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MUSE observations of the lensing cluster SMACSJ2031.8-4036: new constraints on the mass distribution in the cluster core

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ABSTRACT

We present new observations of the lensing cluster SMACSJ2031.8-4036 obtained with the Multi Unit Spectroscopic Explorer (MUSE) integral field spectrograph as part of its commissioning on the Very Large Telescope. By providing medium-resolution spectroscopy over the full 4750–9350 Å domain and a 1×1 arcmin² field of view, MUSE is ideally suited for identifying lensed galaxies in the cluster core, in particular multiple-imaged systems. We perform a redshift analysis of all sources in the data cube and identify a total of 12 systems ranging from $z = 1.46$ to 6.4, with all images of each system confirmed by a spectroscopic redshift. This allows us to accurately constrain the cluster mass profile in this region. We foresee that future MUSE observations of cluster cores should help us discover very faint Lyman α emitters thanks to the strong magnification and the high sensitivity of this instrument.

Key words: galaxies: clusters: individual: SMACSJ2031.8-4036.

1 INTRODUCTION

Galaxy cluster cores contain large concentrations of dark matter, and in such act as powerful gravitational lenses. At its strongest, the deflection of light rays from distant galaxies can create multiple images of a single source (Kneib & Natarajan 2011), and the location of such multiples can be used to infer the total mass distribution in cluster cores (Richard et al. 2010; Zitrin et al. 2012).

Since the discovery of the first lensed systems in cluster cores, dedicated whole-sky cluster searches such as the MASSive Cluster Survey (MACS; Ebeling, Edge & Henry 2001; Ebeling et al. 2010), followed up by multiband Hubble imaging, have provided a large number of multiple systems in individual lensing clusters (Zitrin et al. 2011; Limousin et al. 2012). The largest number of multiple systems so far have been found in the clusters Abell 1689 (34 systems; Limousin et al. 2007), and the recent Frontier fields clusters (Jauzac et al. 2014a,b; Richard et al. 2014 with 68 systems for MACSJ0416.1-2403).

An important part of the mass modelling relies on getting accurate spectroscopic redshifts for the lensed sources, to completely confirm the lensing system and to avoid degeneracies in the mass normaliza-

tion. As the typical magnitude range for lensed sources found with Hubble is ~ 23 –25 AB (Richard et al. 2009; Jauzac et al. 2014a), deep spectroscopy is required. Large spectroscopic campaigns have been performed with multi-object spectrographs (Grillo et al. 2014; Johnson et al. 2014), but they rely on a preselection based on deep multiband Hubble images and are quite inefficient since all multiple images are crowded in the cluster core.

The advent of the Multi Unit Spectroscopic Explorer (MUSE; Bacon et al. 2010), recently commissioned on the Very Large Telescope, may well set a new benchmark in the study of galaxy cluster cores. By providing integral field optical spectroscopy over a sky area of 1×1 arcmin², MUSE perfectly catches the full locus of multiple images in a moderately massive cluster. MUSE acts as a powerful redshift machine to identify faint emission lines of high equivalent width not appearing in classical continuum imaging, in particular Lyman α emitters at $2.8 < z < 6.7$ probing the high-redshift Universe.

Here, we present the first results obtained on deep pointed MUSE observations towards a massive cluster, SMACSJ2031.8-4036. We perform a redshift measurement of all sources in the MUSE field of view and identify multiply-imaged systems based on spectroscopic redshifts, the majority of which are not detected with short exposure Hubble images. This allows us to improve the cluster mass model in this region very significantly. Throughout this

