The LEGA-C Survey: The Physics of Galaxies 7 Gyr Ago

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The LEGA-C (Large Early Galaxy Census) survey is made possible by the refurbishment of the Very Large Telescope VIsible and Multi Object Spectrograph (VIMOS) instrument and the implementation by ESO of a new generation of large spectroscopic surveys. The goal is to obtain high-quality continuum spectra of thousands of galaxies with redshifts up to z = 1, with which key physical parameters that were previously inaccessible can be measured. These include star formation histories and dynamical masses, which greatly improve our insight into how galaxies form and evolve. This article coincides with the first public data release of fully reduced and calibrated spectra.

Our knowledge of stellar populations tells us about the formation and evolution of galaxies. High-quality (continuum) spectroscopy of galaxies reveals the stellar absorption features that trace star formation histories and chemical content. Such data have been available for galaxies in the present-day Universe for some decades and have brought into clear focus the multi-variate correlations between stellar population properties and mass, structure, size, stellar velocity dispersion, nuclear activity and environment. This information has greatly illuminated the processes that drive star formation and the ongoing assembly of present-day galaxies.

The main limitation when examining present-day galaxies for the purpose of reconstructing their formation history is, however, that most of the star formation occurred in the distant past: the mean stellar ages of typical galaxies are typically well over 5 Gyr (Gallazi et al., 2005) and it is difficult to resolve star formation histories from spectra: it is nearly impossible to distinguish stellar populations with ages of, for example, 5, 7 and 9 Gyr from integrated spectra. For this reason the community has put much effort into lookback studies, aimed at directly observing galaxies at earlier cosmic times.

On the one hand, redshift surveys, such as the VIMOS Very Deep Survey (VVDS; Le Fèvre et al., 2005) and the COSMOS spectroscopic survey (zCOSMOS; Lilly et al., 2008) have created large samples of galaxies with spectroscopic redshifts, tracing the evolution of the number density and the luminosity function of galaxies. On the other hand, photometric surveys (for example, UltraVISTA; McCracken et al., 2013) have collected multi-wavelength datasets used to derive photometric redshifts, which have gradually improved to the point that spectroscopic redshift surveys are no longer needed for the purpose of quantifying galaxy evolution (with the exception of the effect of environment). In addition, the photometric surveys provide estimates of integrated galaxy properties such as stellar mass, star formation rate and restframe colours. Adding Hubble Space Telescope (HST) imaging to the mix enables us to reveal the internal structure of distant galaxies (for example, van der Wel et al., 2014a).

The results of these very significant efforts is that we now understand that the galaxy population at large lookback times is in many ways similar to the present-day galaxy population: mass, structure and star formation activity are correlated in the same manner (for example, Franx et al., 2008). At the same time, there are many differences: at higher redshift, star formation rates were much higher (Madau et al., 1996), morphologies less regular (for example, Conselice et al., 2008), and galaxies of the same stellar mass are smaller in size (for example, van der Wel et al., 2014b).

The main limitation of the lookback studies is the challenge of connecting progenitors and descendants: despite our exquisite knowledge of the evolution of the population of galaxies as an ensemble, the evolutionary history of individual galaxies has remained hidden from view. In our Universe, with hierarchical structure growth that is largely stochastic in nature, we should expect that galaxies that are similar today were probably very different in the past, and, analogously, galaxies that were similar in the past will be very different today.

To summarise, our current insight into galaxy evolution is limited by two factors: 1) the archaeological approach of obtaining spectroscopy of present-day galaxies lacks the power to reveal the bulk of star formation history, because galaxies are too old; 2) the lookback approach only reveals the evolution of the population, not of individual galaxies. The solution is both obvious and very challenging: to obtain high-quality spectroscopy of galaxies at

