DOI: 10.18727/0722-6691/5246

The LEGA-C Survey Completed: Stellar Populations and Stellar Kinematics of Galaxies 7 Gyr Ago

Arjen van der Wel[1]
Rachel Bezanson[2]
Francesco D'Eugenio[1]
Caroline Straatman[1]
Marijn Franx[3]
Josha van Houdt[4]
Michael V. Maseda[3]
Anna Gallazzi[5]
Po-Feng Wu[6]
Camilla Pacifici[7]
Ivana Barisic[4]
Gabriel B. Brammer[8]
Juan Carlos Munoz-Mateos[9]
Sarah Vervalcke[1]
Stefano Zibetti[5]
David Sobral[10]
Anna de Graaff[3]
Joao Calhau[11, 12]
Yasha Kaushal[2]
Adam Muzzin[13]
Eric F. Bell[14]
Pieter G. van Dokkum[15]

[1] Astronomical Observatory, University of Ghent, Belgium
[2] Department of Physics and Astronomy, University of Pittsburgh, USA
[3] Leiden Observatory, Leiden University, the Netherlands
[4] Max Planck Institute for Astronomy, Heidelberg, Germany
[5] INAF – Astronomical Observatory of Arcetri, Florence, Italy
[6] National Astronomical Observatory of Japan, Tokyo, Japan
[7] Space Telescope Science Institute, Baltimore, Maryland, USA
[8] Cosmic Dawn Center (DAWN) Niels Bohr Institute, University of Copenhagen, Denmark
[9] ESO
[10] Department of Physics, Lancaster University, UK
[11] Astrophysics Institute of the Canaries, La Laguna, Tenerife, Spain
[12] Department of Astrophysics, University of La Laguna, Spain
[13] Department of Physics and Astronomy, York University, Toronto, Canada
[14] Department of Astronomy, University of Michigan, USA
[15] Astronomy Department, Yale University, New Haven, USA

The Large Early Galaxy Astrophysics Census (LEGA-C) survey is the final Public Spectroscopic Survey to be completed with the now-retired VIsible Multi-Object Spectrograph (VIMOS) instrument at ESO's Very Large Telescope (VLT). Its aim is to characterise with high precision and for a very large sample the stellar population and kinematic properties of galaxies at redshifts 0.6 < z < 1, providing a first assessment of the star formation histories, the absolute mass scale, and the stellar kinematic structure of galaxies at large lookback times (7 gigayears ago). This article coincides with the third and final data release but mostly focuses on the large variety of scientific results achieved so far.

LEGA-C

Before LEGA-C, most of our understanding of the stellar bodies of galaxies at large lookback times derived from photometric measurements. Tremendous progress had been achieved in that way, by quantifying the evolution of the number of stars as a function of cosmic time, their distribution over galaxies with different masses, their structural properties and their crude spectral properties in terms of colours. But these measurements are merely indirect proxies for the quantities that are the most relevant for constraining galaxy formation models: galaxy mass, angular momentum and star formation/assembly history. Moreover, sample sizes are now very large, so we have run up against the limit of systematic uncertainties instead of sample variance. Spectroscopic observations of the stellar continuum provide a more direct way of estimating those quantities with less bias, but it took more than 1000 hours of VLT observing time to collect such expensive data for galaxies at large lookback times.

This article briefly summarises the properties and quality of the data that have now been published in full, along with value-added catalogues, and the broad range of scientific results published so far. In a narrow sense, the LEGA-C survey has now been completed: the data have been collected, processed and published. But in a broad sense, the final data release[1] marks only the beginning. Our hope is that, for many years to come, researchers will use these data for a wide variety of purposes: to find detailed properties of specific galaxies, to utilise the full dataset to shed new light on old problems, to support follow-up surveys at different wavelengths, and to test galaxy formation models.

The data

For full technical details we refer to the recently published Data Release 3 paper (van der Wel et al., 2021). Very briefly, LEGA-C consists of several thousand galaxies at redshifts 0.6 < z < 1 selected only by their *Ks*-band magnitude (van der Wel et al., 2016), a proxy for stellar mass. As a result, the survey contains galaxies of all types and colours above an approximate stellar mass limit of $3 \times 10^{10}\ M_{\odot}$. Of course, the majority of galaxies in the Universe have lower masses than this, but this mass limit does account for most of the mass (and star formation) budget and therefore can be considered as representative. The simplicity of the survey design allows for a precise determination of sample selection effects and completeness, enabling accurate measurements of ensemble properties.