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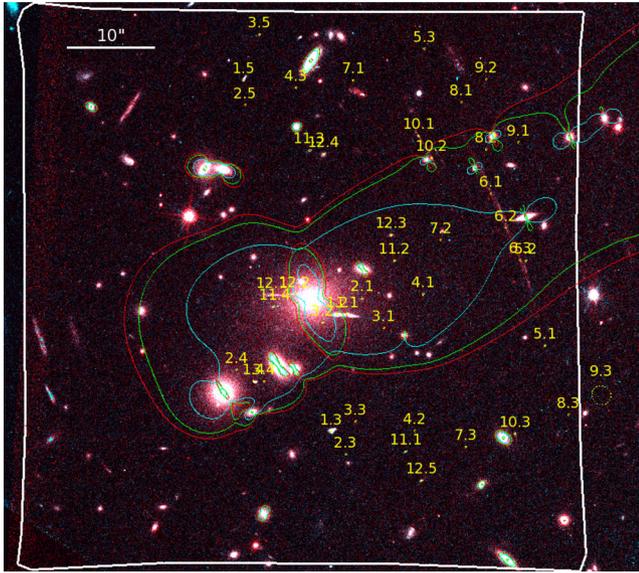


Figure 1. Overview of all multiple-image systems (in yellow) identified over a Hubble colour image combining the *F606W* and *F814W* bands (north up, east left). The white polygon delineates the 1×1 arcmin² region covered by the MUSE observations used in this paper. The cyan, green and red lines show the critical lines predicted by our revised mass model (Section 4) at $z = 1.46$ (system 6), $z = 3.5077$ (systems 1 and 2) and $z = 6.4085$ (system 9).

Letter, we adopt a Λ cold dark matter cosmology with $\Omega_{\Lambda} = 0.7$, $\Omega_{\text{M}} = 0.3$ and $H = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. At the redshift of the cluster $z = 0.331$, 1 arcsec on sky corresponds to a physical distance of 4.763 kpc.

2 OBSERVATIONS

SMACSJ2031.8-4036 (hereafter SMACSJ2031; $\alpha = 20:31:47.843$, $\delta = -40:36:54.76$, $z = 0.331$, Christensen et al. 2012) has been observed with the *Hubble Space Telescope* (*HST*) as part of snapshot programmes 12166 and 12884 (PI: Ebeling), using the Advanced Camera For Surveys (ACS) and Wide Field Camera 3 (WFC3). The ACS data were taken in the *F606W* and *F814W* filters for 1.2 and 1.44 ks, respectively, and the WFC3 data were taken in *F110W* and *F140W* for 0.7 ks each. The data were reduced using MULTIDRIZZLE (Koekemoer et al. 2002) and the astrometry tied to the USNO catalogue.

The Hubble images reveal a bimodal cluster, with two distinct concentrations of cluster galaxies located 1.2 arcmin apart. The *HST* images are centred on the NW subcluster, and therefore the WFC3 data only partially cover the SE subcluster (~ 40 per cent of the MUSE field of view described below).

An early analysis of these images revealed a five-imaged strongly lensed system identified by its morphology, and measured by Christensen et al. (2012) at $z = 3.5077$ using XShooter (images 1.1–1.5 in Fig. 1). Additional candidate radial arcs were discovered around the SE sub cluster, showing the potential for confirming more multiple images in this region.

For this reason, SMACSJ2031 was targeted as part of MUSE commissioning (ESO programme 60.A-9100(B)) to demonstrate the power of MUSE once combined with lensing magnification. A total of 10.4 h of observations were obtained in nominal (WFM-NOAO-N) mode between 2014 April 30 and May 7, and the 1×1 arcmin² field of view was centred on the SE cluster to cover the predicted locus of multiple images (Fig. 1). A small random dithering pattern (within a 0.6 arcsec box) and 90° rotations of the instrument were performed between each exposure of 1200 s.

