CLASH-VLT: A VIMOS Large Programme to Map the Dark Matter Mass Distribution in Galaxy Clusters and Probe Distant Lensed Galaxies

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The CLASH-VLT VIMOS Large Programme builds on the CLASH Hubble Space Telescope multi-cycle treasury programme to carry out a comprehensive spectroscopic campaign on 13 massive galaxy clusters in the southern sky, at a median redshift of 0.4. Observations are 95% complete and provide spectroscopic identification for 500 to 1000 members per cluster, and over 200 background lensed galaxies at $z < 7$. When combined with a homogeneous set of multi-wavelength ancillary observations, this project will allow a determination of cluster mass density profiles with dynamical and lensing methods and a characterisation of the inner structure of cluster dark matter halos with unprecedented accuracy. The final spectroscopic CLASH-VLT dataset will contain ~ 30 000 spectra and redshifts, of which ~ 7000 are cluster members, providing a long-lasting legacy for studies of galaxy evolution in different environments.

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Galaxy clusters have long served as a bridge between astrophysics and cosmology. Their distribution at varying masses, across space and time, is an important tool with which to constrain cosmological models, since their abundance as a function of redshift is very sensitive to both the underlying geometry of the Universe and the growth of structure on large scales. The mass budget of massive clusters consists of 85–90% dark matter and 10–15% baryons, primarily hot X-ray-emitting plasma, and only ~ 1% in stars. Basically the whole baryon budget is observable in galaxy clusters, unlike in the field. Multi-wavelength studies of meaningful samples of clusters thus lead to a better understanding of the physical mechanisms driving galaxy evolution over a range of environmental densities, and how galaxy formation and black-hole accretion processes modulate the cycle of hot and cold baryons.

The first evidence of dark matter (DM) was found in the 1930s by Fritz Zwicky in the Coma cluster, when he noted a large discrepancy between its virial and luminous mass. Remarkably, he also anticipated the effective use of gravitational lensing to measure the total mass of massive clusters and study distant galaxies. In modern cosmology, clusters pinpoint the largest (gravitationally bound) dark matter halos. As a result, the study of their inner mass distribution offers an important method to test the currently favoured Lambda Cold Dark Matter (ΛCDM) structure formation scenario.

Cold dark matter drives the dynamical evolution of structure shown in cosmological simulations and leads to specific predictions for the mass density profiles of DM halos, from galaxy to cluster scale. Significant deviations from these theoretical expectations would imply that the dynamical history of hierarchical formation of clusters does not proceed according to the ΛCDM paradigm: examples are a non-standard contribution to the mass–energy density of the Universe at the epoch of cluster formation, or a different nature for dark matter. The latter could be revealed particularly in the inner, high-density cluster cores, where a non-collisionless behaviour of DM particles might well modify the inner slope of the mass distribution.

These tests however require very accurate determination of the mass density profile of a representative sample of clusters over a wide radial range, from kpc to Mpc scales. This can be achieved only if all methodologies available to measure the mass distribution of clusters are employed, namely gravitational lensing, galaxy dynamics and X-ray hydrostatic equilibrium. (Sunyaev–Zeldovich-based mass profiles are also becoming important in these studies, but will not be dealt with here.) The reason is that each method is most sensitive to a different radial range and is prone to different inherent systematic effects: e.g., structure along the line of sight for lensing, substructure and velocity anisotropy of orbits for dynamical masses, deviations from hydrostatic equilibrium for X-ray masses. Only by combining and cross-checking mass determinations from all these methods can cluster density profiles be recovered with the required accuracy, provided that a high quality and homogeneous dataset is available for a representative sample of clusters, with a known selection function.

Until a few years ago, the observational framework was far from this ideal status. Measured mass profiles with gravitational lensing techniques of a handful of clusters seemed to suggest mass concentrations significantly higher than theoretical expectations; other studies found that the mass distribution in the cores ($R < 100$ kpc) was significantly flatter than in simulated clusters. It was not uncommon to find a lack of consistency in the literature for the measured mass profiles of the same clusters or between different methods (e.g., X-ray *vs*. lensing). Many suspected that poor sample selection, heterogeneous datasets and the presence of several systematics prevented robust analyses and an effective test of ΛCDM models.