The observations were carried out from December 2014 to March 2018, with ~ 20-hour integrations for each of the 32 slit masks. At a spectral resolution of R ~ 3500 the typical spectrum has a signal-to-noise ratio of ~ 15–20 per Ångstrom. The data processing is described in detail by Straatman et al. (2018) and van der Wel et al. (2021), and the collated spectra are shown in Figure 1. Broadly speaking these spectra serve two purposes: measuring stellar kinematic signatures (Bezanson et al., 2018b) and stellar population characteristics (for example, Chauke et al., 2018; Wu et al., 2018a). The detailed characteristics of the spectrum and the basic modelling approach are illustrated for just one example in Figure 2. The LEGA-C survey represents a 30-fold increase in sample size of galaxies with measured stellar kinematics and stellar population properties compared to all previous work combined and, equally importantly, samples the full galaxy population rather than a specifically selected sub-sample of very massive galaxies with mostly early-type morphologies.

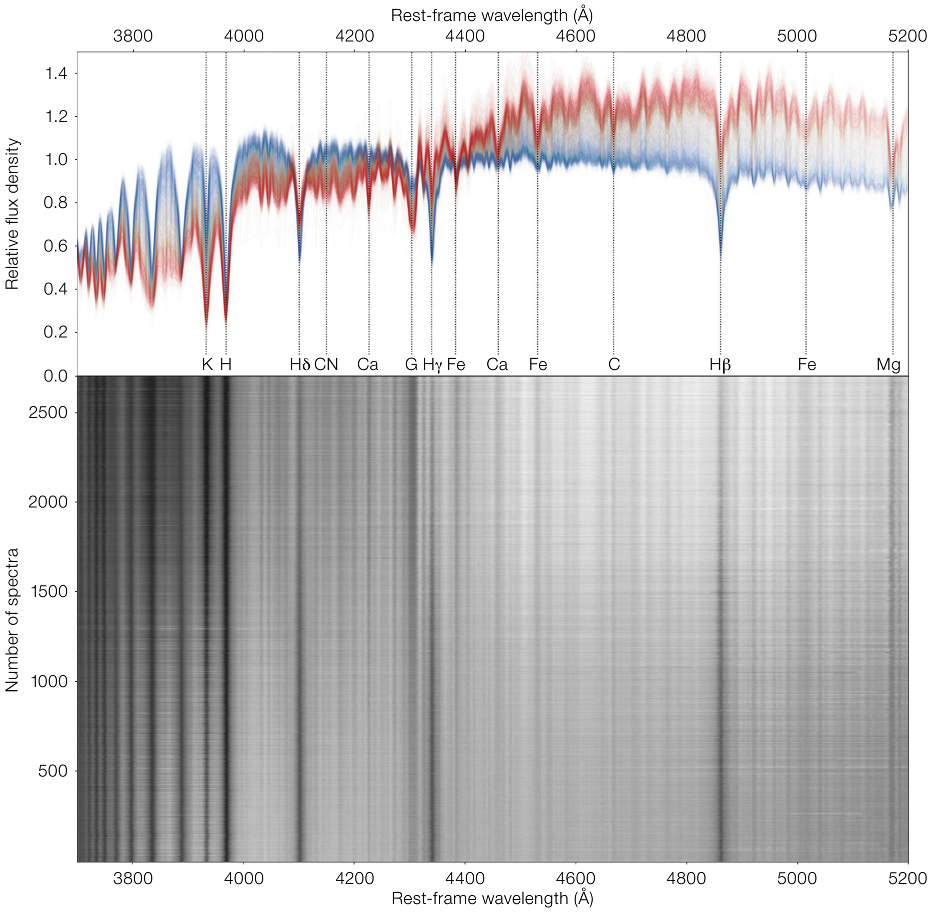
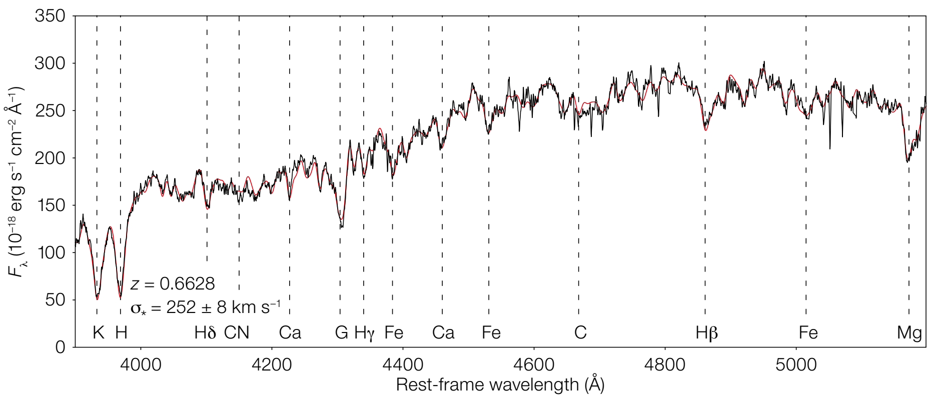