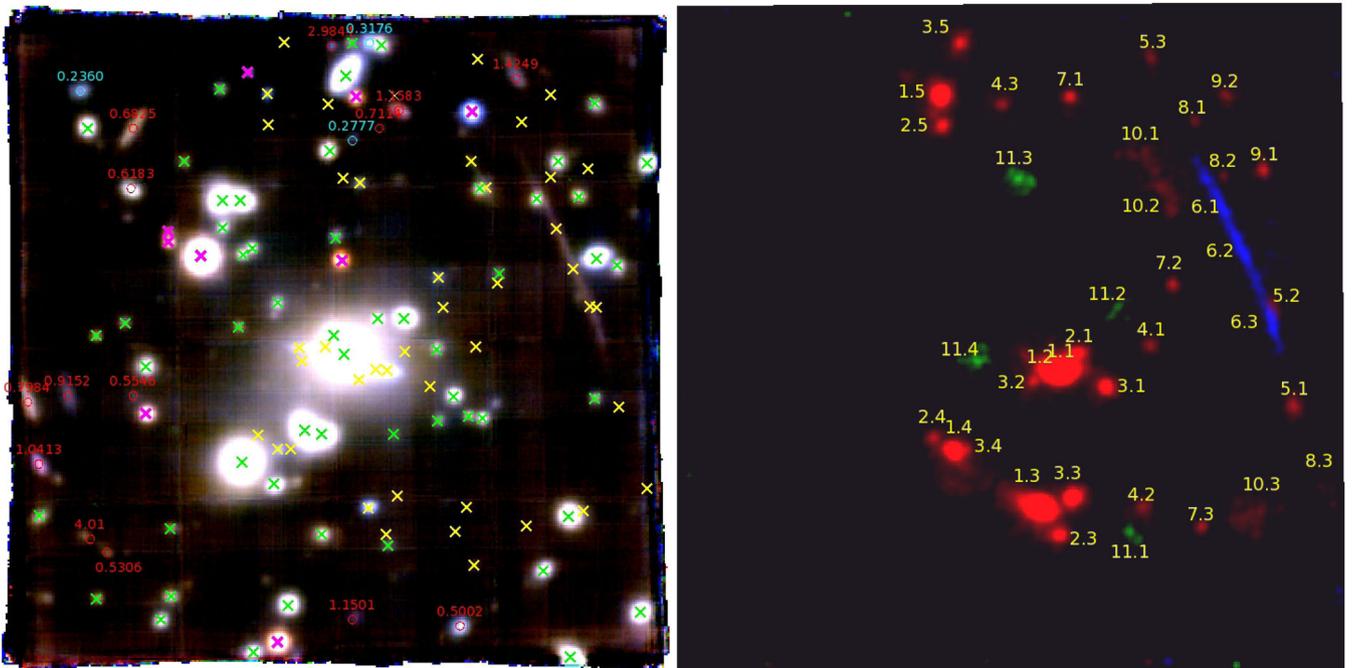


Figure 2. Overview of all redshifts measured in MUSE observations. The left-hand panel shows a MUSE colour image produced by collapsing three contiguous wavelength ranges in the whole cube. The green crosses identify cluster members confirmed by our spectroscopy. Cyan and red circles show the redshifts of foreground and single image background sources, respectively, while the yellow crosses mark the location of multiple images. The right-hand panel shows a combination of all narrow-band images showing the emission lines in multiply imaged systems 1–12. Lyman α emitters are presented in red, while [O II] and C III emitters are shown in blue and green, respectively.

The MUSE data were reduced and combined into a single data cube using the MUSE data reduction software (Weilbacher et al. in preparation), and further processed with the ZAP software (Soto et al. in preparation) which suppresses residuals of sky subtraction using a principal component analysis. Flux calibration was performed based on observations of the spectrophotometric standard HD 49798 (O6 star) and GD108 (subdwarf B star). The final data cube is sampled at a pixel scale of 0.2 arcsec and covers the wavelength range 4750–9350 Å with a dispersion of 1.25 Å per pixel and a resolution increasing from $R \sim 2000$ to $R \sim 4000$ between the blue and red end. The seeing varied from 0.6 to 1.2 arcsec between each exposure and is measured to be ~ 0.95 arcsec in the final combined data cube based on the brightest star in the field. More details about the data reduction and quality of the final products will be given in Patricio et al. (to be submitted).

3 DATA ANALYSIS

We searched the MUSE data cube for spectral features, both for continuum-detected sources and for objects dominated by nebular emission lines. We first produced ‘white-light’ and colour images by collapsing the cube over its full wavelength range or in the blue/green/red wavelengths (Fig. 2, left-hand panel). We ran SExtractor (Bertin & Arnouts 1996) to identify objects in the white-light image and measured their continuum levels at three wavelengths. The spectra of these continuum sources were extracted using the spatial extent measured in the white-light image.

