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16. SCIENTIFIC RATIONALE

Scientific Motivation

Strong gravitational lensing (SL), excluding the rearer cluster lensing, comes in two different 'flavours': compact object-galaxy lensing and galaxy-galaxy lensing. In the first case, a quasi-stellar object (QSO) is strongly lensed by a galaxy, resulting in multiple images of the same source and in arcs or rings that map the lensed host of the QSO. In the second case, both the background source and the deflector are extended objects, and the background source appears as an arc or a ring surrounding the foreground lens.

SL is definitely one of the most effective and successful ways to investigate the distant universe, thanks to its flux magnification effect (e.g. Marshall et al. 2007), and it can also provide unique insights into a large number of open issues in cosmology and extragalactic astrophysics.

Source reconstruction of the lensed QSO and its host gives a direct view of QSO-host co-evolution up to z~2 (Rusu et al. 2014). Moreover, microlensing of multiple QSO images, induced by the stars in the deflector, helps to probe the stellar content of the lens galaxies (e.g. Jimenez-Vicente et al. 2015) and, simultaneously, gives constraints on the inner structure of the quasar, such as accretion disk size, thermal profile (e.g. Anguita et al. 2008), and geometry of the broad line region (e.g., Sluse et al. 2011). Moreover, lensed quasars work as crucial cosmological tests providing firm constraints on the Hubble constant and other cosmological parameters (Blandford & Narayan 1992). The light-curves of the multiple lensed images are in fact offset by a measurable time-delay that depends on the cosmological distance between the lens and the source and on the gravitational potential of the lens (Refsdal 1964), which enables a one-step measurement of the expansion history of the Universe and of the Dark matter (DM) halos of massive lenses. The H0LICOW Collaboration (Suyu et al. 2014), for instance, has successfully measured the Hubble constant with a precision of 3.8% from a sample of 3 lenses (Bonvin et al. 2017). With tens of systems, we can reach 1% precision, comparable to the latest estimates from the Cosmic Microwave Background Radiation anisotropies. However, lensed quasars are very rare, since they require the chance alignments of quasars with foreground massive deflectors.

Galaxy-galaxy SL is by far the most accurate mass-measurement technique available for the central regions of galaxies, providing a one-shot, purely gravity-dependent measurement of the total projected mass enclosed by the lensed images. By modelling the arc features around massive lens galaxies using grid-based methods, we can determine the total mass, density profile, and mass fraction of DM substructures, with a precision unachievable in any other way. Remarkably, beyond the local group, SL provides the only way to discover and quantify mass substructures (e.g., Mao & Schneider 1998). With tens of newly confirmed lenses, the average slope of the mass density distribution can be estimated with a precision of 1-2% (Barnabè et al. 2011), dark substructures can be pinpointed down to ~3×10^8 solar masses, and their mass fraction constrained down to ~1% (Vegetti & Koopmans 2009). Finally SL, combined with dynamical and stellar population analysis, provides an excellent means of disentangling luminous from DM in galaxies (Koopmans et al. 2006; Tortora et al. 2010) and can put constraints on the stellar Initial Mass Function (Spiniello et al. 2012, 2015; Barnabè et. al. 2013).

Unfortunately, in all these mentioned cases, and especially for cosmography, the biggest limitation remains the paucity of confirmed lenses.

Gotta catch'Em All!