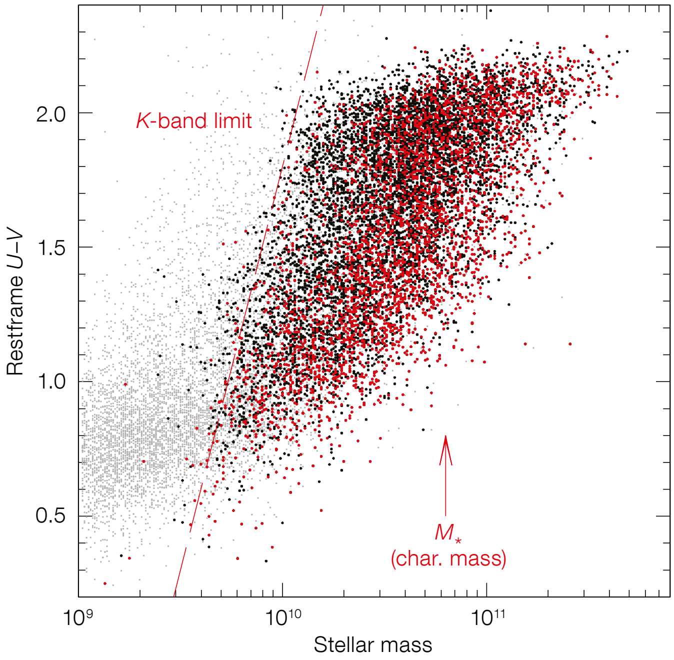

Figure 1. Rest-frame UV colour *vs.* stellar mass of the *K*-band selected primary galaxy sample of the LEGA-C survey at redshift $0.6 < z < 1.0$. Light grey points refer to the full UltraVISTA sample; black points: primary galaxy candidates; and red points: primary galaxies included in the LEGA-C survey.

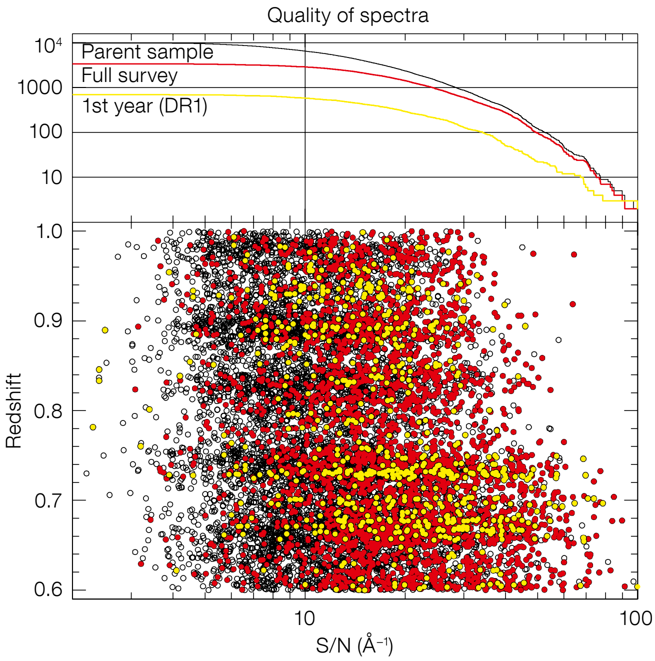

Figure 2. Redshift and signal-to-noise (S/N) distribution of the LEGA-C primary sample. The parent sample from which targets are selected is shown in black; the survey design includes objects shown in red; while the observed sample is shown in yellow/black.

large lookback times. This is the aim of the LEGA-C survey (van der Wel et al., 2016).

The LEGA-C survey

The challenge lies in obtaining continuum spectra of sufficient resolution and depth for faint targets. The design of the LEGA-C survey is constrained by several practical factors:

1) the resolution should be at least $R \sim 2000$ to distinguish individual features and constrain the kinematic properties of the targets;
2) the signal-to-noise ratio (S/N) should be at least 10 per resolution element, and preferably ~ 20;
3) the maximum redshift is $z \sim 1$, otherwise targets become too faint and the diagnostic features shift into the near-infrared, where ground-based near-infrared spectrographs are still a factor ~ 100 slower in survey speed for the purpose of continuum spectroscopy;
4) the sample size should be in the 1000s, otherwise the population is either undersampled or biased toward particular types of galaxies, either of which would preclude the general goals of constraining the evolutionary history of galaxies in general.

Given these constraints, we started the LEGA-C survey in December 2014 with VIMOS in multi-object (MOS) mode. The survey is led and coordinated from the Max Planck Institute for Astronomy in Heidelberg, Germany, and has co-investigators across Europe and indeed the globe.