In addition, we produced pseudo-narrow-band images by performing a running average of five adjacent wavelength planes (6.25 Å width) in the whole cube, using a weighting scheme to enhance the detection of typical $\sigma \sim 100 \text{ km s}^{-1}$ emission lines. We ran SExtractor again in each of these narrow-band images, and compared the detections with the previous continuum measurements to identify emission lines associated with continuum sources and isolated emission lines. Examples of continuum-subtracted narrow-band detections are given in Fig. 2 (right-hand panel). All emission lines are well-detected and resolved over multiple wavelength planes throughout the cube.

Redshifts were measured for both continuum- and emission-line-dominated sources by identifying a combination of emission and absorption line features. The large majority of continuum sources identified are formed by cluster members (53) and foreground sources (3), easily recognizable with K 3933 Å and H 3969 Å absorption features (green and cyan crosses, respectively, in the left-hand panel of Fig. 2). Background sources are all identified through their emission lines or Lyman α break, in particular [O III] 5007 Å at $z < 0.8$, [O II] 3727 Å at $z < 1.5$, but for the large majority with Lyman α 1216 Å at $z > 2.8$ (Table 1). As Lyman α is usually the only spectral feature visible in the MUSE wavelength range, we rely on its typical asymmetric shape and the absence of a doublet or other emission lines to ascertain the redshift (Fig. 3). We also measured the redshifts of candidate arcs and multiple images visible in *HST* images, through [O II] at $z = 1.46$ (system 6), C III] 1907, 1909 Å at $z = 2.2556$ (system 11) or a Lyman α break at $z = 3.41$ (system 12).

We searched through the redshifts measured in the cube for multiple images based on a preliminary mass modelling of the cluster core, which used only the five-imaged system at $z = 3.5077$ (Christensen et al. 2012). We found reliable connections for 43 sources forming a total of 12 systems (combining continuum and emission-line dominated sources), with the predictions from the model always lying within 1 arcsec from the detection. We then

Table 1. Multiple image systems (top part) and other single image lensed sources (bottom part). From left to right, we give their positions (J2000.0), measured redshifts, magnifications, main line feature detected and corresponding line flux. Ly α b refers to the Lyman α absorption break. Positions marked with brackets are not detected with MUSE but are predicted by the lens model (see the text for details).

