DOI: 10.18727/0722-6691/5305

Stellar Population Survey Using 4MOST (4MOST-StePS)

Angela Iovino [1]
Amata Mercurio [2]
Anna Rita Gallazzi [3]
Francesco La Barbera [2]
Marcella Longhetti [1]
Crescenzo Tortora [2]
Stefano Zibetti [3]
Francesco Belfiore [3]
Matteo Bianconi [4]
Giovanni Busarello [2]
Enrico M. Corsini [5]
Luca Costantin [6]
Gabriella De Lucia [7]
Roberto De Propris [8]
Francesco D'Eugenio [9]
Fabio Fontanot [7]
Rubén García-Benito [10]
Michaela Hirschmann [7]
Christopher Haines [11]
Filippo Mannucci [3]
Sean McGee [4]
Paola Merluzzi [2]
Lorenzo Morelli [11]
Alessia Moretti [12]
Anna Pasquali [13]
Bianca Poggianti [12]
Lucia Pozzetti [14]
Giulia Rodighiero [5]
Patricia Sánchez-Blázquez [15]
Arjen van der Wel [16]
Alexandre Vazdekis [17]
Benedetta Vulcani [12]
Anita Zanella [12]
Marianna Annunziatella [6]
Alice Concas [18]
Letizia P. Cassarà [19]
Giovanni Cresci [3]
Mirko Curti [9]
Adriana de Lorenzo-Cáceres [17]
Anna Ferre Mateu [17]
Rosa M. González Delgado [10]
Chiara Mancini [5]
Camilla Pacifici [20]
Enrique Perez-Montero [10]
Alessandro Pizzella [5]
Pablo G. Perez-Gonzalez [6]
Scott C. Trager [21]
Daniela Vergani [14]

[1] INAF–Brera Astronomical Observatory, Italy
[2] INAF–Capodimonte Astronomical Observatory, Naples, Italy
[3] INAF–Arcetri Astronomical Observatory, Florence, Italy
[4] University of Birmingham, UK
[5] University of Padua, Italy
[6] Centre for Astrobiology (CSIC-INTA), Torrejón de Ardoz, Spain
[7] INAF–Trieste Astronomical Observatory, Italy
[8] Turku University, Finland
[9] Kavli Institute for Cosmology, Cambridge, UK
[10] Andalucia Institute of Astrophysics, Granada, Spain
[11] University of Atacama, Copiapò, Chile
[12] INAF–Padua Astronomical Observatory, Italy
[13] Heidelberg University, Germany
[14] INAF–Bologna Astrophysics and Space Science Observatory, Italy
[15] Madrid Complutense University, Spain
[16] Ghent University, Belgium
[17] Canary Islands Institute of Astrophysics, Tenerife, Spain
[18] ESO
[19] INAF–Institute of Space Astrophysics and Cosmic Physics, Milan, Italy
[20] Space Telescope Science Institute, Baltimore, USA
[21] University of Groningen, the Netherlands

Galaxy spectra encode in their continuum and absorption/emission features a wealth of information on galaxy physics, mass assembly and chemical enrichment history. The 4MOST-StePS survey will collect high-quality spectra (with a median signal-to-noise ratio of about 30 Å^{-1}, and resolution R ~ 5000) for a sample of about 3300 galaxies brighter than I_{AB} = 20.5 within the RA-Dec-z footprint of the WAVES-Deep survey. These spectra will provide a precise empirical description of the evolutionary path of massive galaxies in the intermediate redshift range (0.3 < z < 0.7) between the LEGA-C and SDSS surveys. The locations of the galaxies within the cosmic web, unveiled by WAVES-Deep, will disclose the connection between galaxy properties and environment, down to the scales of galaxy pairs.

Scientific context

The complex physical processes that cause the formation and evolution of luminous structures to deviate from the assembly history of dark matter (DM) halos are yet to be fully understood. On galactic scales (below ~ 1 Mpc), highly non-linear processes are at play (for example, energetic feedback, both from active galactic nuclei [AGN] and star formation, and mergers). A detailed comparison between observational data, simulations and advanced theoretical models can shed light on the mechanisms that regulate the connection between galaxies and their DM halos.

Good quality (both in resolution and signal-to-noise ratio [SNR]) spectra provide information about the current physical conditions of the multiple components in a galaxy (stars, gas and, indirectly, DM), while simultaneously unveiling the archaeological treasure that is encoded in its stellar populations. The whole past star formation and chemical-enrichment history of a galaxy are reflected in its present stellar population properties. The chemical abundance of gas and stars in a galaxy holds the memory of the baryonic cycle that regulates its star formation, by balancing the inflow of pristine gas, the outflow of metal-loaded gas blown out by stellar/AGN winds, and the re-accretion of this metal-enriched gas (Hunt et al., 2020).

