The SINFONI Nearby Elliptical Lens Locator Survey (SNELLS)

Russell J. Smith[1]
John R. Lucey[1]
Charlie Conroy[2]

[1] Centre for Extragalactic Astronomy, Durham University, United Kingdom
[2] Harvard Smithsonian Centre for Astrophysics, Cambridge, USA

The SINFONI Nearby Elliptical Lens Locator Survey (SNELLS) is a novel search for strong gravitational lenses among the local early-type galaxy population (redshift $z_{lens} < 0.055$). Observations of lensing by nearby galaxies can provide especially robust measurements of stellar mass in galaxies, with minimal corrections for dark matter contributions. In turn this leads to constraints on the initial mass function (IMF), i.e., the relative number of stars as a function of their mass at birth. To date, we have discovered two new multiple-image systems, and recovered the one previously known example. Analysing all three systems, we find the mean stellar mass-to-light ratio in these very massive early-type galaxies is consistent with a Milky Way IMF, in contrast to the "heavy" IMFs derived for ellipticals in some recent studies.

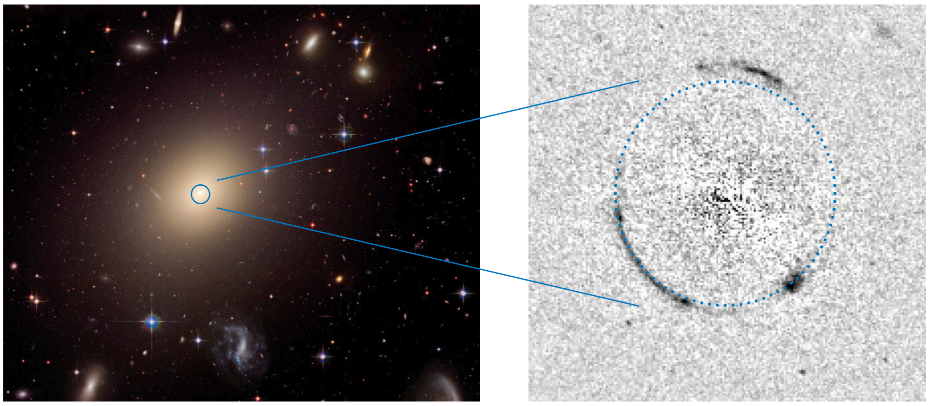

Figure 1. HST imaging of ESO325-G004, the only low-redshift strong-lensing elliptical galaxy known prior to the SNELLS programme. The left panel shows a colour composite (filters F475W, F625W, F814W) from the Hubble Heritage project. The right panel shows the $z = 2.14$ gravitationally lensed arcs (F475W data after subtracting a smooth model for the foreground lens). The Einstein radius is shown by the blue circle.

Nearby lenses as IMF probes

The stellar initial mass function controls a multitude of galaxy properties, including their evolving luminosities, supernova rates, element abundances, content of exotic stellar remnants, etc. The IMF is also the key output from theoretical star formation models. The question whether all stars are formed according to the same IMF as in the Milky Way thus has broad relevance to many fields of astrophysics.

The spectra of giant elliptical galaxies, which formed most of their stars in intense bursts at high redshift, show signatures of an excess of low-mass stars, indicating a "bottom heavy" IMF compared to the Milky Way (Conroy & van Dokkum, 2012). Measurements of large stellar mass-to-light ratios ($M_{☆}/L$), via lensing (e.g., Treu et al., 2010) and dynamical (e.g., Cappellari et al., 2013) analyses seem to support this result on average, although careful comparison reveals substantial scatter at a galaxy-by-galaxy level, and differences in the trends with mass (Smith, 2014).

Galaxy-scale strong gravitational lensing can provide robust measurements of the total mass in galaxies, with errors of only a few percent in favourable cases. With no dependence on the dynamical or thermal state of tracer material, lensing is free from many of the degeneracies afflicting other mass probes. The most challenging step in deriving IMF constraints from such measurements is to estimate the fraction of the lensing mass comprised by stars, rather than dark matter. In "typical" lens systems, where the deflector galaxy is at $z = 0.2$–0.5, the dark and stellar components contribute comparable mass within the Einstein radius, R_{Ein}. As a result, IMF variations are hard to decouple from modifications to the inner dark matter halo profile, e.g., halo "contraction" in response to the stellar component.

The sensitivity of lensing-based IMF estimates to the dark matter component can be reduced by analysing lenses at lower redshift, where R_{Ein} is generally smaller, compared to the effective radius of the stellar distribution. Another advantage of low-redshift lenses is that detailed follow-up observations can be made to characterise other relevant properties, e.g., high signal-to-noise (S/N) spectra for age and metallicity estimates, spatially resolved spectroscopy for detailed dynamical modelling, etc.