| ID | α (h) 20:31: | δ (deg) −40:37: | z_{spec} | μ | line | flux $10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$ |
|------|------------------------|---------------------------|-------------------|----------------|---------------|---|
| 1.1 | 52.90 | 32.5 | 3.508 | 19.9 ± 1.9 | Ly α | 185 ± 5 |
| 1.2 | 52.99 | 32.5 | 3.508 | 11.7 ± 1.2 | Ly α | 169 ± 4 |
| 1.3 | 53.05 | 45.8 | 3.508 | 6.8 ± 0.2 | Ly α | 270 ± 3 |
| 1.4 | 53.83 | 40.1 | 3.508 | 2.5 ± 0.1 | Ly α | 42 ± 0.6 |
| 1.5 | 53.93 | 06.0 | 3.508 | 3.5 ± 0.1 | Ly α | 110 ± 2 |
| 2.1 | 52.74 | 30.7 | 3.508 | 4.7 ± 0.2 | Ly α | 22.4 ± 0.6 |
| 2.2 | [53.12] | [31.1] | | | | |
| 2.3 | 52.91 | 48.4 | 3.508 | 4.7 ± 0.1 | Ly α | 21.1 ± 0.8 |
| 2.4 | 53.99 | 38.8 | 3.508 | 2.7 ± 0.1 | Ly α | 10.4 ± 0.6 |
| 2.5 | 53.90 | 08.9 | 3.508 | 3.9 ± 0.1 | Ly α | 16.4 ± 0.7 |
| 3.1 | 52.53 | 34.1 | 5.623 | 5.3 ± 0.2 | Ly α | 37.6 ± 1.4 |
| 3.2 | 53.14 | 33.5 | 5.623 | 2.6 ± 0.1 | Ly α | 17.7 ± 1.1 |
| 3.3 | 52.81 | 44.6 | 5.623 | 8.2 ± 0.3 | Ly α | 56.6 ± 1.8 |
| 3.4 | 53.72 | 40.1 | 5.623 | 2.2 ± 0.1 | Ly α | 11.6 ± 0.9 |
| 3.5 | 53.76 | 00.9 | 5.623 | 3.3 ± 0.1 | Ly α | 24.8 ± 1.4 |
| 4.1 | 52.14 | 30.3 | 3.340 | 4.1 ± 0.1 | Ly α | 8.3 ± 0.7 |
| 4.2 | 52.22 | 45.7 | 3.340 | 5.0 ± 0.1 | Ly α | 12.6 ± 1.0 |
| 4.3 | 53.40 | 06.9 | 3.340 | 5.2 ± 0.1 | Ly α | 9.9 ± 0.8 |
| 5.1 | 50.92 | 36.1 | 3.723 | 9.1 ± 0.2 | Ly α | 14.3 ± 1.0 |
| 5.2 | 51.11 | 26.5 | 3.723 | 18.1 ± 0.8 | Ly α | 6.8 ± 0.7 |
| 5.3 | 52.12 | 02.5 | 3.723 | 5.1 ± 0.1 | Ly α | 6.5 ± 0.7 |
| 6.1 | 51.46 | 18.9 | 1.425 | 19.5 ± 1.0 | [O II] | 582 ± 13 |
| 6.2 | 51.31 | 22.8 | 1.425 | 11.8 ± 0.5 | [O II] | 578 ± 12 |
| 6.3 | 51.17 | 26.4 | 1.425 | 18.2 ± 0.6 | [O II] | 553 ± 11 |
| 7.1 | 52.83 | 06.1 | 5.240 | 4.9 ± 0.1 | Ly α | 14.5 ± 0.8 |
| 7.2 | 51.96 | 24.2 | 5.240 | 4.2 ± 0.1 | Ly α | 8.1 ± 0.6 |
| 7.3 | 51.71 | 47.6 | 5.240 | 4.1 ± 0.1 | Ly α | 6.7 ± 0.5 |
| 8.1 | 51.75 | 08.6 | 5.613 | 15.0 ± 0.5 | Ly α | 3.4 ± 0.4 |