Figure 1. Compilation of 2707 normalised spectra with measured stellar velocity dispersions and Hγ indices. Top: The colour coding is based on the order of Hγ absorption (strongest/youngest: blue; weakest/oldest: red). Bottom: Horizontally aligned, vertically sorted by Hγ absorption. Emission lines are removed, and the rich structure in the spectra reflects the stellar population information content. The figure is adapted from van der Wel et al. (2021).

Figure 2. (Below) Example spectrum of a massive elliptical galaxy at redshift $z = 0.66$, illustrating the rich information content of each spectrum. In black we show the data, in red the model used to infer velocity dispersion and stellar population information. The figure is adapted from van der Wel et al. (2021).



Stellar populations

Galaxy age, as a concept, is somewhat ill-defined. Stars typically form over periods of many gigayears and the time since the formation of the first few stars is not the most relevant age parameter when it comes to characterising a galaxy's formation history (besides, it is impossible to measure from integrated spectra). A median or mass-weighted age is arguably the most informative single number, but this too is difficult to measure and highly sensitive to modelling assumptions. Light-weighted ages are close to the data, and are therefore easier to measure, but they are also less informative as they mostly tell us when the most recent period of high star formation activity occurred.

We start our exploration of the star formation history of galaxies in the most empirical manner possible. The Hδ absorption line strength is highly age-sensitive and its bimodal distribution (Wu et al., 2018a) reflects and confirms what we already know about the bimodality of the galaxy population in terms of colour and star formation activity. The right-hand panel of Figure 3 shows the size–stellar mass distribution of galaxies, where more massive galaxies are generally older than less massive galaxies, and old galaxies are more compact than similarly massive young galaxies. These trends are even seen for galaxies that, *a priori*, are selected as non-star-forming (Barone et al., 2021). This confirms that, even at early cosmic times, the separation of actively star-forming and quiescent galaxies must be relatively long lived: fast or frequent transitions from a highly star-forming state to a quiescent state would produce a blurred, unimodal distribution of an age indicator such as Hδ absorption (but see Chauke et al. [2019] for evidence of rejuvenation events that move galaxies from a quiescent state back to an actively star-forming state for a brief period of time). We recently showed that galaxies from the state-of-the-art TNG cosmological simulation have similar ages — as judged by mock spectroscopic data — but with a less well defined bimodality (Wu et al., 2021); despite impressive progress in the ability of modern simulations to produce realistic galaxy populations, the processes that regulate the shutdown of star formation are not yet fully understood.

Individual spectral features such as Hδ absorption provide a qualitative sense of galaxy age, but to gain a quantitative understanding of age and, more generally, star formation history we need more. By modelling the full spectrum with modern stellar population synthesis models one can hope to retrieve dust attenuation properties (Barisic et al., 2020), as well as the full star formation and metal enrichment history of a galaxy. Whether this can in fact be achieved is very much an open question but with a number of simplifying assumptions we have already learned several important lessons. The main simplifying assumption we have made so far (Chauke et al., 2018) is that all stars have solar metallicity and solar abundance ratios, which is a useful starting point given the relatively high stellar masses of the galaxies in the sample: true metallicities are unlikely to differ by more than a factor of two. We find that the most massive galaxies have the oldest ages, typically 4 or 5 gigayears, putting their peak star formation redshift at $z = 3$–5. Interestingly, Milky Way-mass disc galaxies at $z \sim 0.8$ are often still in the middle of their main formation phase, while at the present day, for the Milky Way itself and its siblings, star formation activity has been on the decline for many gigayears. This highlights the importance and power of applying the archaeological approach at large lookback times: we now witness the dynamical state and stellar population characteristics right in the middle of their main formation period, whereas for present-day galaxies this information remains mostly hidden in even the highest-quality datasets.

