DOI: 10.18727/0722-6691/5313

The 4MOST Strong Lensing Spectroscopic Legacy Survey (4SLSLS)

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Almost all science that can be done with strong gravitational lenses requires knowledge of the lens and source redshifts. The 4MOST Strong Lensing Spectroscopic Legacy Survey (4SLSLS) will follow up strong lens candidates discovered in the Euclid survey and the Legacy Survey of Space and Time. 4SLSLS will provide pairs of redshifts for 10 000 strong-lensing galaxies (lenses) and background galaxies (sources). Velocity dispersions will also be measured for 5000 lenses. This sample will enable discoveries about the evolution of galaxies, the study of intrinsically faint objects and of the cosmological model.

Scientific context

General Relativity (GR) is based on the principle that massive objects warp spacetime. Because of this, light passing close to massive objects is deflected. If the surface mass density of the object is great enough, then multiple images of a single background source can form; this is the regime of strong gravitational lensing.

For each strong lens system, the images observed depend on the light profile of the background source, the mass and mass distribution of the foreground lens, the cosmological distances between observer, lens and source and the nature of gravity. Strong lenses are therefore sensitive probes of both astrophysics and cosmology. As such, strong lenses have been used to constrain the masses and density profiles of galaxies (Auger et al., 2010; Shajib et al., 2021), the dark subhalo and field-halo populations (Vegetti et al., 2014; Ritondale et al., 2019), cosmological parameters (Collett & Auger, 2014; Wong et al., 2020), the high-redshift luminosity function (Barone-Nugent et al., 2014), the nature of high-redshift sources (Newton et al., 2011) and the validity of GR (Schwab, Bolton & Rappaport, 2010; Collett et al., 2018). For many of these analyses, the shortage of suitable strong lenses is a major limiting factor.

To date, several hundred galaxy-galaxy strong lenses have been discovered in heterogeneous searches of photometric and spectroscopic survey data (Myers et al., 2003; Bolton et al., 2006; Gavazzi et al., 2012; Negrello et al., 2014; More et al., 2016; Hartley et al., 2017; Petrillo et al., 2019; Jacobs et al., 2019; Li et al., 2020). The reason known lenses are rare is because even the most massive galaxies are only capable of deflecting light by an arcsecond or two. Only a small fraction of the sky has been observed to sufficient depth and with good enough image resolution to identify a typical Einstein ring. Several ongoing, and forthcoming, wide and deep sky surveys offer improved depth, area and resolution compared to existing data (Miyazaki et al., 2006; Ivezic et al., 2008; Laureijs et al., 2011). These surveys have the potential to increase the current galaxy-scale lens sample by orders of magnitude (Collett, 2015; Marshall, Blandford & Sako, 2005). Between Euclid and the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST), up to 300 000 lenses are discoverable. However, these surveys will not provide adequate redshift information for science: this is what 4SLSLS will deliver.

With a large increase in the known strong lens population, current work could be extended to new regimes, including lower lens masses, higher-redshift lenses and intrinsically fainter sources. A critical component of any results derived from this increased discovery space is the confirmation of any identified strong lens candidate with a spectroscopic redshift for the lens and the source behind it.

Spectroscopy is needed for two main reasons:
1. Features on the sky often look similar to strong lenses but are not. Ring galaxies, star-forming tidal features and interacting galaxies are often particularly hard to distinguish. Spectroscopy confirms that the putative lens is indeed closer than the putative arcs.
2. Strong lensing observables are naturally in angular units (Einstein radius, unlensed angular size of source, lens mass, etc). Converting them into physical quantities requires precise spectroscopic redshifts.

Specific scientific goals

The primary purpose of 4SLSLS is to enable the strong lensing community to exploit the large increase in sample sizes. Having a homogeneous sample of 10 000 lenses with a well understood selection function represents a huge step forward for the community. Here we highlight three main science goals that are a priority for the project team.

Galaxy formation — the inner structure of lenses

Dark matter and baryons exist in comparable amounts within the Einstein radius (Auger et al., 2010) and as a result galaxy-scale lenses are well suited to the study of both components. Strong lensing is a particularly useful tool to simultaneously address questions related to the inner structure of massive galaxies.

What fraction of the cosmological baryon content is converted into stars?

Virtually all current measurements of galaxy stellar masses are obtained by converting observed luminosities into masses on the basis of synthetic stellar population models which have not been calibrated against model-independent stellar mass measurements. These models introduce a systematic uncertainty in the total baryonic mass locked in stars. The main uncertainty is the stellar initial mass function (IMF), the choice of which can plausibly vary the stellar mass-to-light ratio of a galaxy by a factor of two. Constraining stellar mass-to-light ratios of galaxies provides a unique way of gaining insight into the stellar IMF and the physics of star formation.

What is the inner density profile of the dark matter halo?