| 8.2 | 51.51 | 13.9 | 5.613 | 14.0 ± 0.6 | Ly α | 2.7 ± 0.3 |
| 8.3 | 50.69 | 43.9 | 5.613 | 4.1 ± 0.1 | Ly α | 0.4 ± 0.1 |
| 9.1 | 51.19 | 13.1 | 6.408 | 14.8 ± 0.9 | Ly α | 10.3 ± 0.8 |
| 9.2 | 51.51 | 06.0 | 6.408 | 13.8 ± 0.6 | Ly α | 5.5 ± 0.7 |
| 9.3 | [50.36] | [41.7] | | | | |
| 10.1 | 52.18 | 12.4 | 3.856 | 14.1 ± 0.4 | Ly α | 4.0 ± 0.8 |
| 10.2 | 52.05 | 14.9 | 3.856 | 4.1 ± 0.1 | Ly α | 9.6 ± 1.3 |
| 10.3 | 51.22 | 46.1 | 3.856 | 6.1 ± 0.2 | Ly α | 8.9 ± 1.3 |
| 11.1 | 52.31 | 48.1 | 2.256 | 3.7 ± 0.1 | C III] | 2.5 ± 0.8 |
| 11.2 | 52.42 | 26.5 | 2.256 | 3.4 ± 0.1 | C III] | 1.4 ± 0.6 |
| 11.3 | 53.27 | 14.0 | 2.256 | 5.6 ± 0.1 | C III] | 9.6 ± 2.6 |
| 11.4 | 53.62 | 31.6 | 2.256 | 4.9 ± 0.3 | C III] | 6.3 ± 1.4 |
| 11.5 | [53.27] | [30.8] | | | | |
| 12.1 | 53.64 | 30.3 | 3.414 | 5.6 ± 0.4 | Ly α b | |
| 12.2 | 53.42 | 30.2 | 3.414 | 4.3 ± 0.3 | Ly α b | |
| 12.3 | 52.45 | 23.6 | 3.414 | 4.4 ± 0.1 | Ly α b | |
| 12.4 | 53.13 | 14.4 | 3.414 | 7.3 ± 0.2 | Ly α b | |
| 12.5 | 52.15 | 51.4 | 3.414 | 3.2 ± 0.1 | Ly α b | |
| s1 | 55.37 | 49.2 | 4.010 | 3.5 ± 0.1 | Ly α | 12.8 ± 1.1 |
| s2 | 53.37 | 01.2 | 2.984 | 3.4 ± 0.1 | Ly α | 38.7 ± 1.5 |
| s3 | 51.80 | 04.1 | 1.425 | 4.2 ± 0.2 | [O II] | 75.6 ± 2.3 |
| s4 | 52.79 | 07.4 | 1.158 | 3.1 ± 0.1 | [O II] | 60.2 ± 2.0 |
| s5 | 53.16 | 56.3 | 1.150 | 2.1 ± 0.1 | [O II] | 19.1 ± 1.7 |
| s6 | 55.85 | 41.7 | 1.041 | 2.3 ± 0.1 | [O II] | 48.7 ± 1.7 |
| s7 | 55.61 | 35.0 | 0.9152 | 2.5 ± 0.1 | [O II] | 62.7 ± 1.4 |
| s8 | 55.94 | 35.6 | 0.7984 | 2.0 ± 0.1 | [O II] | 100.7 ± 1.3 |
| s9 | 52.97 | 09.0 | 0.7114 | 2.2 ± 0.1 | [O II] | 3.9 ± 0.8 |
| s10 | 55.06 | 09.2 | 0.6825 | 1.7 ± 0.1 | [O II] | 75.7 ± 1.9 |
| s11 | 55.07 | 15.2 | 0.6183 | 1.8 ± 0.1 | [O II] | 47.8 ± 1.9 |
| s12 | 55.05 | 35.0 | 0.5546 | 1.4 ± 0.1 | [O II] | 4.2 ± 1.0 |
| s13 | 55.27 | 50.1 | 0.5306 | 1.9 ± 0.1 | K,H | |
| s14 | 52.28 | 57.2 | 0.5002 | 1.4 ± 0.1 | [O II] | 112.8 ± 3.9 |