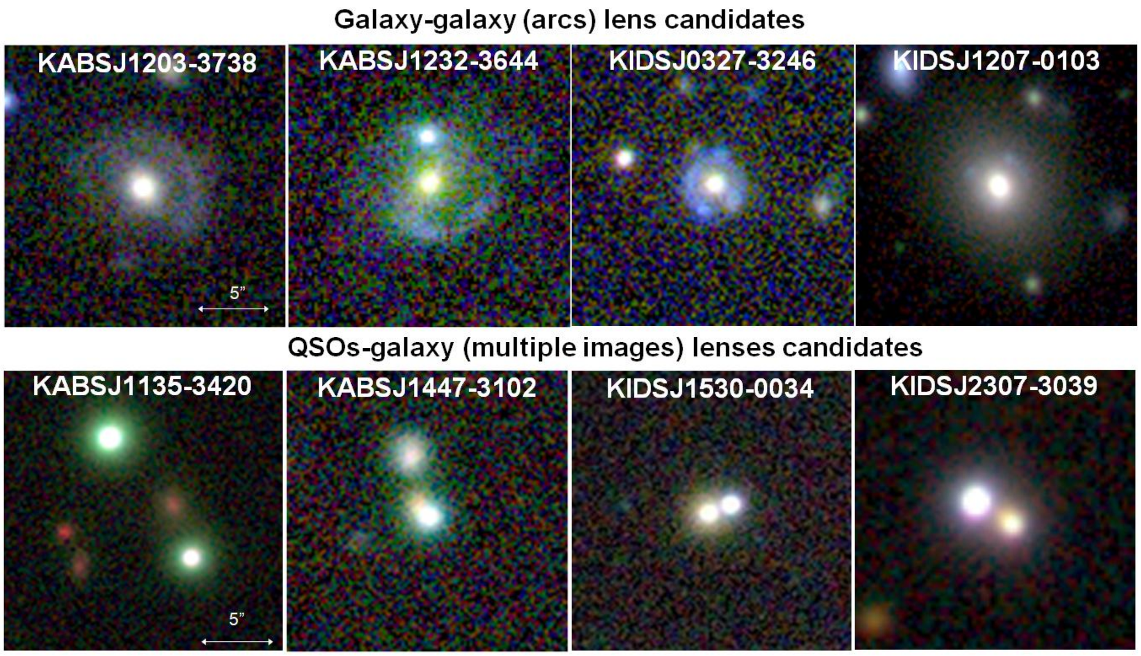
For this reason we have built up a team of experts with the goal of finding the largest possible number of SL events – both QSOs-galaxy and galaxy-galaxy – exploiting the improved image quality and the more extended and homogeneous sky coverage achieved with new, deep optical surveys. In particular, we focus on the VST Kilo Degree Survey (KiDS, de Jong et al. 2015, 2017), because of its depth, exquisite image quality, and quite stringent seeing constraints (limiting magnitude of 25 at 5σ in 2'' aperture and mean FWHM of 0.7" in r-band) and the KiDS VST-ATLAS Bridging Survey (KABS, Napolitano et al., in prep.), which provides optical imaging of an almost previously uncovered region of the Southern Sky.

In order to identify our SL candidates, we have exploited and developed a number of state-of-the-art techniques. In particular, to study/identify gravitational arc events, in Petrillo et al. (2017, 2018a), we worked out a morphological classification scheme based on a Convolutional Neural Network, to identify strong gravitational lenses, selecting new many lens candidates within 900 deg^2 of the upcoming KiDS-DR4 (Petrillo et al. 2018, in prep.). The identified candidates are then checked through visual inspection and graded based on their reliability.

For lensed QSOs, we combined different morphological and photometric methods based on infrared and optical colour pre-selection as well as direct image analysis and visual inspection. In two recently published companion papers (Spiniello et al. 2018; Agnello & Spiniello 2018), we showed that this combination of different methods increases the completeness and helps in finding a large number of high-grade lensed QSO candidates.

After almost 2 years, we have collected a list of ~300 high-grade candidates within the KiDS and KABS surveys (100 lensed quasars and 200 lensed galaxies; a few of the best ones are shown in Fig.1), which need spectroscopic confirmation and redshift measurements to translate our lens model results (e.g. the Einstein radii) into physical mass measurements.

This Proposal
We ask for 42 hours to spectroscopically confirm a selected sample of bright (i < 21) and high grade 30 lensed QSO and 20 lensed galaxy andidates, to definitively confirm their lensing nature and to obtain the source and lens redshifts. We also aim at calculating, for the spectra with the best S/N, the velocity dispersions of the lens, which will provide an independent constraint on total mass.



<u>Figure 1</u>: Some of the high-grade arc/ring (above) and lensed QSO (below) candidates from KiDS and KABS. Each panel shows a 20"x20" rgb cutout.

17. IMMEDIATE OBJECTIVES

We will confirm the lensing nature and get the redshifts for 30 lensed QSOs and 20 arcs/rings.
This campaign will produce publication ready results. The spectroscopic confirmation of previously unknown lenses identified with our novel techniques is a publishable result per se. Moreover, the validation of these lenses represents the first step to build a solid sample to: a) perform studies of lens statistics, and b) reduce the uncertainties on mass density slope, DM fraction and mass substructure in the lenses.
Moreover, we have identified a few rare systems where the lenses are compact massive galaxies, which are possibly relics of high-redshift "red-nuggets" that missed the channel of galaxy size growth. Once spectroscopically confirmed, these SL will give us a unique chance to study their mass distributions, helping to shed light on their formation and the role of galaxy mergers (Tortora et al. 2018).
<u>Complementarity with other SALT Programs:</u> This proposal is by construction complementary to the SALT lensing legacy program 2015-2-MLT-006 (PI: Serjeant) in which part of our team is involved. In 2015-2-MLT-006 the selection criteria, based on the magnified Herschel sub-mm flux of the background source, identifies targets (both lens and lensed source) which are redder and at higher redshifts (z_{lens}>0.4; Negrello et al. 2017) than the ones selected with the optical selection in the present proposal (z_{lens}<0.4). Therefore the combination of these programs will ensure a unique chance to probe the evolution of lens galaxies up to z=1.