The study of galaxies in the local Universe has greatly enriched our understanding of galaxy evolution. The spectra from the Sloan Digital Sky Survey (SDSS; York et al., 2000) have provided a robust z ~ 0 anchor to both theoretical and empirical approaches, proving to be an immensely valuable tool to understand the physics of galaxies. Unfortunately, the so-called archaeological reconstruction from z ~ 0 galaxies is limited by inherent physical degeneracies between different parameters (for example age and metallicity) and by the similarity of stellar population spectra with ages greater than 5 Gyr; together these prevent an accurate reconstruction of a galaxy's ancient star formation history. To circumvent this problem a direct look-back approach is needed, i.e., observing galaxies at high redshifts to make a direct census of different populations at different remote cosmic epochs. High-quality galaxy spectra, observed in different environments and across a continuous range of cosmic times, provide precise measurements of a variety of physical parameters of galaxies, enabling the star formation and chemical enrichment histories at early times to be unveiled. This strategy in turn opens up the possibility of connecting lower-redshift galaxies to their statistically plausible progenitors. So far, the only notable survey designed to obtain high-quality spectra in the relatively distant Universe is LEGA-C (van der Wel et al., 2021), covering the redshift window $0.6 \leq z \leq 1.0$ for a sample of ~ 3200 galaxies within the COSMOS field. LEGA-C spectra (median SNR ~ 20 Å^{-1}, resolution R ~ 2500) have shown the power of high-quality continuum spectroscopy as a fundamental tool with which to study galaxies, but many questions remain open. Analysis of LEGA-C spectra has shown that, contrary to what was previously thought, even the most massive galaxies today may experience new star formation episodes between z ~ 0.8 and z ~ 0 (Chauke et al., 2018; Wu et al., 2021). Identifying the mechanisms that give rise to a rekindling of star formation activity will provide crucial information needed to reconstruct the evolutionary paths of galaxies.

However, the intermediate window remains unexplored, as even at these modest redshifts it is challenging to produce a large sample of high-quality spectra.

A first step towards filling this gap is provided by the WEAVE-Stellar Population Survey, using the WEAVE multi-object spectrograph at the William Herschel Telescope (WEAVE-StePS; Iovino et al., 2022). WEAVE is a spectrograph similar in overall performance to 4MOST, and over the next 5 years WEAVE-StePS will observe ~ 25 000 galaxies over ~ 25 deg^2, selected to be brighter than I_{AB} ~ 20.5 mag and at redshift $z > 0.3$. WEAVE-StePS spectra, observed at resolution R ~ 5000, will access important physical properties of galaxies, such as a basic characterisation of the star formation history, as well as stellar and nebular metallicities and dynamical properties. However, this large sample will be at a typical SNR of ~ 10 Å^{-1} in the I band, and the uncertainties in the parameters will rapidly grow, on average, for fainter/less massive galaxies.

Specific scientific goals

The 4MOST Stellar Population Survey (4MOST-StePS) seizes the opportunity to piggyback on the WAVES-Deep areas (Driver et al., 2019), to obtain deep low-resolution-mode observations (T_{exp} ~ 30 hours) for a sample of ~ 3300 bright galaxies ($I_{AB} \leq 20.5$) embedded within the RA-Dec-z footprint of WAVES-Deep (i.e., at $0.3 < z < 0.7$). The design of 4MOST-StePS mimics that of WEAVE-StePS, targeting the massive tail ($\log(M_*/M_\odot) \geq 10.5$) of the galaxy population, but the focus is on a smaller yet representative sample of galaxies, similar in size to LEGA-C, trading the sample size for a much higher SNR (see Figure 1).