The next step is removing the assumption of constant, solar metallicity, starting with passive galaxies which have stronger absorption features, making them easier to model. Barone et al. (2021) show that the qualitative trends seen in Figure 3 hold: more compact galaxies are older than less compact galaxies. Meanwhile, dropping the assumption of solar abundance ratios, Beverage et al. (2021) find that the oldest galaxies have lower metallicities than younger passive galaxies. In the long term, extending these results to the general galaxy population will be one of the main outcomes of LEGA-C.

Stellar kinematics

The initial goal of LEGA-C as regards stellar kinematics was simply to measure the spatially integrated stellar velocity dispersion σ, allowing us to establish scaling relations and estimate dynamical masses. The final sample includes more than 3500 galaxies with measured σ, presenting an unprecedented view of the Faber-Jackson relation (Bezanson et al., 2018b) and the Fundamental Plane (de Graaff et al., 2021; and see the left-hand panel of Figure 3). Despite important changes in the galaxy population since $z \sim 1$ — the number of stars roughly doubles, and the morphological mix of early- and late-type galaxies evolves significantly — these scaling relations are essentially unchanged, *modulo* the luminosity evolution expected from the ageing of stellar populations (de Graaff et al., 2020). As shown by de Graaff et al. (2021) it is of specific interest that old and young galaxies lie on the same Fundamental Plane, even though they occupy different regions in it, and with larger scatter for young galaxies. Despite vastly different evolutionary histories and different internal structures, all galaxies follow certain "rules" that force them to occupy a narrow region in the 3D parameter space of dynamical mass, stellar mass and size. Having determined this plane across half of cosmic time arguably puts the strongest constraints on galaxy formation models.

Stellar kinematic structure complements stellar population characteristics as a probe of assembly history: long-term, sustained star formation is usually associated with a disc-like structure, whereas an active merger history, especially during or after the main star formation epoch, leads to scrambled stellar orbits and a dynamically "hotter", more spheroi-

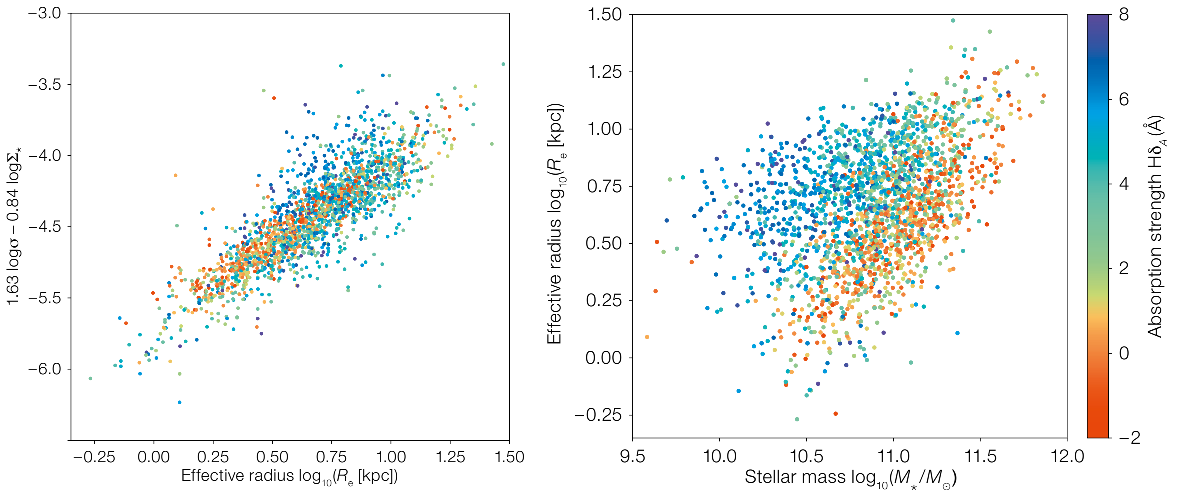


Figure 3. Left: Edge-on projection of the Fundamental Plane, with the effective radius on the x-axis, and a combination of the stellar velocity dispersion σ and the stellar surface mass density Σ on the y-axis. Right: Effective radius versus stellar mass. The colour coding denotes the Hδ absorption strength, which is a proxy for light-weighted stellar age.