Among the mass probes, strong gravitational lensing, which has produced so many spectacular images of cluster cores with the Hubble Space Telescope (HST), has the unique ability to resolve the inner structure of dark matter halos down to galaxy scale, provided that a sufficient number of multiple images with distance information is available. In addition, close to the critical lines, lensing can magnify background galaxies by a factor of ten or more. Massive clusters can thus be used as gravitational telescopes, albeit on small (~ 1 square arcminute) fields, for serendipitous discoveries of very faint distant galaxies, which would otherwise escape detection. The advantage of this technique was already demonstrated more than a decade ago by the detection of a handful of lensed galaxies out to $z \sim 7$ and by high signal-to-noise (S/N) spectra of a few highly-magnified Lyman-break galaxies at $z \sim 2$–3.

The CLASH project

In order to enable landmark progress in the measurement of the mass distribution of massive clusters, and carry out a systematic search for distant magnified galaxies, the Cluster Lensing And Supernova survey with Hubble (CLASH) project was approved in 2011. It is one of the three Multi-Cycle Treasury Programmes with Hubble (Principal Investigator: M. Postman; see Postman et al., 2012). A total of 524 orbits were allocated to obtain panchromatic 16-filter (with the Advanced Camera for Surveys [ACS] and Wide Field Camera 3 [WFC3], from the near-ultraviolet to the near-infrared) imaging for 25 massive clusters. Observations were spread over several epochs to enable the search for Type-Ia supernovae at $z > 1$ to improve constraints on cosmological parameters; in this article we will not cover this aspect of the CLASH programme.

The CLASH[1] sample was carefully chosen to be representative of 20 relaxed clusters, on the basis of their symmetric and smooth X-ray emission, spanning a wide redshift range (0.18–0.90, median = 0.4). The limiting X-ray temperature is 5 keV, approximately corresponding to a mass limit of $M > 5 \times 10^{14}\ M_{\odot}$. Five additional clusters were included as known powerful lenses to maximise the chance of finding magnified galaxies at $z > 7$. Observations were completed in 2013 and their analysis has produced a very rich variety of new results. They range from a definite determination of the degree of concentration of the mass profiles as a function of cluster mass (Merten et al., 2014), to a census of star-forming galaxies at $z \sim 9$–10, some 500 million years after the Big Bang (Coe et al., 2013; Bouwens et al., 2014).

The CLASH-VLT project

Building on the CLASH HST panchromatic imaging project, and a wealth of multi-wavelength data covering a much larger area for each cluster, a VIMOS Large Programme (LP), hereafter CLASH-VLT[2], was approved in Period 86 (P86) to carry out an unprecedented spectroscopic campaign on the 14 CLASH clusters accessible from the Very Large Telescope (VLT). The project was conceived to literally provide the third dimension to the CLASH survey, with the spectroscopic identification of large samples of cluster members and background lensed galaxies, such as giant arcs and multiple images.

Specifically, the CLASH-VLT LP had 225 hours allocated (200 hours of multi-object spectroscopy [MOS] and 25 hours of pre-imaging), initially distributed over P86–P89, with the following objectives:

1) Obtain spectroscopic confirmation of ~ 500 cluster members in each cluster out to at least twice their virial radius. This goal was set, with the aid of kinematic data from cosmological simulations, to recover the dynamical mass profile with the same accuracy as the strong + weak lensing profiles.
2) Measure redshifts for over 200 lensed galaxies in the cluster cores, including several highly magnified galaxies out to $z \approx 7$ (when Ly-α moves out of the VIMOS optical window). This provides confirmation of multiply imaged systems detected in the HST images and the angular diameter distances of lensed sources, which are crucial inputs for accurate strong lensing models. Additional targets include optical counterparts of Chandra X-ray sources in the cluster fields and host galaxies identified in the supernova programme, if they are bright enough.
3) Provide an unprecedented legacy dataset to investigate galaxy populations in a range of environments with the full set of multi-wavelength data.

At the time of writing the data acquisition is nearly complete with only 5% (10 hours) remaining to be executed.