The determination of the inner dark matter density profile can provide unique constraints both on dark matter physics, for example by testing the self-interaction scenario (Elbert et al., 2018), and on baryonic physics: the dark matter distribution responds to processes such as adiabatic contraction from gas infall (Gnedin et al., 2011), feedback from the central supermassive black hole (Martizzi, Teyssier & Moore, 2013) and dynamical friction (Romano-Díaz et al., 2008). Cosmological hydrodynamical simulations generally predict, in the centres of massive galaxies, dark matter profiles steeper than the Navarro–Frenk–White model used to describe dark matter-only simulations (Schaller et al., 2015; Xu et al., 2017; Peirani et al., 2017). Current strong lensing observations suggest a larger diversity in dark matter profiles (Oldham & Auger, 2018), although the number of galaxies for which such measurements are available is still very limited. Confirming or ruling out this tension can be very useful for improving the accuracy of the subgrid physics recipes adopted in simulations.

Strong lensing is one of the very few methods available for simultaneously constraining galaxy stellar masses and dark matter density profiles independently of a stellar population model. 4SLSLS will statistically combine strong lensing measurements from a large set of systems (for example, Sonnenfeld & Cautun, 2021). Our forecasts show that 4SLSLS will constrain the average stellar IMF normalisation of a sample of 5000 lenses with a precision of 5%, while measuring the average dark matter density slope with a precision of 0.1 (see Figure 1). With such precision, we will be able to settle the dark matter core vs. cusp issue in massive lens galaxies and put much tighter constraints on the stellar IMF of these objects than is currently possible. Moreover, by combining lensing constraints with 4SLSLS velocity dispersion measurements it will be possible to address additional questions, such as how the IMF varies as a function of galaxy properties and within each galaxy as a function of position (Sonnenfeld et al., 2018).

Probing the cosmological parameters with 4SLSLS

The Einstein radius of a strong lens is a function of lens mass and cosmological distances. Measuring cosmological distances as a function of redshift can teach us about the underlying cosmological model of the Universe, but doing this with strong lenses requires additional information to break the degeneracy between mass and distances. 4SLSLS will provide two pathways to break this degeneracy: directly by providing a lensing-independent measurement of the mass through velocity dispersions, and indirectly by confirming exotic strong lenses with information beyond a single Einstein radius. Grillo et al. (2018) showed that velocity dispersions can in principle be used to constrain the dark energy content of the Universe. However, connecting the scales probed by unresolved kinematics with the Einstein radius requires a knowledge of the lens density profile. A large sample of lenses with sources at different redshifts is critical to inferring cosmological parameters and marginalising over any trends in the redshift evolution of lens density profiles. Forecast constraints show that constraints on Ω_M at the level of 5% can be derived with 5000 lenses. The assumption that GR holds over cosmological distances is a key aspect of ΛCDM, but GR is poorly tested on extragalactic length scales. In addition to probing cosmological parameters, the 5000 4SLSLS systems with velocity dispersions will test GR by comparing observed deflection angles to those predicted from the kinematic mass (Schwab, Bolton & Rappaport, 2010). 5000 lenses will constrain the amount of spatial curvature produced per unit mass to the 1% level, without assuming a fixed background cosmological model. This is 10 times better than any other extragalactic test of GR (Collett et al., 2018). 4SLSLS will also confirm a population of ~ 300 double-source plane lenses: in these systems the ratio of the Einstein radii is sensitive to cosmology (Collett et al., 2012), but not to the primary lens mass. After lens modelling of the Euclid data, these systems will yield an 8% constraint on the equation of state of dark energy, independent of any other dataset or a 4% constraint with a weakly informative prior from the distance to the CMB.