dal system. But the integrated velocity dispersion does not tell us about the dynamical structure of a galaxy: a high σ may reflect a thin, fast-rotating disc or a rounder system with a high degree of quasi-random motion. One of the pleasant surprises of the LEGA-C data is that for nearly 800 galaxies we can measure stellar rotation curves along the slit (Bezanson, 2018a; van Houdt et al., 2021; see Figure 4), despite their large distances and the ground-based seeing (which is similar in angular extent to the galaxies themselves). As a first result, we showed that $z \sim 0.8$ quiescent galaxies are more rotationally supported ("discy") than their present-day counterparts (Bezanson et al., 2018a); such galaxies must gradually lose net angular momentum over time, presumably through merging.

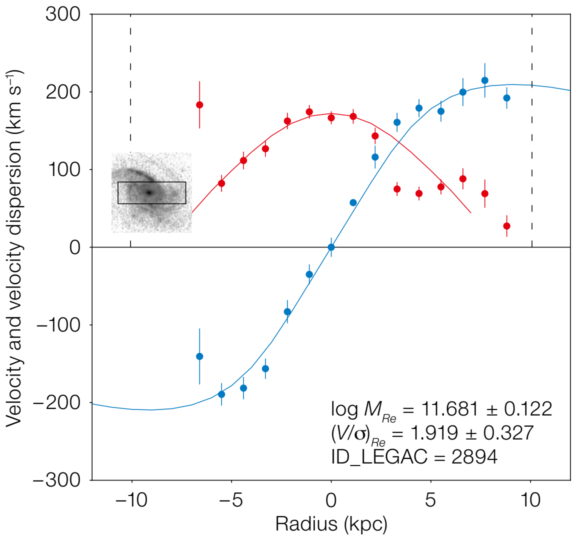


Figure 4. Spatially resolved stellar kinematic measurements with an axisymmetric model. The radial velocity is shown in blue and the velocity dispersion in red. These data constrain the dynamical mass (M) and the rotational structure (V/σ). The inset shows the Hubble Space Telescope image of this late-type galaxy, overlaid with the LEGA-C slit geometry as a rectangle. The kinematic information is extracted along the slit. The figure is adapted from van Houdt et al. (2021).

To take full advantage of the spatially resolved kinematic information, we construct dynamical models (van Houdt et al., 2021; illustrated in Figure 4) to obtain the most accurate determination to date of the mass profiles of galaxies at large lookback times, as well as their kinematic structure, that is, the degree of rotational support. For the first time we have spatially resolved stellar dynamical information for both late- and early-type galaxies at large lookback times. We find that most star-forming galaxies are dominated by rotationally supported stellar discs, and that quiescent galaxies show a large variety. The fastest-rotating galaxies show little sign of star formation, but at the same time the most massive systems are often characterised by quasi-random motions, analogous to the slow rotators seen in the present-day Universe. These trends imply that galaxies do not (necessarily) undergo a change in dynamical structure when they transition from a star-forming to a quiescent state.

Synthesis

Galaxy structure and star formation history are closely linked; the true power of LEGA-C is therefore the availability of both stellar kinematics and stellar population information. We have only just begun to explore this direction, and for the general galaxy population we have so far only shown the global correlation between morphology, velocity dispersion and stellar population age (Figure 5). We see that young galaxies generally have late-type morphologies with disc-like structures, whereas old galaxies have early-type, bulge-dominated morphologies. At a fixed (integrated) velocity