The VIMOS low-resolution LR-blue grism was primarily used. When lensed sources with high photometric redshifts were present, the medium-resolution (MR) grism was selected instead. VIMOS multiplexing capabilities and field of view, covering approximately 10 Mpc at the median redshift (~ 0.4) of the sample, are very well suited for this project. Additional key observations for this programme are archival imaging data obtained with the Subaru Suprime-Cam for most clusters, with ESO Wide Field Imager (WFI) images for the southernmost target RXJ2248. Subaru multi-colour imaging is ideal for weak lensing studies, owing to its image quality, field of view and depth. In fact, this has formed the basis for the CLASH weak lensing mass density profiles (e.g., Umetsu et al., 2012). Subaru data are however also excellent for spectroscopic target selection, providing photometric catalogues for slit-mask design, after their coordinates are registered to the VIMOS pre-imaging astrometric system.

Eight to twelve VIMOS pointings are used for each cluster, spanning an area of 15–20 square arcminutes, while keeping one quadrant locked onto the cluster core to increase the total exposure time on faint lensed sources. Data are reduced with the VIMOS Interactive Pipeline and Graphical Interface (VIPGI) software developed in Milan, with important contributions from Marco Scodeggio and Alexander Fritz. This pipeline is also used for other VIMOS LPs (e.g., COSMOS and VIPERS). Significant time had to be invested to recover the correct sky positions associated with each spectrum in an automated fashion, because the chances of misidentification with the standard VIPGI algorithm are not negligible in crowded cluster fields. To date, 75 % of the data are fully reduced with measured redshifts and positions.

First results

A summary of the success rate in identifying cluster members is shown in Figure 1. This shows that the goal of 500 members was achieved in most cases and often exceeded. For three clusters, the number of confirmed cluster members is around 1000 or more, which is unprecedented at these redshifts. Note that observations for MACSJ2129-0741 were interrupted early on due to significant Galactic cirrus contamination and that MACSJ0429-0253 was dropped from the original sample to compensate for the relatively slow observational progress in the highly oversubscribed 1 to 5 hours right ascension range.

Thousands of these spectroscopic redshifts, mostly confined to the z = 0.1–1.2 range, but also extending to z ~ 5, have been used to calibrate and check the accuracy of the CLASH HST-based photometric redshifts (Jouvel et al., 2014), which are an important first ingredient for strong lensing models. Using the 16-band HST photometry, an accuracy of $\Delta z/(1+z) = 0.03$ can be achieved.

An example of the results from the spectroscopic campaign of MACSJ0416-2403 is shown in Figure 2. The completion of observations of this target, which is also part of the recently launched Frontier Fields campaign with HST, will yield almost a thousand cluster members. Significant large-scale structure along the line of sight is visible in the 3D cone diagram, whose impact on lensing mass reconstruction will have to be carefully evaluated.

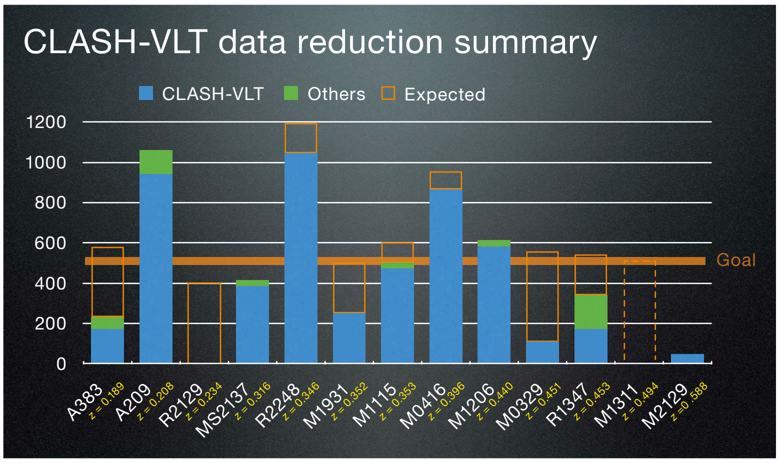

Figure 1. The number of spectroscopically confirmed cluster members for each target of the CLASH-VLT Large Programme is shown. The small fraction of redshifts from the literature is shown in green and the orange histograms indicate the expected number of members from data still under reduction, extrapolating from the measured success rate. Observations for MACSJ1311-0310 are still ongoing. Observations for MACSJ2129-0741 were suspended due to significant Galactic cirrus contamination.