Upon completion, likely in 2018, we will have collected more than 3000 spectra of galaxies in the redshift range $0.6 < z < 1.0$ in the COSMOS field, at Right Ascension 10 hr and Declination +2°. The sample is selected based on *K*-band magnitude — in order to approximate a selection by stellar mass and avoid biases due to extinction — from the publicly available UltraVISTA catalogue by Muzzin et al. (2013). The selection is independent of any other parameter and the sample, shown in Figure 1, therefore spans the full range of galaxy properties in terms of morphology, star formation activity and dust attenuation across the galaxy population with stellar mass in excess of about 10^{10} $M_\odot$. This primary sample is complemented by ~ 900 fillers — lower-mass galaxies and higher-redshift galaxies. With the high-resolution red grating (HR_red) and integration times of 20 hours per target, the required resolution and S/N can be achieved. The typical wavelength range of 6300–8800 Å samples essential features such as the Balmer/4000 Å break, all Balmer lines except Hα, the *G*-band, and multiple Fe, Ca and Mg features.

VIMOS slits are assigned to the primary targets first, prioritised by apparent *K*-band magnitude as far as slit collisions permit. Then one or more blue stars for telluric absorption correction and several alignment stars are included in the slit mask design. The remaining slit real estate is used for fillers: higher-redshift objects with bright *K*-band magnitudes, fainter targets in the $0.6 < z < 1.0$ redshift range, and other fainter sources, respectively. With slit lengths of ~ 10 arcseconds, VIMOS can simultaneously observe ~ 130 objects, bringing the on-sky survey execution time to 640 hours. In Visitor Mode 128 nights were allocated to achieve this goal, spread out over 200 actual nights (due to fractional-night scheduling). This allocation makes LEGA-C the

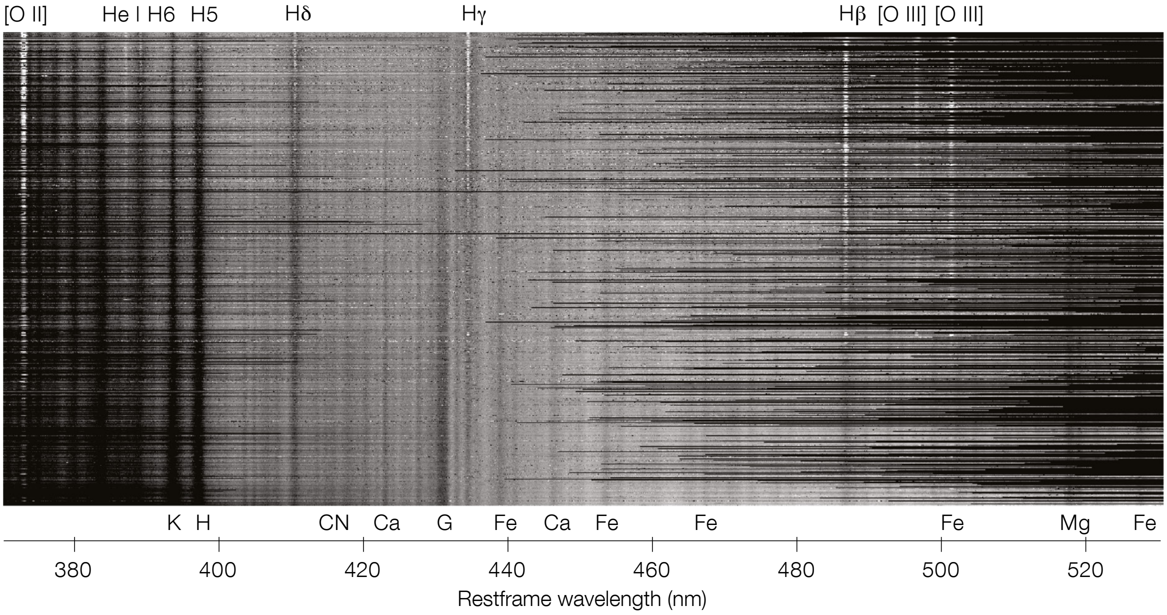

Figure 3. 1D extracted restframe spectra of 654 primary-sample galaxies observed in the first year of LEGA-C. Each row shows one spectrum, where the galaxies are sorted from high star formation activity (at the top) to low star formation activity (at the bottom).

most expensive extragalactic spectroscopic survey to date on an 8-metre-class telescope. The redshift and expected S/N distribution of the resulting primary galaxy sample is illustrated in Figure 2.

