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THE CFHTLS STRONG LENSING LEGACY SURVEY

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Abstract. This communication presents the CFHTLS Strong Lensing Legacy Survey (SL2S). Thanks to the unsurpassed combined depth, area and image quality of the Canada-France-Hawaii Legacy Survey it is becoming possible to uncover a large statistically well-defined sample of strong gravitational lenses which spans the dark halo mass spectrum predicted by the concordance model from galaxy to cluster haloes. We describe the innovative technical efforts concerning the development of several automated procedures to find strong lenses of various mass regimes in CFHTLS images. A preliminary sample of 40 strong lensing candidates has been discovered in the CFHTLS T0002 release covering an effective field of view of 28 deg^2. These strong lensing systems consist mainly of gravitational arc systems with splitting angles between 2 and 15 arcsec. Interestingly, this sample shows that it is possible to uncover for the first time a large population of strong lenses from galaxy groups with typical halo mass of about $10^{13}h^{-1}M_{\odot}$. The SL2S project main scientific aims are (i) to determine the dark matter halo mass spectrum (ii) to constrain the dark matter halo evolution (iii) and to quantify their influence on galaxy and galaxy-group formation and evolution.

1 Introduction

In recent years, accurate measurements of cosmological parameters have led astrophysicists to a concordance cosmological model in which the Universe is made of ∼4% of baryonic matter, ∼26% of non-collisional (cold) dark matter (CDM) and ∼70% of a negative pressure dark energy driving the observed acceleration of the Universe expansion. Gravitational instabilities of initial density perturbations resulted in a hierarchical growth and clustering of dark matter haloes that produced the present-day observed Universe from galactic scales to the largest structures (galaxy clusters, filaments). This model provides a satisfactory description of the origin and evolution of linear-scale clustering, as it has been widely confirmed by the halo mass spectrum derived from CDM numerical simulations. But on smaller (galaxy) and intermediate (group and cluster of galaxies) scales, the concordance model is less successful in explaining important properties of the visible Universe and their relations with dark matter. Numerical simulations still fail to reproduce several observational results, mostly because of the complexity of non-linear physical processes involved. Astronomical observations of light and mass distributions are therefore key ingredients to provide insights on the relations between light and mass and the transitions from linear to non-linear evolutions of haloes.

Observation of gravitational lensing effects produced by mass concentrations is a powerful tool to probe directly the dark matter haloes and their interplay with visible mass. Both strong and weak lensing regimes are therefore widely used to explore the dark matter distribution properties, either from observation of individual spectacular cases or from statistical analyses of large samples of lensed galaxies or quasars.

1.1 *Total mass on galaxy scales*

On galaxy scales, ongoing lens surveys are now providing reliable descriptions of galaxies and a rather clear understanding on the key issues regarding the star and dark matter distributions. Using a large sample of

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well-studied strong lenses, it is possible to describe galaxy structure and the transition between the inner stellar matter-dominated and the outer dark matter-dominated galaxy haloes, without being sensitive to the mass-sheet degeneracy. It complements well galaxy-galaxy lensing methods that explore galaxy haloes on much larger scales. Past serendipity surveys (APM; Hewett et al. 2000) and the recent systematic Sloan Lens ACS survey (SLACS; Bolton et al. 2006), outline the strengths of well-defined samples over sparse ones for galaxy scale masses. However the SLACS is limited to small rings (<3") and to nearby lenses ($z_{max}(lens) \leq 0.3, z_{max}(source) \leq 0.6$). An extension of the method to larger redshifts should enlarge the sample significantly and will benefit from the higher efficiency of strong lensing at redshift ~ 0.5 for galaxy sources at redshift above 1.

1.2 Total mass on cluster and group scales

An important issue of dark haloes evolution is to understand the transition between galaxy-scale to cluster-scale halo structures. Quasar lenses and gravitational arcs have mostly probed two regimes of halo masses: galaxies and clusters of galaxies, but bring only weak constraints on the intermediate mass range ($10^{12} - 10^{14}$ M$_\odot$) which is so important for the assembling of large scale structures. The study of groups of galaxies in the CNOC survey using weak lensing (Parker et al. 2005) yielded the first constraints of their averaged mass-to-light ratios but nothing on their inner structures nor whether groups are self-similar.

As for giant arcs in clusters of galaxies, large optically selected samples of strong lensing groups of galaxies are not available yet. The Red-sequence Cluster Survey (Gladders et al. 2003) is probably the first attempt to systematically find strong lensing around cluster and groups of galaxies. However their relatively low detection sensitivity has lead to the discovery of only eight cluster-like structure at $z > 0.64$ over a 90-deg^2 field.