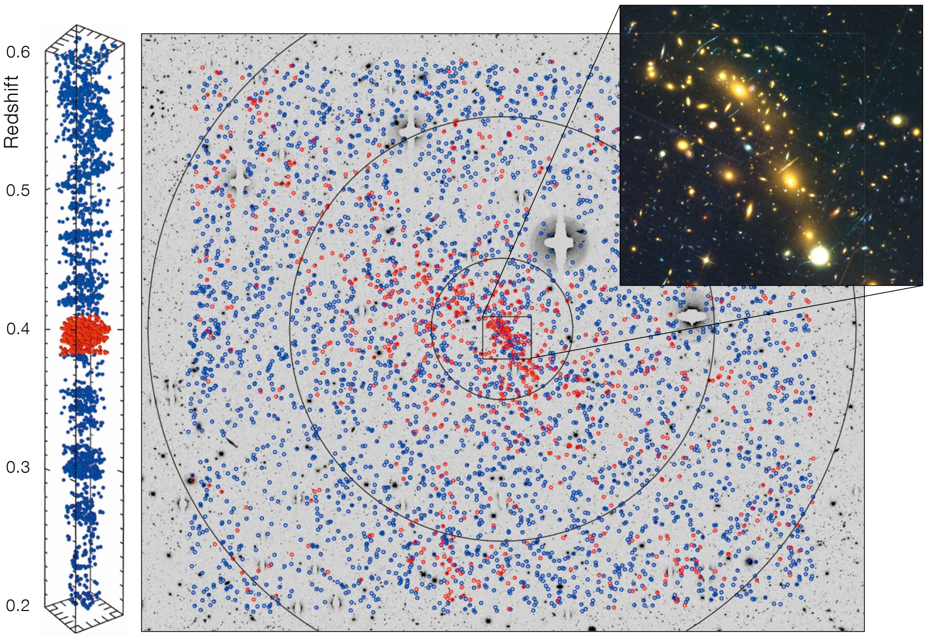

Figure 2. Spatial distribution of galaxies with reliable redshifts on a Subaru/Sup-Cam *R*-band field of MACSJ0416.1-2403 (29 by 25 arcminutes). Red symbols indicate 880 cluster members confirmed to date (galaxies with restframe velocities within ± 3000 km s^{-1} from the median z of 0.396), blue symbols are the other 3307 galaxies over the z range 0.02–4.15. Large circles with 1, 3, 5 Mpc radii centred on the northern brightest cluster galaxy (BCG) are indicated. The HST image (ACS-WFC3 colour composite) is a magnified view of the core (2 by 1.8 arcminutes). To the left, the corresponding 3D distribution in redshift space (only over the redshift range 0.2–0.6) is shown.

Matter distribution

By combining such a large spectroscopic dataset with the HST Treasury data, deep multicolour wide-field imaging and existing Chandra/XMM data, CLASH-VLT was designed to produce a major advance in our ability to measure DM and baryonic mass profiles over the radial range of 10 kpc to ~ 5 Mpc by combining lensing, dynamical and X-ray methods. An example of such an accurate determination of the mass density profiles from different probes is shown in Figure 3 for MACSJ1206.2-0847 (see Biviano et al., 2013 for details). Note the excellent agreement between the dynamical mass