The spectra

The data are reduced using a combination of the ESO pipeline and our own pipeline based on customised algorithms for sky subtraction, object extraction and co-addition. In Figure 3 we show extracted 1D spectra of 654 primary targets observed in the first year of observations. The galaxies are sorted by their specific star formation rate (star formation rate per unit stellar mass), with the most actively star-forming galaxies at the top. The high star formation rate galaxies show nebular emission lines, Balmer lines in absorption and emission, but also metal lines. The more passive systems show stronger metal features and across this sample up to 50 unique absorption features are readily visible, illustrating the superb depth of the spectra. Kinematic information is revealed thanks to the high spectral resolution: Ca and Fe features appear more Doppler broadened for the spectra near the bottom, as those galaxies are more massive.

Figures 4 and 5 show typical examples of 1D spectra in more detail. In Figure 4 we show ten galaxies ordered by their basic morphology as traced by the Sérsic index: galaxies with high Sérsic indices, that is, more concentrated light profiles usually associated with early-type morphologies, are at the top; galaxies with low Sérsic indices, that is, disc-like morphologies, are at the bottom. The correspondence with morphology is clearly seen in the HST image cut-outs from the COSMOS survey (Scoville et al., 2007). LEGA-C reveals that for the first time, beyond the present-day Universe, a clear correlation exists between morphology and spectral properties: early-type galaxy spectra are characterised by strong metal absorption line features and a lack of strong Balmer absorption and nebular emission lines; while for late-type galaxies this is reversed.

In Figure 5 we show five late-type galaxies ordered by inclination. Absorption lines are detected regardless of viewing angle. The example spectra illustrate a unique aspect of the LEGA-C survey: even the dustiest and the bluest galaxies show absorption line features with high fidelity, despite the challenges presented by the low surface brightness and bright, blue stellar populations with strong continuum features.

Towards understanding the physics of galaxy formation

The high-quality spectra shown in Figures 3–5 allow us to measure with good accuracy and precision a large range of physical parameters that were previously inaccessible for galaxies at large lookback times. These parameters fall into two broad categories: stellar populations and kinematics. The basic stellar population measurements are mean stellar age and metallicity, and eventually a more general description of the star formation history. Now that LEGA-C has overcome the challenge of creating spectra of galaxies at significant lookback times, we actually have a clear advantage over present-day galaxy studies when it comes to reconstructing the full star formation history. At the redshifts studied, stars will typically be younger than 3 Gyr in essentially all LEGA-C galaxies, which is an age range over which different generations of stars can be resolved in age. This will inform us directly what the stellar masses of progenitors at $z > 1$ must be. Our knowledge of those potential progenitors is very substantial indeed, such that we can, for the first time, follow the evolution of individual galaxies across a significant part of cosmic time, right into the epoch when star formation activity was highest in a cosmically average sense.