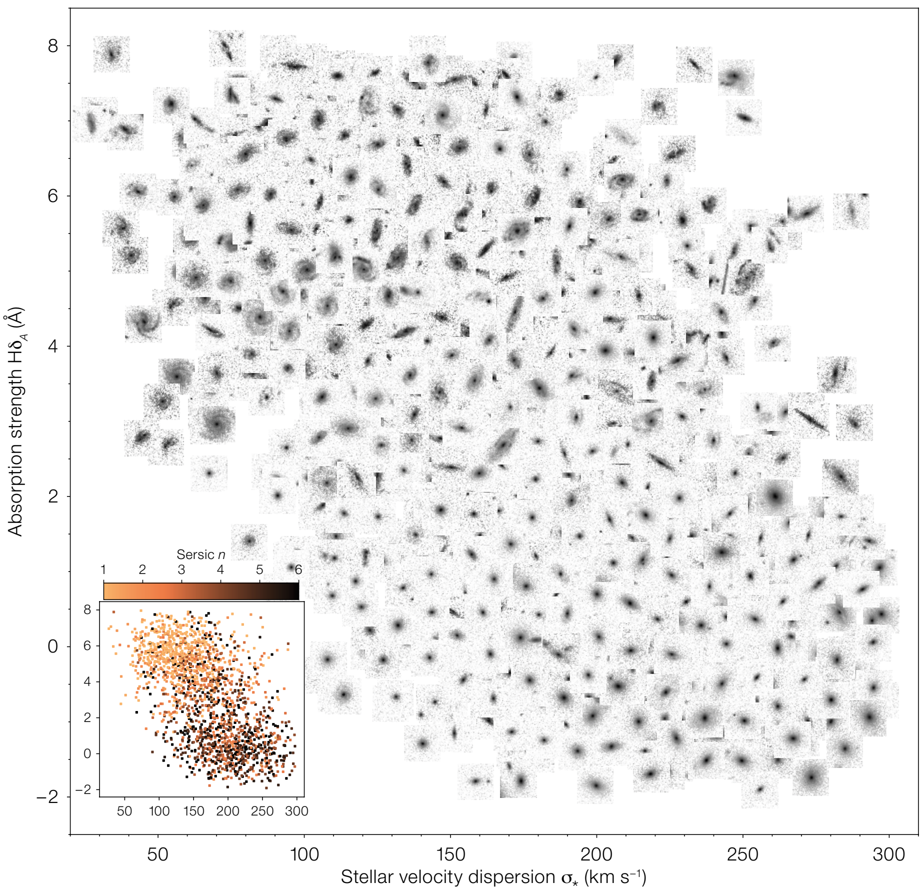


Figure 5. Hδ absorption strength — indicative of stellar population age — versus stellar velocity dispersion. Hubble Space Telescope images reflect the variation in morphology throughout this parameter space. The inset panel shows the Sérsic index (Sérsic, 1963), a structural property that distinguishes between disc- and bulge-dominated galaxies (n = 1 and n = 4, respectively). The figure is adapted from van der Wel et al. (2021).

dispersion, on the other hand, we see a large variety of morphologies, structures and ages.

Much more can be learned by reconstructing star formation histories and folding in the spatially resolved kinematics, and until now we have only examined in detail the connection between structure and stellar populations for a very specific type: post-starburst galaxies, defined as galaxies with high recent, but low current star formation activity, implying a sudden cessation of star formation or quenching 0.5–1 gigayear before the time of observation. These are the youngest quiescent galaxies, and we find that they are also among the most compact (Wu et al., 2018b): they stand out as young galaxies with very small sizes in Figure 3, breaking the general trend. This compactness is immediately linked to the recent starburst (Wu et al., 2020), as also evidenced by age gradients seen in the LEGA-C data: their centres are younger than their outer parts (D'Eugenio et al., 2020), which is the reverse of the gradients seen for the general population (old centres; young outskirts). We emphasise that this evolutionary trajectory is not rare at this cosmic epoch, but also that the majority of galaxies do not seem to follow it. Rather, for quiescent galaxies we see a positive correlation between age and size (at a fixed mass), and the younger quiescent population is rather similar in size and stellar kinematic structure to the star-forming population (Wu et al., 2020). This implies, as already mentioned above, that a (sudden) change in structure is not necessarily required to explain a declining star formation rate, but also that there are multiple pathways by which to evolve from actively star-forming to quiescent.

Looking ahead

In many ways we have just started the exploration of the rich LEGA-C dataset. In the near future we will present a consistent framework for estimating galaxy ages and metallicities, by comparing results from different models and fitting techniques. This provides the backbone for a full assessment of the star formation and chemical enrichment histories of the galaxy population at $z = 0.6$–1. Furthermore, supported by the absolute calibration of the galaxy mass scale and first determination of the angular momentum locked up in the stellar bodies of galaxies, we are in a great position to test the predictions of these fundamental quantities from the cosmological, hydrodynamical simulations.