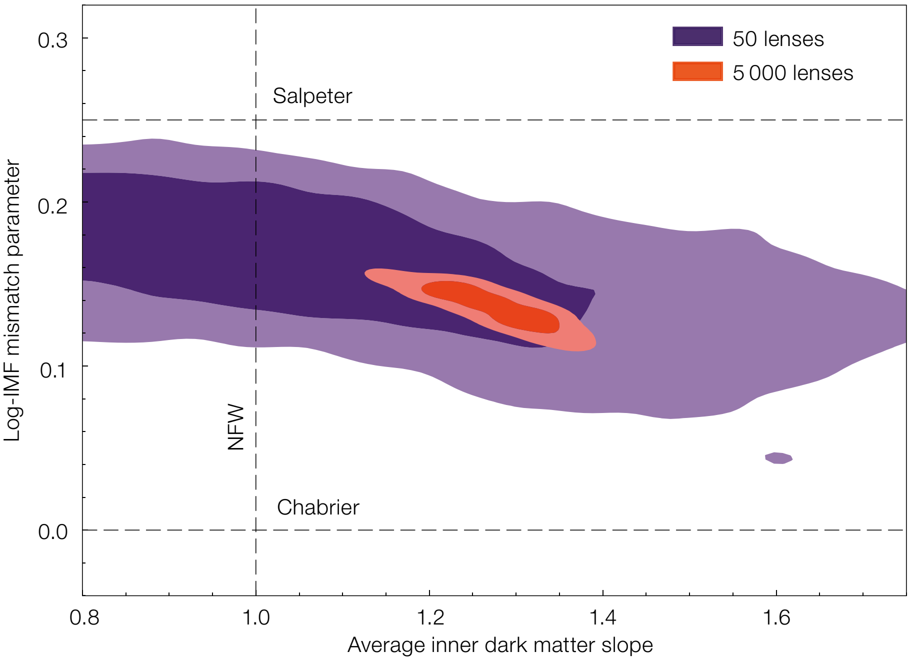

Figure 1. Red contours: Forecast on the inference of the average inner slope of the dark matter density profile and the stellar IMF mismatch parameter (that is, the ratio between the true stellar mass of a galaxy and the stellar mass obtained from stellar population fitting assuming a Chabrier IMF) from the statistical combination of strong lensing data on a sample of 5000 4SLSLS lenses. Purple contours: forecast on a sample of 50 lenses, approximately the number of galaxy-scale strong lenses with currently available lens and source spectroscopic redshifts. Contour levels correspond to 68% and 95% enclosed probability regions.

Using highly magnified sources to constrain intrinsically faint galaxy populations

The frontier of galaxy evolution is set by those galaxies at the limiting reach of the largest telescopes. Observations therefore benefit immensely from the flux amplification and spatial resolution enhancement provided by lensing magnification. The benefits brought by strong lens magnification to the study of high redshift sources were neatly demonstrated recently by Rigby et al. (2017). They showed that even HST-resolution imaging of unlensed z = 2.5 systems cannot come close to probing the intrinsic spatial scales that can be reached by strong lensing. Many studies have used lens systems to probe the galaxy assembly and star formation. Observations of lensed sources have helped us to: understand the role of high-redshift mergers in galaxy formation (Wuyts et al., 2014); measure the size of star-forming clumps to connect them to kinematic stability (Livermore et al., 2015; Swinbank et al., 2015); spatially resolve star-forming clumps to constrain the physical properties of the ISM (Frye et al., 2012); establish the conditions in the ISM which regulate star-forming and starbursting activities (Dye et al., 2022); probe gas-phase metallicity to determine growth channels (Yuan et al., 2011; Jones et al., 2015; Wang et al., 2017); and identify and investigate massive, post-blue-nugget galaxies (Napolitano et al., 2020). High-resolution rest-frame-UV spectroscopy has studied outflow composition and energetics, probing the physics of feedback-driven outflows (Pettini et al., 2002; Frye, Broadhurst & Benítez, 2002; Yuan, Bu & Wu, 2012; Jones, Stark & Ellis, 2018). Today, the main limiting factors are sample size and heterogeneous selection functions. 4SLSLS will provide the first statistically large sample of spectroscopically confirmed intrinsically faint galaxies with well-defined selection functions. By virtue of the size of the 4SLSLS sample, prime sources for targeted follow-up (for example with adaptive-optics-fed 10-metre- & ELT-class spectrographs) can be selected on the basis of source properties and redshifts. As a result, 4SLSLS will enable an unprecedented understanding of the nature of galaxies up to z = 1.5 at enhanced spatial resolution.

Target Selection and Survey area

The large number of strong lenses that will be discovered means that spectroscopic confirmation must move beyond one-by-one observations of individual sources. Already, most of the current Dark Energy Survey and Kilo-Degree Survey lenses do not have spectroscopic redshifts. To combat the expanding scale of the strong lens follow-up problem, 4SLSLS is the community's move to multi-object spectroscopy, albeit with sparse densities (~ 20 lenses per square degree from Euclid and a further ~ 8 per square degree from the LSST; see Collett, 2015). By sharing the focal plane of a multi object spectrograph with larger surveys, strong lens redshifts can be obtained efficiently. 4SLSLS targets will be discovered across the LSST and Euclid Southern footprints. We will target lens candidates with a photometric redshift consistent with $z_s < 1.5$, where the OII doublet falls out of the 4MOST wavelength band. This represents about a third of the LSST and Euclid sample. All but the most massive 4SLSLS targets will be lens-source blends, with the fibre centred to maximise source flux.

Acknowledgements

TEC is funded by a Royal Society URF. This work is supported by the European Research Council grant 945536 LensEra. Data are available from the first author upon request. For the purpose of open access, the authors have applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising.

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P. Horálek/ESO

This magnificent image shows ESO's Visible and Infrared Survey Telescope for Astronomy (VISTA), located at Paranal Observatory. The Milky Way galaxy sweeps behind the telescope with several nebulae visible, like the Gum Nebula and the Carina Nebula.