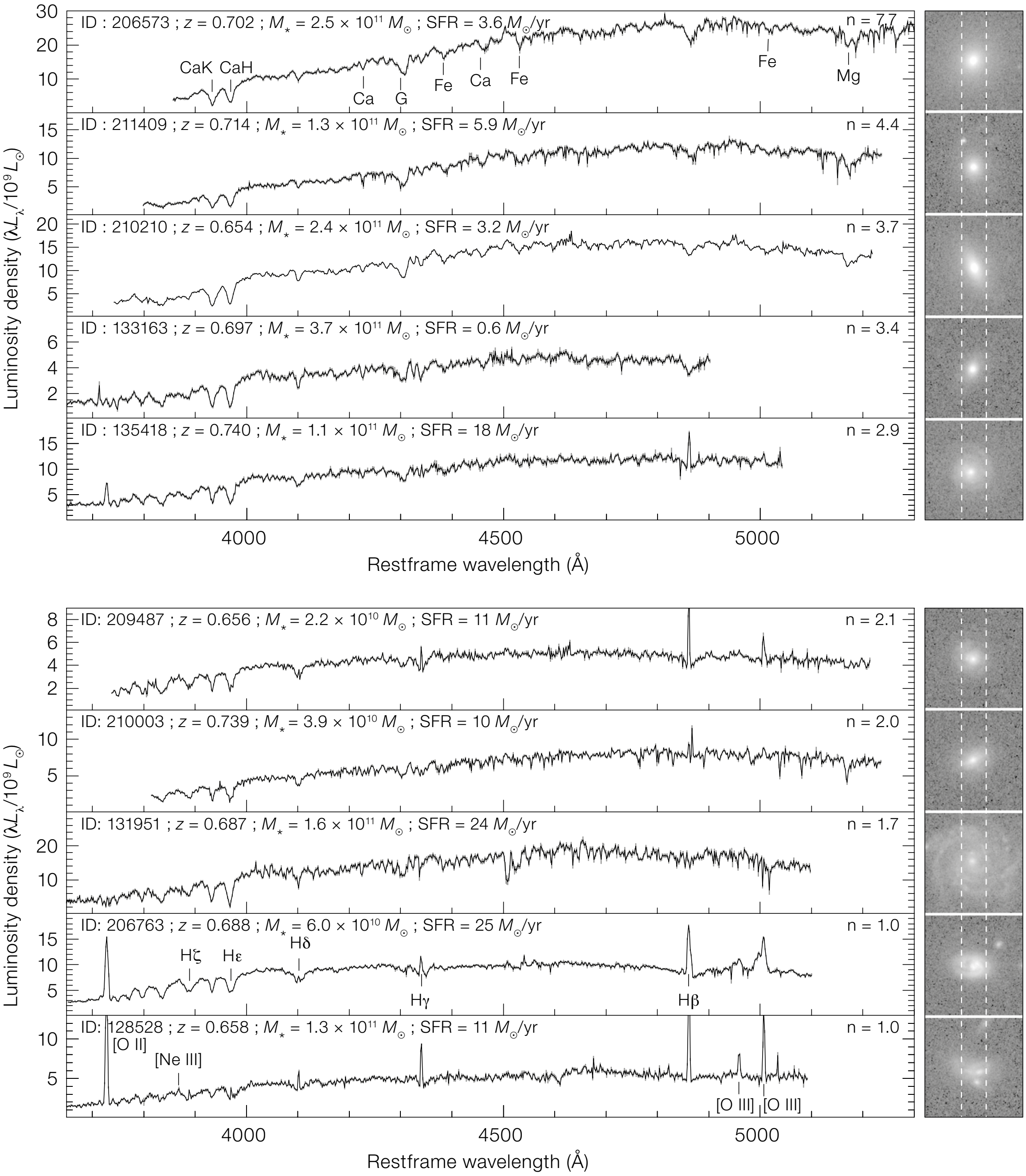

Figure 4. Spectra of ten typical LEGA-C targets ordered by morphology (using the Sérsic index). Flux density uncertainties are indicated in grey. HST image cut-outs are shown on the right. Labels (left) record object ID, redshift, stellar mass and star formation rate; with Sérsic index at right.

The primary kinematic measurement is the stellar velocity dispersion. Collisionless star particles are excellent tracers of the gravitational potential and thus the total mass, which opens new avenues of exploration. A practical application is to test whether the much-maligned stellar mass estimates are robust at large lookback times for all galaxy types. At these times velocity dispersions and central mass density are thought to be key factors in determining the star formation activity of a galaxy. Now that we have direct measurements for distant galaxies that support this notion (see Figure 6) we can ask the question of how some galaxies cease to form stars and evolve sedately afterward. Furthermore, the evolution of velocity dispersions in combination with other properties (for example, size) informs us about the rate of growth of passive galaxies through merging. A secondary kinematic measurement is the gas velocity dispersion. Gas motions are affected by numerous other forces besides gravity and, while gas kinematics is widely used as a tracer of mass, it remains to be tested how large are the uncertainties. A comparison between gas and stellar velocity dispersion now allows us to make this test.