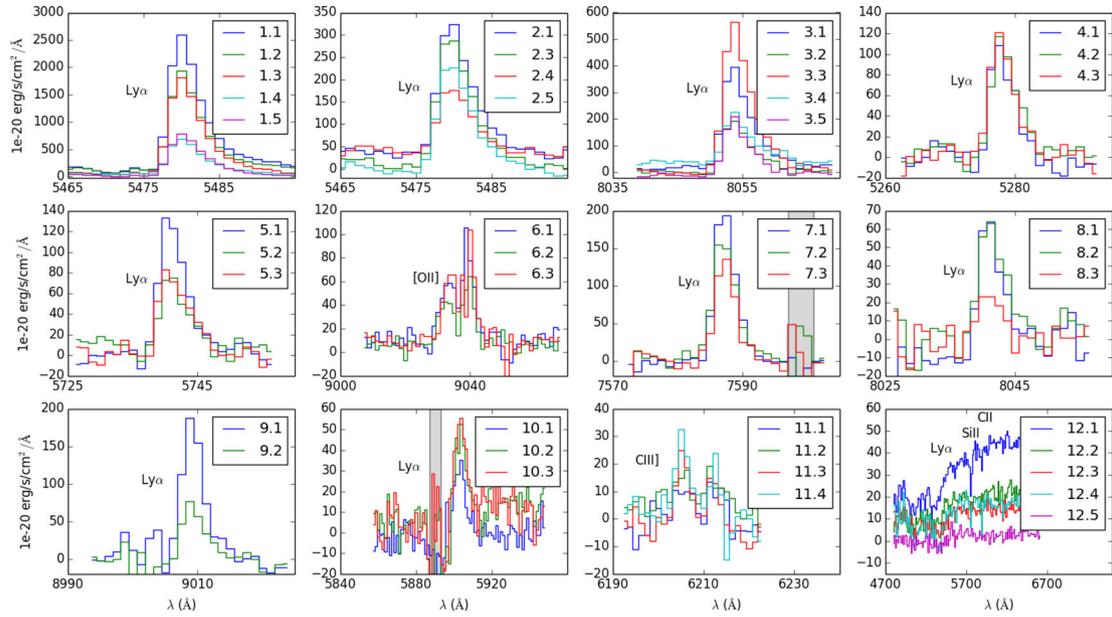


Figure 3. Extracted spectra of the strongest emission line in all identified multiple images, grouped by lensing system (in reading order). One can clearly see the asymmetric profile of all Lyman α emission lines, as well as the doublet for [O II] and C III]. In system 12, the main feature is the Lyman α break as well as rest-frame UV absorption lines (Si II 1304 Å, C II 1334 Å). The grey areas mark the location of strong sky line residuals.

Table 2. Best-fitting model parameters of the cluster-scale dPIE profiles (SE and NW sub-clusters) and the scaling relation of cluster members (shown for an L^* galaxy. From left to right: centre in arcsec from the origin fixed at the location of the brightest cluster galaxy ($\alpha = 20:35:11.835, \delta = -40:27:08.47$), ellipticity and position angle, core and cut radii, central velocity dispersion. Values in brackets are fixed in the modelling.

| Potential | $\Delta\alpha$ (arcsec) | $\Delta\delta$ (arcsec) | e | θ (deg) | r_{core} (kpc) | r_{cut} (kpc) | σ (km s^{-1}) |
|--------------|----------------------------|----------------------------|------------------------|---------------------|----------------------------|---------------------------|------------------------------------|
| SE | $0.5^{+0.2}_{-0.1}$ | $-0.5^{+0.2}_{-0.2}$ | $0.29^{+0.04}_{-0.04}$ | $3.0^{+2.7}_{-3.7}$ | 29^{+2}_{-2} | [1000] | 614^{+24}_{-22} |
| NW | $62.2^{+0.5}_{-0.5}$ | $25.3^{+1.0}_{-0.9}$ | $0.47^{+0.08}_{-0.06}$ | $6.2^{+6.4}_{-1.6}$ | 124^{+15}_{-13} | [1000] | 1062^{+26}_{-54} |
| L^* galaxy | | | | | [0.15] | 32^{+6}_{-5} | 117^{+7}_{-8} |

compared the extracted spectra for all 12 multiple images and found a very good match, as seen in Fig. 3. Together with our improved mass model (see Section 4), this clearly confirms these sources as multiple systems.

4 CLUSTER MASS MODELLING

Following our previous work on cluster mass modelling (Limousin et al. 2007; Jauzac et al. 2014a), we used the locations and redshifts of the 12 multiple systems identified to constrain a parametric mass model of the cluster using the LENSTOOL (Jullo et al. 2007) software.¹ In short, we adopt a dual pseudo-isothermal elliptical mass distribution (dPIE, also known as truncated PIEMD, see Elíasdóttir et al. 2007), which corresponds to an isothermal profile with two characteristic radii: a core radius r_{core} (producing a flattening of the mass distribution at the centre), and a cut radius r_{cut} (producing a drop-off of the mass distribution on large scales). Our preliminary mass model of SMACSJ2031, which we used in Christensen et al. (2012) to derive magnification factors, assumed a single cluster-scale dPIE component centred on the SE cluster as well as individual

galaxy-scale dPIE profiles on each cluster member following a scaling relation with luminosity (see e.g. Richard et al. 2010).

With the addition of new multiple images, we refine this mass model by incorporating a second cluster-scale mass component centred on the NW cluster, located 1.2 arcmin away. This extends the critical line in the NW–SE direction (Fig. 1) and gives a much better match with the new systems 6–10 located in this region. One can clearly see the effect of this extension of the critical line towards the upper-right corner of the MUSE field of view, with an absence of multiple images identified in the lower-left corner. The best-fitting parameters of the new mass model are presented in Table 2.