On the observational side, the LEGA-C dataset will not be superseded in the foreseeable future. Large multiplex instruments on 8-metre-class telescopes (for example, the Multi-Object Optical and Near-infrared Spectrograph [MOONS] on the VLT) have the potential to extend the stellar population story to $z > 1$, but this will take a dedicated survey with ~ 100-hour integration times. Moreover, these fibre instruments do not provide spatially resolved information. Much of the value of LEGA-C is in the spatially resolved information enabled by the slit mask design, but no near-infrared multi-slit spectrographs are planned for the VLT. ESO's Extremely Large Telescope (ELT) will provide spectacular spatially resolved observations of high-redshift galaxies, but samples of hundreds, let alone thousands, of galaxies with high-signal-to-noise stellar spectroscopic data will likely remain out of reach.

Acknowledgements

Based on observations made with ESO Telescopes at the La Silla Paranal Observatory under programme IDs 194-A.2005 and 1100.A-0949 (The LEGA-C Public Spectroscopy Survey). The LEGA-C project is supported by the ERC Consolidator Grant 683184.

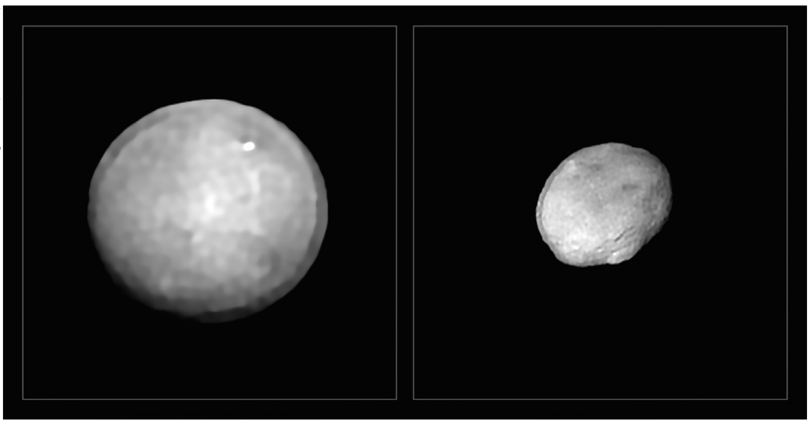
References

Barisic, I. et al. 2020, ApJ, 903, 146
Barone, T. M. et al. 2021, MNRAS, in press, arXiv:2107.01054
Beverage, A. G. et al. 2021, ApJL, 917, L1
Bezanson, R. et al. 2018a, ApJ, 858, 60
Bezanson, R. et al. 2018b, ApJL, 868, L36
Chauke, P. et al. 2018, ApJ, 861, 13
Chauke, P. et al. 2019, ApJ, 877, 48
de Graaff, A. et al. 2020, ApJL, 903, L30
de Graaff, A. et al. 2021, ApJ, 913, 103
D'Eugenio, F. et al. 2020, MNRAS, 497, 389
Sérsic, J. L. 1963, Boletín de la Asociación Argentina de Astronomía, 6, 41
Straatman, C. M. S. et al. 2018, ApJS, 239, 27
van der Wel, A. et al. 2016, ApJS, 223, 29
van der Wel, A. et al. 2021, ApJS, in press, arXiv:2108.00744
van Houdt, J. et al. 2021, ApJ, in press, arXiv:2108.08142
Wu, P.-F. et al. 2018a, ApJ, 855, 85
Wu, P.-F. et al. 2018b, ApJ, 868, 37
Wu, P.-F. et al. 2020, ApJ, 888, 77
Wu, P.-F. et al. 2021, AJ, in press, arXiv:2108.10455

Links

[1] Lega-C: the final data release is accessed via the ESO Archive Science Portal: https://archive.eso.org/scienceportal/home?data_collection=LEGA-C

ESO/Vernazza et al./MISTRAL algorithm (ONERA/CNRS)



Ceres and Vesta are the two largest objects in the asteroid belt between Mars and Jupiter, approximately 940 and 520 kilometres in diameter. These images have been captured with the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) instrument on ESO's Very Large Telescope as part of a programme that surveyed 42 of the largest asteroids in our Solar System. These two asteroids are also the two most massive in the sample.