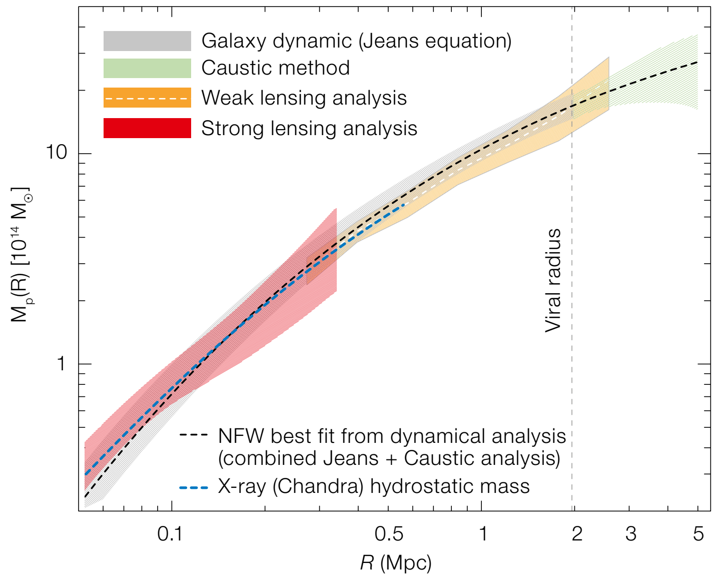

Figure 3. Projected mass density profiles of MACSJ1206.2-0847 at $z = 0.44$ obtained from dynamical analysis from CLASH-VLT data (from Biviano et al., 2013), compared with those from strong lensing (Zitrin et al., 2012), weak lensing (Umetsu et al., 2012) and Chandra X-ray data. The overall agreement is very good despite completely independent data and methodologies. The kinematical analysis allows the mass to be measured out to 5 Mpc (~ 15 arcminutes), corresponding to 2.5 times the virial radius.

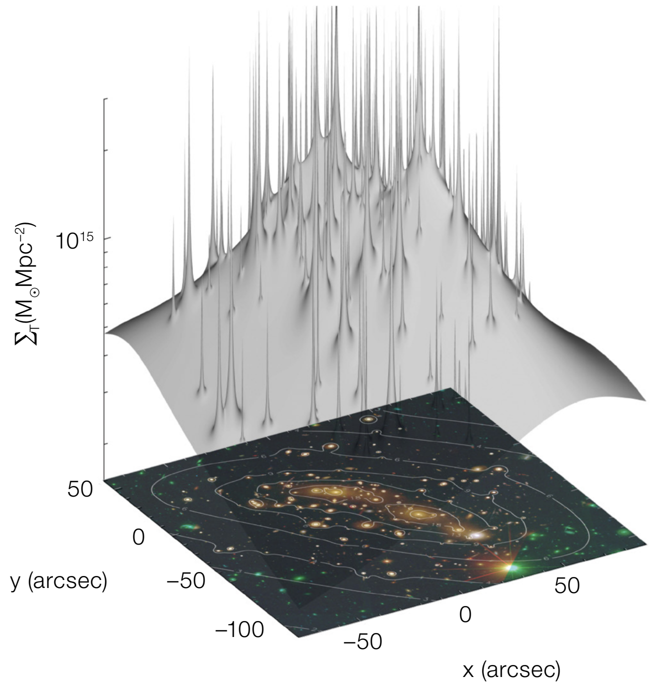

Figure 4. The total surface mass density distribution in the inner regions of MACSJ0416.1-2403 reconstructed from the best-fitting strong lensing model. It is based on spectroscopy of ten multiply imaged systems and over 100 spectroscopic members in the cluster core. The two extended dark matter halos, and many sub-halos corresponding to cluster members, are visible in the overlaid iso-mass contour map (from Grillo et al., 2014).

and other measurements, although completely independent data and methodologies are used. This shows that a number of systematic uncertainties inherent in these methods are well under control in this case.

The overall shape of the mass profile is found to be in very good agreement with cosmological ΛCDM simulations. However, by subtracting the baryonic contributions (stars + gas) and extending the analysis to the inner core (radius < 50 kpc), a DM profile significantly flatter compared to DM-only simulations is found. The reason for this tension with ΛCDM structure formation scenarios is currently not fully understood. It might well be due to dynamical effects of the baryons near the cluster centre of the DM distribution. Alternatively, it might be caused by a non-negligible self-interaction cross-section of DM particles which can make the core "puffier". A careful mass reconstruction of the cores of the entire CLASH sample should shed more light on this important issue. Also note in Figure 3 that by using the caustic method (Diaferio & Geller, 1997), where the escape velocity of galaxies is measured from the distribution of restframe radial velocities at varying radii, the cluster mass estimate can be extended well beyond the virial radius.

In Sartoris et al. (2014), we have shown that this accurate determination of the kinematics and lensing mass profiles can be used to directly confirm the pressureless assumption for the DM equation of state. This test exploits an effect of general relativity for which photons (lensing) and galaxies (kinematics) behave differently as test particles of the gravitational potential, whose shape depends on both density and pressure profiles.