18. DATA REQUIREMENTS FOR PROPOSAL COMPLETION
NONE

19. TECHNICAL JUSTIFICATION

Our science goal is to definitively confirm the lensing nature of the high-grade candidates. We plan to measure the redshifts of the sources (both arcs and QSOs) from bright emission lines (e.g., [OII], [OIII], Hβ) and at the same time pin down the lens spectra in absorption (e.g, 4000Å break, CaII, Fe and Mg), obtaining also their velocity dispersion, where the S/N will allow such analysis. A wide optical wavelength coverage is thus needed in order to maximize the likelihood of identifying emission lines from the sources (generally with redshift between 0.5 and 3) as well as absorption features from the lenses (typically z<0.5 early-type galaxies, ETGs) and a resolution of R~1000 is enough to derive the velocity dispersion of the lenses.

Thus, we require 1.5" long-slit observations with RSS and the PG0900 grating, covering from 3200 to 9000 Å, with a resolution in the range R = 600-2000.

Our targets, selected from the KiDS and KABS Surveys, are distributed over large fractions of the sky and are observable in the whole semester with good airmasses (see Fig. 2).

We define our observing strategy, described hereafter, based on our experience with previous SALT observations and data reduction (see also example in Fig. 3) and on the attached RSS ETC estimates for the different cases.

<u>QSO lensing:</u> In this case there are two main challenges: 1. Often the separation between the multiple lensed quasar images is very small (sometimes below 1 arcsec). 2. The signal of the lens is often blended and contaminated by the bright QSO components. We therefore need excellent seeing constraints for our observations. **Considering the typical brightness of our lensed-QSO candidates (i.e., i<21), a seeing of 1.5'' and dark time, we find that a total exposure time of 1800 s (2700 s including 900 s overheads) is sufficient to reach S/N > 10 (per resolution element).** The total scientific exposure would be carried out divided in 3x600 s dithered exposures, to facilitate sky subtraction and cosmic-ray removals.

<u>Galaxy lensing:</u> The most demanding task here is the determination of the redshift from the background object, often much fainter than lensed-QSOs and spatially diluted. **Using a typical integrated flux along the arcs of r=22-23, a seeing of 1.5'' and dark time**, **we calculate that 2700 s (3600 s including 900 s overhead) per candidate, divided in 3x900 s dithered exposures, are enough to have S/N~5 (per resolution element).** This will allow us to a) determine the redshift of the background source by detecting its emission lines and b) detect both the continuum and the absorption lines of the foreground lens (usually bright ETGs) at a S/N>>10, enabling to also constrain the lens velocity dispersion.

To achieve all our goals we require good seeing/sky conditions; therefore, a P1/P2 allocation is preferred. However, for large separation QSO lensing systems and bright lensed arcs, P3 allocation should still allow us to obtain estimates of the redshifts.

In conclusion, **we ask for a total of 42 hours, to observe 30 QSOs and 20 arc/ring candidates.**

20. REFERENCES

A list of all relevant references.

Agnello et al. 2015, MNRAS, 448, 1446; Agnello & Spiniello 2018, arXiv:1805.11103; Anguita et al. 2008, A&A, 480, 327; Blandford & Narayan 1992, ARA&A, 30, 311; Barnabè et al. 2011, MNRAS, 415, 2215; Barnabè et al. 2013, MNRAS, 436, 253; Bonvin V., et al. 2017, MNRAS, 465, 4914; deJong et al. 2015, A&A, 582, A62; deJong et al. 2017, A&A, 604, A134; Jimenez-Vicente et al. 2015, ApJ, 799, 149J; Koopmans et al. 2006, ApJ, 649, 599; Lanusse et al. 2018, MNRAS,473,3895; Mao & Schneider 1998, MNRAS 295, 587; Marshall et al. 2007, ApJ, 671, 119; Negrello et al. 2007, MNRAS, 465, 3558; Ostrovski et al. 2017, MNRAS, 465, 4325; Petrillo et al. 2017, MNRAS, 472, 1129; Petrillo et al. 2018, arXiv:1807.04764; Refsdal 1964, MNRAS, 128, 307; Rusu et al. 2014, MNRAS, 444, 2561; Sluse et al. 2011, A&A, 528, A100; Shu et al. 2016, ApJ, 824, 86; Spiniello et al. 2012, ApJ, 753, L32; Spiniello et al. 2015, ApJ, 803, 87; Spiniello et al. 2018, arXiv:18051.2436 ; Suyu, et al. 2014, ApJ, 788, L35; Vegetti & Koopmans 2009, MNRAS, 400, 1583; Tortora et al. 2010, ApJ, 721, L1; Tortora et al. 2018, arXiv:1806.01307