1.3 Strengths of the SL2S

No homogeneous sample of strong lenses have been built so far that cover the full dark matter halo mass spectrum because of the lack of a large, deep sky survey with a sub-arc-second seeing. We show here, that the combined depth, area, and exquisite image quality of the CFHT Legacy Survey (CFHTLS) enable us to find strong lensing systems around a wide mass spectrum of structures. Indeed, the three 7×7-deg^2 wide patches together with the four 1×1-deg^2 deep patches of CFHTLS allow us to build up a large sample of strong galaxy-, group-, and cluster-scale lenses with a well-defined selection function and sampling variance, as well as to explore halo properties at different depths and redshifts. Using the most recent simulations (lensing optical depths) of Oguri (2006), we predict typically, for any giant arc detected in a cluster, about 4 times more arc(et)s systems in haloes corresponding to group masses, and 20 times more gravitational rings associated with lens galaxy haloes (assuming equivalent detection limit and angular magnification). The preliminary number of group-lenses, based on the first (beta) version of the arc detection software, is found to be $\sim 0.5\,\mathrm{deg}^{-2}$ in the CFHTLS data. Extrapolating Oguri's distribution to the total area of the CFHTLS Wide component (170 deg^2) yields ~ 75 group arcs, ~ 400 galaxy rings, and ~ 20 cluster arcs: the largest sample to date.

2 Automated software for Strong Lensing candidates detection

One of the primary objectives of the SL2S is to provide a complete and homogeneous sample of strong lenses with known detection efficiency with regard to a series of observational parameters. This quantitative approach requires a prior automation of the detection procedures. Even if the total number of lenses in the CFHTLS will be large, the number density of lenses will be small per Megacam field whatever the deflector mass regime (cluster, group or galaxy). We are currently developing three complementary algorithms optimized for various regimes of strong lensing. The first one is a gravitational ARC detector (mostly for groups and clusters). The second is a detector of compact $RING$ candidates (which will then require higher resolution images for meaningful modelling). The third one is a $MULTIPLET$ detector for other classes of badly resolved multiple image systems. We will only briefly describe the first two programs, the last one is still in a preliminary stage. Note that all these methods will ultimately require subsequent spectroscopic confirmation.

2.1 ARC detector

Giant arcs are in principle the most straightforward images to identify and detect through a direct pattern recognition (Lenzen 2004). They are known to occur around massive clusters ($> 10^{14}h^{-1}M_\odot$) and show radii

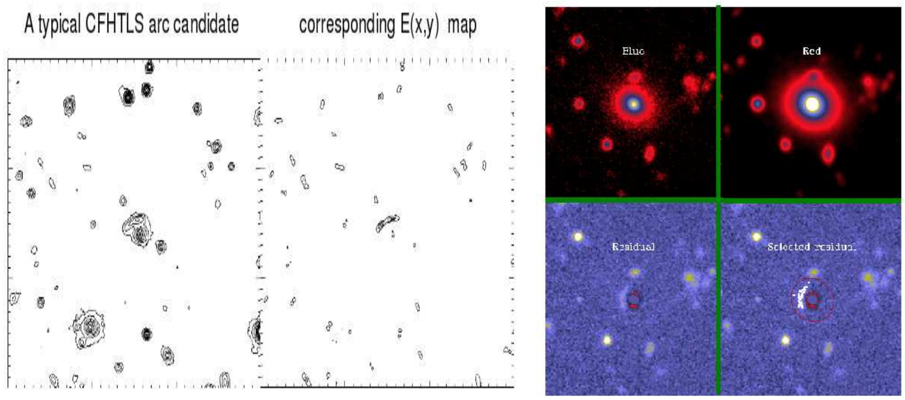

Fig. 1. Left: example of an elongated structure detected by ARC around an elliptical deflector (Alard 2006), Right: example of a compact ringlet identified by RING.

up to ∼40" in very luminous X-ray clusters. When arcs appear around groups of galaxies, their radii are five to ten times smaller and the seeing makes them more difficult to identify from ground-based imaging. A full description of the technique overcoming this difficulty is given elsewhere (Alard 2006). The arc-detector algorithm detects elongated structures. Once a set of pixels is identified as a potential candidate, we compute its general properties, size, color, curvature, etc. To ease the pattern recognition the routine also requires both the $g' - i'$ color and surface brightness of the elongated objects to be constant. Finally we produce a catalogue of candidates and a set of associated color images for visual inspection according to a selected set of parameters that fully describe the detection procedure.

The arc detector is very efficient at detecting extremely faint arcs over a large range of splitting angles and will be used on subsequent CFHTLS releases.