The two-component mass model now reproduces all 12 multiple systems with an rms of 0.41 arcsec in the image plane. Although the centroid precision of the emission lines is much better than this for the MUSE data (typically 0.1 arcsec) such a scatter is expected because of additional lensing structures along the line of sight (see the discussion in Jullo et al. 2010). An illustration of the ability to reproduce the systems is shown in the critical lines presented in Fig. 1 as we expect a symmetry of multiple images against the corresponding critical line. The projected cluster mass profile (radially integrated from the location of the brightest galaxy in the SE cluster) is presented in Fig. 4, together with the strong-lensing constraints. We can see that the profile is best constrained within

¹ publicly available on the dedicated web page.

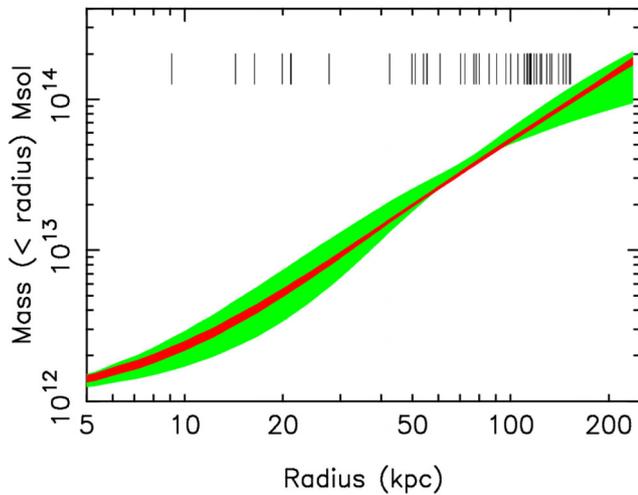


Figure 4. Projected cluster mass profile integrated over the radial distances from the centre of the SE cluster (red curve). The radial distance of all multiple images used as strong-lensing constraints are marked with black ticks. We overplot in green the range of mass profiles allowed by the previous mass model (which only used constraints from system 1), showing the gain in precision obtained with the MUSE data.

10–150 kpc by the large number of multiple images. The precision obtained on the integrated mass in this region is a few per cent, about five times better than the previous model.

We use this mass model to estimate the magnifications for all background sources, and report the values in Table 1. Errors on the magnification factors are estimated for each source by producing 500 mass models sampling the posterior probability distribution of the dPIE parameters, and measuring the distribution of magnifications at this location. Thanks to the high density of constraints in the cluster core, the relative error on magnification factors are typically 5–30 per cent, which is similar to the precision reached in the Hubble Frontier Fields (Jauzac et al. 2014a).

We also check that all of the 14 other background sources identified (s1–s14 in Table 1, ranging from $z = 0.5$ to 4.01) are indeed predicted to be single images by this model, as they are all located in the SE corner of the MUSE field of view. Three counter images identified are not detected in the observations for the following reasons: image 9.3 is predicted to lie outside of the MUSE field of view, and images 2.2 and 11.5 are predicted to be located under the brightest cluster member, thus suffering from strong cluster light contamination.

To summarize, the sensitivity, resolution and wide field of view of MUSE, when coupled with the strong-lensing region of a cluster core, form the perfect combination to detect numerous lensing systems and use them as constraints to measure the cluster mass profile. Further, more detailed analysis could include the resolved constraints from cluster members in the cluster core, for which we can measure the individual velocity dispersions with the MUSE data.

In addition, accounting for the magnification factor, we show here that we can reliably measure the redshifts for Lyman α emitters that are intrinsically as faint as 2×10^{-19} erg s $^{-1}$ cm $^{-2}$ (images 8.1 and 8.2) and up to $z = 6.4$ (system 9). The multiplicity of these sources in the strong-lensing regime helps to confirm these faint lines to be Lyman α . We expect that targeting lensing cluster with MUSE will result in the detection of a large number of such faint emitters at high redshift.

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