21. ADDITIONAL RELEVANT FIGURES AND GRAPHICS

Any additional figures or graphics not already inserted in the text boxes can be placed here, provided the 4 page limit is maintained.

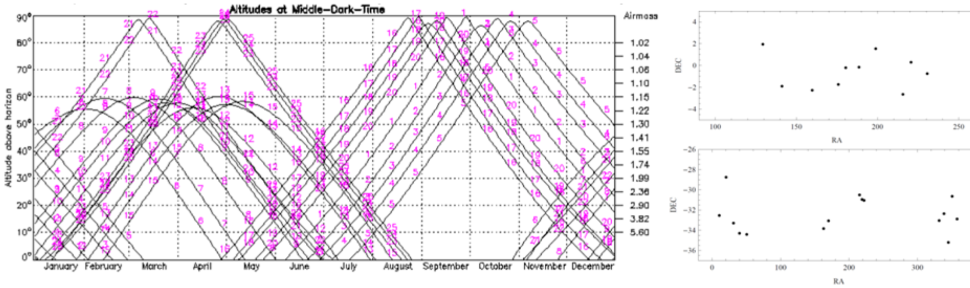


Figure 2: Visibility diagram of a sample of 25 selected lens candidates from the KiDS and KABS surveys (left panel). Right ascensions (RA) and declinations (DEC) of the 25 candidates in the equatorial (right-upper panel) and southern (right-lower panel) fields. These diagrams demonstrate that our targets are distributed across large areas of the sky and are observable for the whole semester. In order to not clutter the visibility plot, we just show visibility and RA-DEC diagrams of 25 out of 50 candidates. Notice that the rest of the candidates follow the same spatial and visibility distribution. Only two example lenses (1 lensed QSO and 1 arc), together with two dummy targets, are included in the target list in Sec. 12, and the same systems are used to generate the instrument simulations in Sec. 15.

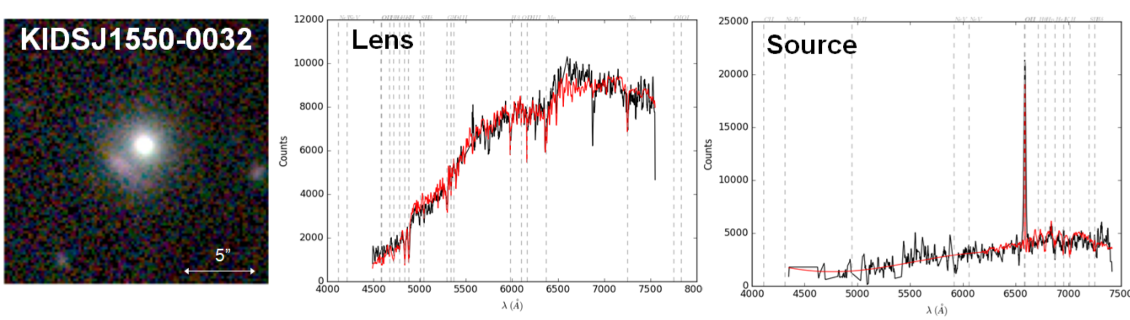


Figure 3: KIDS J1550-0032, the first KiDS lens candidate, discovered using CNNs in Petrillo et al. (2017), and validated with SALT, with the same configuration and averaged exposure time requested in the present proposal. This candidate was in fact added in the observing queue of the SALT program 2015-2-MLT-006 (PI: Serjeant) as a P3/P4 filler target for when no other target was available and observed in semester 2017-2.

The left panel shows a 20"x20" rgb cutout, whereas middle and right panels show extracted spectra for the lens and the source, respectively. Black lines are the observed spectra, while red lines are the best fitted template spectra. We find a lens redshift of z=0.23 (confirming our photometric redshift estimate) and a source redshift of z=0.77, confirming the lensing nature of KIDS J1550-0032. This pilot observation demonstrates that our observing strategy works and that the integration times are well calculated.