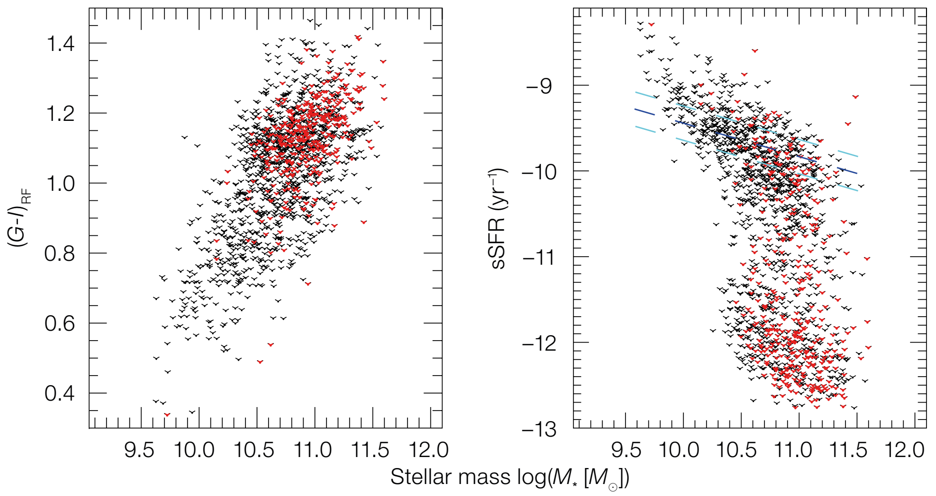

Figure 1. Overview of the target galaxy sample in terms of stellar mass (based on Bruzual & Charlot (2003) models and assuming Chabrier (2003) initial mass funciton), optical colours and specific star formation rate (sSFR). Left panel: rest-frame ($G–I$) colour vs. stellar mass. Right panel: sSFR vs. stellar mass plots for galaxies selected at $I_{AB} \leq 20.5$ and $0.3 < z < 0.7$. Values of rest-frame colours, stellar masses and sSFR are obtained from a compilation of spectroscopic data in the COSMOS field. Black points indicate the total sample selected using 4MOST-StePS constraints in magnitude and redshift, and red points indicate the highest quartile SNR sub-sample. The blue and cyan lines on in the right panel displays the main sequence location and its scatter (Speagle et al., 2014).

The goal is to capture the richness (including the inherently stochastic nature) of the various processes involved in galaxy evolution, and to pin down the different mechanisms (both internal and external) capable of modulating/shutting down star formation activity in galaxies. The superb high-quality individual spectra of 4MOST-StePS will yield the fundamental physical properties needed to address a range of questions accessible only for a tiny (< 5%) and biased minority of the galaxies observed by WEAVE-StePS at the William Herschel Telescope.

4MOST-StePS galaxies will amount to a statistically robust, intermediate-redshift sample, complementing both the LEGA-C higher-redshift sample and the SDSS local sample.

The main physical quantities we will obtain for our sample are:

– The mean age of the stellar component, and the timescale of the star formation activity. The rest-frame ultraviolet and its absorption indices — sensitive tracers of young stars — will be used to identify recent minor episodes of star formation on top of an old stellar population, providing a census of the so-called ‘rejuvenation’ phenomenon, whereby passive galaxies go back (temporarily) to an actively star-forming state. This observable will constrain the evolutionary patterns of galaxies in the mass–star-formation-rate space, and clarify to what extent the passive evolution scenario can apply to present-day passive and massive galaxies in different environments;
– The metal abundances in stars and gas. A SNR of ≥ 20 Å^{-1} is needed to obtain accurate measurements of metal-sensitive absorption features, limiting stellar metallicity uncertainty to < 0.1 dex for the most evolved galaxies and to < 0.2–0.25 dex for younger, star-forming

systems (Gallazzi et al., 2005, 2014). This allows the evolution of different scaling relations and their intrinsic scatter to be tracked. Unbiased values of metallicity can be obtained with detailed analysis of single element abundance ratios (for example, [Mg/Fe], [Ca/Fe], [C/Fe]), measured with an accuracy of 0.1 to 0.25 dex (depending on the element) for intermediate-age populations based on an SNR > 30 $Å^{-1}$. Gas-phase metallicity can also be accurately measured using the faint auroral lines (for example, Maiolino & Mannucci, 2019) that can be detected in these high-SNR spectra, after stacking. These quantities can constrain the physical processes of chemical enrichment in galaxies, as well as the timescale of quenching processes and of the main star formation event (Sánchez-Blázquez et al., 2003; Carretero et al., 2004);
– Characterisation of the kinematics of the stellar and gaseous components (velocity distribution, inflows/outflows). An accurate estimate of dynamical masses can be obtained with a formal accuracy of ~ 25% (40%) using spectra with SNR ~ 30 (20) $Å^{-1}$, by using Jeans modelling of the 4MOST aperture velocity dispersion of individual galaxies. Its comparison with stellar masses is crucial to linking the evolution of galaxies to their DM halos (Tortora et al., 2018) and to providing dynamical constraints on one of the most disputed ingredients in stellar populations, i.e., the shape of the stellar initial mass function (IMF; for example, Tortora, Romanowsky & Napolitano, 2013). The excellent spectral quality will reveal the demographic of gas outflows/inflows traced by interstellar absorption and broad high-velocity nebular emission as done at z ~ 0 with the SDSS galaxy spectra (Concas et al., 2017, 2019).