One can anticipate that such accurately determined cluster masses for the full sample of CLASH clusters will be very useful to calibrate scaling relations. These are used to estimate cluster masses from other proxies (e.g., X-ray observables, galaxy velocity dispersions, luminosities) for the upcoming new generation of large cluster surveys for cosmological applications (e.g., Dark Energy Survey [DES], eROSITA and Euclid space missions).

The availability of large redshift catalogues in cluster fields significantly improves lensing-based reconstructions of the cluster mass distribution. For example, to obtain an unbiased estimate of the weak lensing shear map, it is crucial to isolate a pure sample of background galaxies. For this aim, spectroscopic redshifts are needed to calibrate photometric redshifts or colour selection criteria. In addition, strong lensing modelling, and hence an accurate determination of the mass distribution in cluster cores, heavily relies on the redshift measurement for a large number of multiple images and arcs over the widest redshift range. It is also very important to have a large sample of spectroscopic members in order to achieve an unbiased accounting of galaxy-sized halos. This was demonstrated in the detailed modelling of the inner mass distribution of MACSJ0416.1-2403 (see Figure 4 and Grillo et al., 2014). From this high-resolution mass map, we can measure for the first time the subhalo mass function, i.e., characterise the inner structure of large DM halos, and compare it with cosmological simulations.

Lensed and high-*z* galaxies

With exposure times ranging between 2 and 6 hours, we have secured redshifts for the main multiply imaged lensed systems in each cluster, which is a key input for strong lensing models. Models and magnification maps using a subsample of these redshifts have been made publicly available, as part of the CLASH survey ancillary data products. A diagram summarising this effort is shown in Figure 5, which gives the magnitude–redshift distribution of lensed sources with measured redshift to date. Galaxies with Ly-α in emission as faint as 26 AB magnitude have been identified.

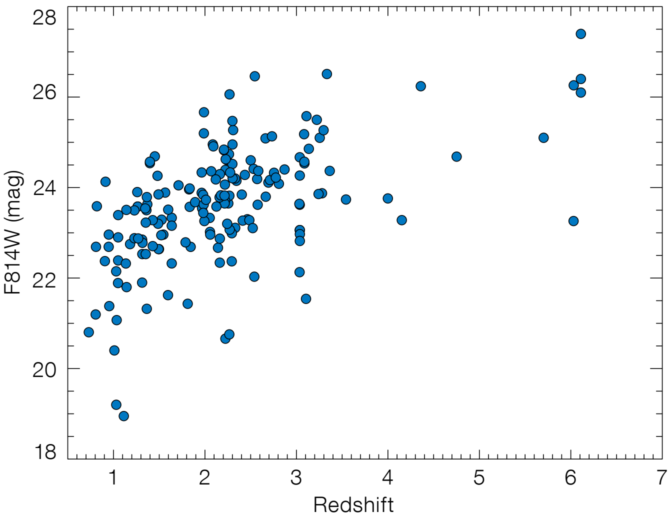

Figure 5. Magnitude–redshift distribution of the spectroscopically confirmed lensed galaxies obtained so far from the CLASH-VLT programme (184 redshifts corresponding to approximately 80% of the final sample).