2.2 RING detector

The ring detector is aimed at detecting compact rings around centers of isolated galaxies ($< 10^{13}h^{-1}M_\odot$). Most of the ring radii are in the range 0.5-2.0" and rings are usually hidden within the deflector. Seeing and intrinsic galaxy morphologies, like dust lanes and face-on spirals, conspire to make the ring detection challenging. The basic ingredients of the procedure are the following. Presently, we focus on the 4 Deep fields which have been observed in 5 filters and for which multi-color photometric catalogs are built. We select all objects catalogued as E/S0 galaxies in the CFHTLS catalogs created with HyperZ (R. Pelló, private communication), which returns the photometric redshift estimates, the best-fit spectral type and information of the absolute magnitudes in different spectral bands. The routine filters out the large scale light distribution of the deflectors, by creating normalized $g' - i'$ color images of all the potential deflectors or by simply subtracting out a simple spline profile via direct fitting or wavelet filtering on each broad-band images. The routine selects the lens candidates based on the computed residuals above sky noise in the range 0.5-1.5". We are testing and optimizing the method thanks to a first training sample of 10 lens candidates common to the COSMOS field (HST/ACS imaging, Faure et al. 2006) and the CFHTLS-D2 field. The first results are encouraging: most of the rings with radii larger than 0.8" seem to be recovered. In short, the method is able to select among a great number of massive ellipticals a small number that have a good chance to be actually a strong lensing event.

3 CFHTLS-SL2S release T002 preliminary sample

The CFHTLS Terapix release T0002 is described in `http://terapix.iap.fr`. It covers an unmasked area of 28 deg^2, to a depth of $I_{AB} < 24.5$ at subarcsec seeing. In a nutshell, the preliminary sample of Terapix release T0002 is made of 40 lenses spanning a broad range of arc radii, up to a redshift of ∼1 (fig 2). The CFHTLS-SL2S seems to be especially sensitive to a class of lenses rarely observed until now, where the lensing deflector is a galaxy group with arc radii ranging 2.5"-7" (20 candidates out of 40). The rest of the sample

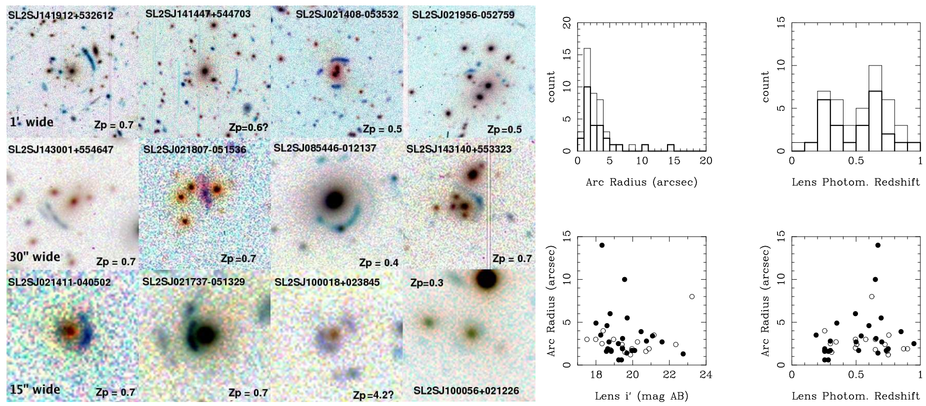

Fig. 2. Left: Mosaic of selected SL2S candidates of CFHTLS Terapix release T0002, outlining the richness of galaxy group lenses. Right: photometric redshifts and arc radii of the full sample SL2S Terapix release T0002 sample.

is divided into giant arcs lensed by massive clusters, and very compact arc, singly highly magnified objects or rings surrounding massive isolated ellipticals.

4 CFHTLS-SL2S observational follow-ups and science goals

The prime objective of the SL2S, to build a well-defined statistical sample, requires detailed simulations as well as complete sets of follow-up observations. Simulations are scheduled in the coming year as soon as the detection techniques are optimized. A high-resolution imaging program with HST has started in Cycle 15 to allow fine-tuned modelling of the SL2S candidates. Spectroscopic observations on 8-m class telescopes are indispensable to get precise redshifts for the lenses (massive galaxies and group/cluster membership) and the sources, and proposals on all facilities are regularly submitted. Additional X-ray data (XMM-LSS) as well as SWIRE and COSMOS data are available on sub-areas of the SL2S and will ultimately provide a very complete database.
The science goals of the SL2S can be summarized as follows: (i) to constrain the dark matter halo evolution (ii) to determine the dark matter halo mass spectrum (iii) to quantify the dark matter halo influence in galaxy and galaxy-group formation and evolution (in parallel to the X-ray and visible properties).

An overview of the SL2S is available at `http://www.cfht.hawaii.edu/~cabanac/SL2S/` , or Cabanac et al. (2006).

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