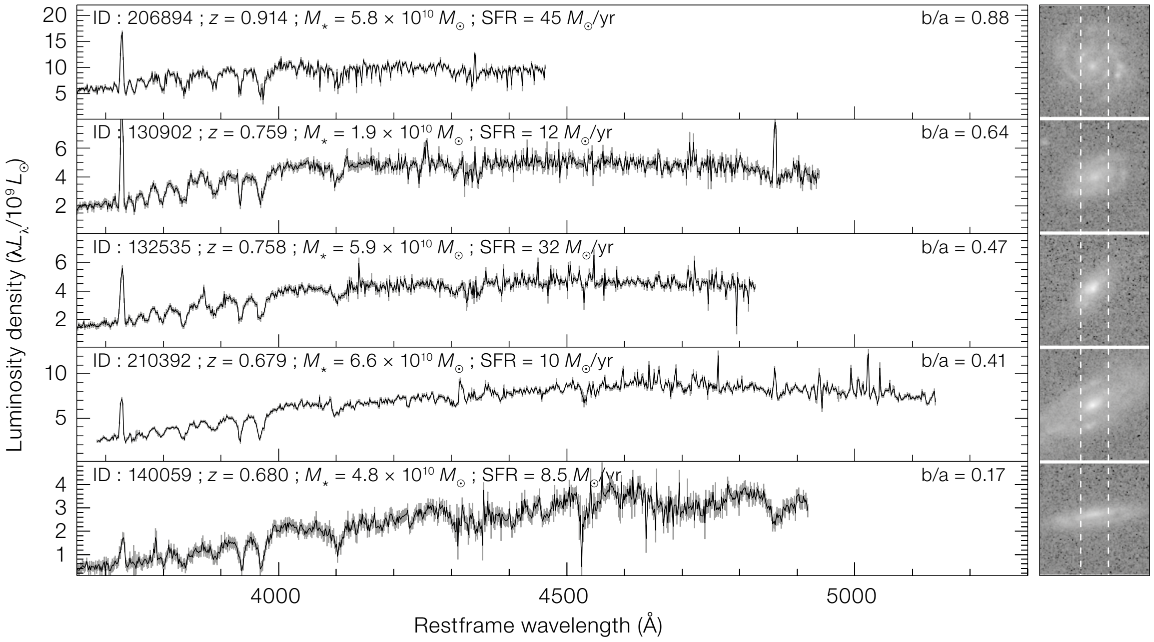

Figure 5. Spectra of five LEGA-C disc galaxies ordered by inclination (axis ratio *b/a*). Details as Figure 4.

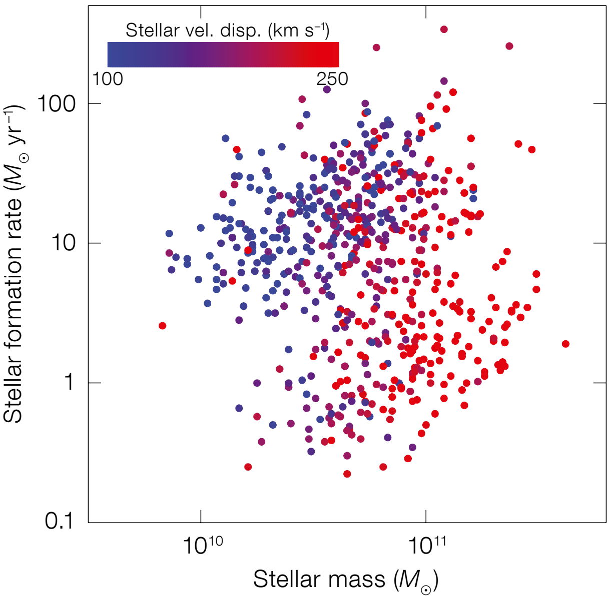

Figure 6. Star formation rate *vs.* stellar mass for the primary LEGA-C sample observed in the first year. The colour coding represents the stellar velocity dispersion.

Finally, despite the fact that the LEGA-C spectra are seeing limited, we have spatial information on both the stellar population characteristics and the kinematics. While the primary goal of the LEGA-C survey is to obtain integrated spectral properties, exploring this aspect will undoubtedly prove to be highly interesting. Stellar rotation curves and age gradients provide strong constraints on the physics of galaxy formation and the connection to the dark matter halo hosts.

Timeline

At this point we have collected approximately 45 % of the dataset based on the first two years of observation. This article coincides with the first data release[1] that includes fully calibrated 1D and 2D spectra of the data taken in the first year: 925 galaxies (22 % of the full survey). Figure 2 shows the redshift and S/N distribution of the data obtained in the first year: as can be seen, LEGA-C is on schedule to be completed by 2018 and, excitingly, the data quality is precisely as good as anticipated, confirming the competitiveness of VIMOS.

A second data release will follow by the end of 2016. This will double the sample and expand to higher-level data products in the form of derived physical parameters, such as velocity dispersions and line indices. There will be updated data releases in subsequent years. For more technical information on the sample selection, observations, data reduction and modelling techniques, please refer to the LEGA-C survey paper (van der Wel et al., 2016).

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Links

[1] Access to Phase 3 LEGA-C data: http://archive.eso.org/wdb/wdb/adp/phase3_spectral/form