All these quantities will be complemented by the environment information provided by WAVES-Deep and compared with state-of-the-art large-scale cosmological simulations (Fontanot et al., 2017, 2021). The 4MOST-StePS sample will be the ideal observational counterpart to synthetic spectral energy distributions obtained from galaxy formation simulations in a cosmological context — including the stellar continuum and the nebular emission lines of various origins (Hirschmann et al., 2017).

The interplay between theoretical rendition and 4MOST-StePS observed spectra will enable a uniquely accurate two-way comparison of theoretical predictions with observational data. This kind of approach is needed for a quantitative understanding of the processes driving the evolution of massive galaxies. 4MOST-StePS data will lift the degeneracies of the interpretation that WEAVE-StePS will not be able to do, given its lack of detail.

Finally, our observational strategy will provide a tail of galaxies with excellent SNR (> 40 $Å^{-1}$ in the I band; red points in Figure 1), enabling innovative science. For this higher-SNR sample, we will derive precise individual abundance ratios, constrain the stellar IMF from key sensitive features, detect even tiny fractions (at the 1% level) of residual young stars, detect faint auroral lines for direct gas metallicity estimates in star-forming galaxies and identify gas flows probed by absorption and emission lines. The higher moments of the line-of-sight velocity dispersion will also be retrievable, improving dynamical mass estimates. The high-SNR sample will be used to test for systematics in our estimates (for example the accurate reconstruction of star formation histories at lower SNR values).

Target selection and survey area

We will pool our targets with those of Consortium Surveys in the ~ 66-deg^2 footprint of the WAVES-Deep survey (four so-called Deep Drilling Fields and the GAMA23 Deep field). The choice of these sky regions is driven by observational strategy advantages and significant scientific benefits. All the WAVES-Deep areas possess a variety of ancillary photometric data that can be used to complement the 4MOST high-quality spectroscopic information on a wider wavelength range. In these fields, we can take advantage of the repeated passes needed to achieve the sampling rate requested by WAVES-Deep and successfully pursue our 30-hour exposure time strategy, while using a minimal fraction of fibre hours: less than 0.5% of the total amount available to Community surveys in low-resolution mode.

Our sample is positioned within the Large-Scale Structure web, revealed in fine detail by WAVES-Deep (see Driver et al., 2019). This accurate environmental information will enable us to explore the connection between the different galaxy properties and the environment where galaxies reside in an evident and advantageous synergy with WAVES-Deep.

4MOST-StePS will push the 4MOST spectrograph to the limit of its performance, well beyond its redshift machine capabilities. Our survey will obtain high-quality data, bridging the gap in our knowledge in the intermediate redshift range, which still lacks such high-quality data, and will put to full use the environment characterisation provided by WAVES-Deep. The synergy with the science case of WAVES-Deep is a win-win opportunity that our project fully exploits, making 4MOST-StePS a low-cost survey with the potential for a very high scientific return.

References

Bruzual, G. & Charlot, S. 2003, MNRAS, 344, 1000
Carretero, C. et al. 2004, ApJ, 609, L45
Chabrier, G. 2003, PASP, 115, 763
Chauke, P. et al. 2018, ApJ, 861, 13
Concas, A. et al. 2017, MNRAS, 468, 1747
Concas, A. et al. 2019, A&A, 622, A188
Driver, S. P. et al. 2019, The Messenger, 175, 46
Fontanot, F. et al. 2017, MNRAS, 464, 3812
Fontanot, F. et al. 2021, MNRAS, 504, 4481
Gallazzi, A. et al. 2005, MNRAS, 362, 41
Gallazzi, A. et al. 2014, ApJ, 788, 72
Hirschmann, M. et al. 2017, MNRAS, 472, 2468
Hunt, L. et al. 2020, A&A, 643, A180
Iovino, A. et al. 2022, submitted to A&A
Maiolino, R. & Mannucci, F. 2019, A&ARv, 27, 3
Sánchez-Blázquez, P. et al. 2003, ApJ, 590, L91
Speagle, J. S. et al. 2014, ApJS, 214, 15
Tortora, C., Romanowsky, A. J. & Napolitano, N. R. 2013, ApJ, 765, 8
Tortora, C. et al. 2018, MNRAS, 473, 969
van der Wel, A. et al. 2021, ApJS, 256, 44
Wu, P.-F. et al. 2021, AJ, 162, 201
York, D. G. et al. 2000, AJ, 120, 1579