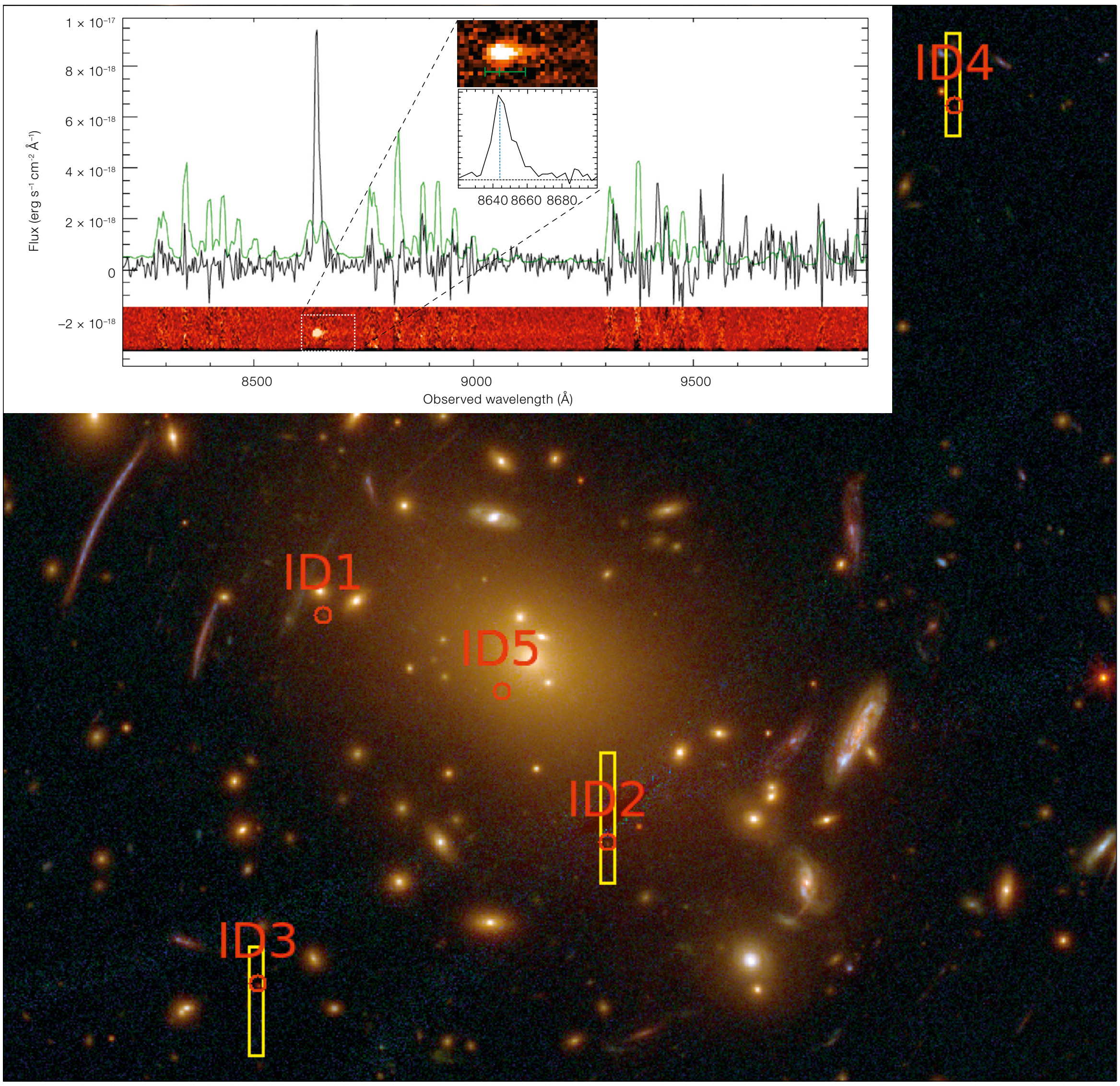

Figure 6. The quintuply lensed galaxy at $z = 6.11$ in the cluster RXC J2248.7-4431 (from Balestra et al., 2013; see also Monna et al., 2014). The image is an HST colour composite and the five locations of the lensed galaxy are shown as ID1–5. The inset shows a spectrum of ID3 (F814 AB mag = 26.1) obtained with VIMOS + MR grism, with 2 hours integration. The Ly-α line has a flux of 1.6×10^{-16} erg cm^{-2} s^{-1}, and a continuum signal is also clearly detected.

The most distant example is part of the quintuply lensed galaxy at $z = 6.11$ in the cluster RXC J2248.7-4431 (Balestra et al., 2013 [see Figure 6]; Monna et al., 2014). After correcting for magnification (μ ~ 6), modelling of the spectrophotometric properties suggests that this is a young (< 300 Myr), compact, sub L^* galaxy with little dust content and a star formation rate of ~ 10 $M_\odot$/yr. Since the magnification typically ranges between 3 and 10 in CLASH clusters, one can probe sub-L^* systems at z ~ 6–9, in a complementary fashion to field studies which are sensitive to $L \gtrsim L^*$ galaxies. This faint galaxy population is thought to play an important role in reionising the Universe, owing to its relatively high space density and possibly high escape fraction of ionising radiation.

