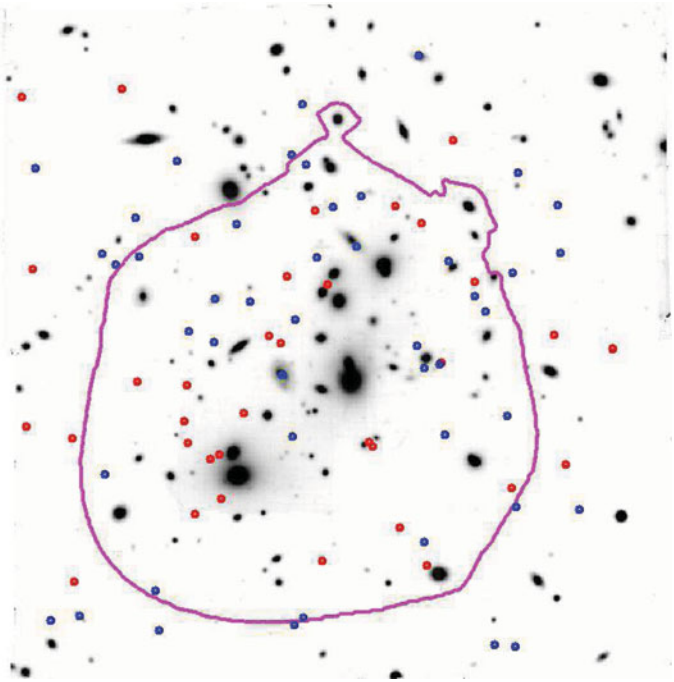

Figure 1. Overview of the redshifts measured in the MUSE dataset of the Frontier Field cluster Abell 2744. The image covers a 2x2 arcmin^2 field of view. Dark/blue circles mark the location of background galaxies at $z < 1.5$, while grey/red circles make the location of sources at $z > 3$. The contour delineate the region within which we expect to find all multiply imaged galaxies in the cluster core.

One of the most interesting dataset is the Frontier Field cluster Abell 2744, which is targeted by a mosaic of 2x2 MUSE fields, fully covering the HST/WFC3 field-of-view and the region of multiple images (see Fig. 1). In this cluster we measured the redshifts for more than 100 background sources, including new multiple images not detected in individual Hubble images, as well as more than 150 cluster members. Similar results were found in the two other Frontier Field clusters MACS0416 and Abell 370 (see contributions by Benjamin Clément and David Lagattuta, this volume).

Overall, the majority of the background galaxies were identified at $z = 3 - 6.7$ through Lyman-α emission, a redshift range at the end of the epoch of reionisation. After correction for magnification, the unlensed Lyman-α fluxes are in the range 0.2-20 10^{-18} erg/s/cm^2, allowing us to constrain the Lyman-α Luminosity Function down to very faint luminosities ($2{\times}10^{40}$ erg/s). We expect to detect several dozens of faint LAEs over all MUSE clusters. We will compare the populations of star-forming galaxies with strong UV continuum (selected through their Lyman-break) with LAEs detected within the same volume to constrain the transmissivity of the intragalactic medium (Bina *et al.* in prep.).

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