Prospects

The final spectroscopic dataset from the CLASH-VLT survey will contain ~ 30 000 spectra and associated redshifts, of which ~ 7000 are cluster members. It is therefore easy to anticipate that the overall CLASH-VLT spectrophotometric database will have a broad legacy value in studies of the evolution and transformation of galaxies in a range of environments. A full characterisation of the underlying stellar populations of cluster galaxies and structural properties can be obtained from our homogeneous imaging data (HST in the core, Subaru on the entire cluster volume) and spectroscopic classification.

As an example, a snapshot of the spectral properties of the galaxy population in the MACSJ1206.2-0847 cluster is given in Figure 7. The stacked galaxy spectra in increasing radial bins show the typical gradient of the underlying stellar populations, from high to low density regions. The baryonic stellar content also includes the contribution from the intracluster light, which is clearly visible in both the Subaru and HST images. The exploitation of the CLASH-VLT dataset in this direction has just started (Presotto et al., 2014; Annunziatella et al., 2014; Kuchner et al., 2014).

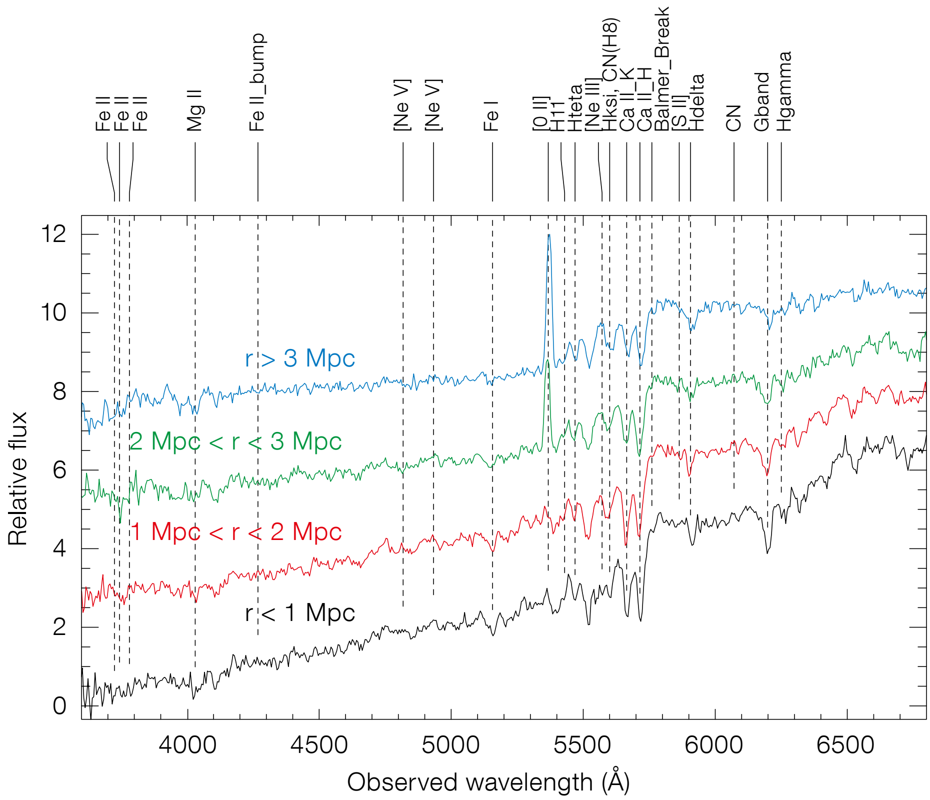

Figure 7. Co-added spectra of cluster galaxies in different radial bins of the cluster MACSJ1206.2-0847 ($z = 0.44$, ~ 70 spectra per bin), showing the typical stellar population gradient in clusters, from high densities in the core to low densities in the outskirts.

Updated information on the CLASH-VLT survey can be found at the public CLASH-VLT page[2], which includes a list of publications and the public release of a number of redshift catalogues including the MACSJ1206.2-0847 and two Frontier Field clusters. Redshift catalogues and spectra will gradually be ingested into the ESO advanced data products archive, similar to some other LPs. This will facilitate the scientific exploitation well beyond the envelope envisaged in the original proposal and consolidate its legacy for the future.

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Links

[1] CLASH page at STScI: http://www.stsci.edu/~postman/CLASH/
[2] Public CLASH-VLT page: https://sites.google.com/site/vltclashpublic/home