Until recently, however, there was only one confirmed strong-lensing giant elliptical at $z < 0.1$. ESO325-G004 was identified as a lens through high-resolution imaging with the Hubble Space Telescope (HST), which revealed a system of arcs forming a partial Einstein ring (Figure 1). The redshift of the arcs was measured with X-shooter, securing a measurement of the total mass within R_{Ein} (blue circle in Figure 1, left). After correction for the small dark-matter component, the estimated stellar mass-to-light ratio $M_{☆}/L$ is found to be compatible with a Milky Way IMF (Smith & Lucey, 2013).

The results for ESO325-G004, and the apparent contrast with evidence for heavy IMFs in such galaxies, prompted us to begin a search for other strong lenses among the low-redshift ellipticals. Our aim is to construct a statistically useful sample of nearby lenses, with which to test for variations in the IMF in massive ellipticals as compared to the Milky Way.

An infrared integral field lens search

The characteristics of our search method can best be described through comparison to the Sloan Lensing ACS Survey (SLACS), introduced by Bolton et al. (2006). SLACS was a very successful

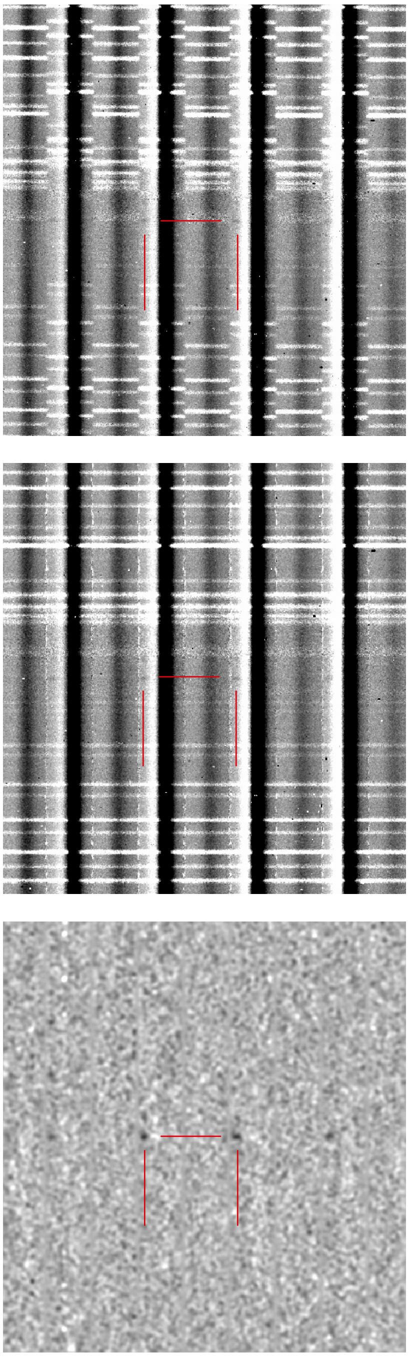

Figure 2. Detection of emission lines from the SNELLS data. The first panel shows a small section of the raw A - B difference image from the observation of SNL-1. Parts of nine image slices are visible. The lens galaxy produces the bright positive and negative vertical traces; horizontal lines are residual sky. The second panel shows the reduced difference image after wavelength calibration. The third panel shows the "detection" image, after removing residual sky and lens galaxy signals, normalising by the noise, filtering bad pixels, and smoothing. The Hα emission line at $z = 0.926$, inconspicuous in the upper panels, is readily detected after this additional processing.

spectroscopic lens discovery programme, based on detecting anomalous background emission lines in Sloan Digital Sky Survey (SDSS) fibre spectra. Searching $\sim 10^5$ potential lenses, a total of 84 systems were identified as suitable for lensing analysis, after confirmation with HST imaging. The survey yield is thus one lens per ~1000 observed candidates.

An important limitation of the SLACS approach is its use of a single "global" spectrum derived from the SDSS fibre aperture: the faint lensed arc emission is observed against the whole integrated spectrum from the bright foreground galaxy, reducing contrast so that only systems with bright arcs can be detected. Since such lenses are rare, large volumes must be searched, with the result that SLACS samples rather distant galaxies, with $z_{lens} = 0.2$–0.3.

In SNELLS, we overcome this contrast problem by using integral field unit (IFU) data to concentrate the source flux spatially as well as spectrally. Since the lensed images are typically 1–3 arcseconds from the lens galaxy centre, the IFU allows us to detect arcs against a lower continuum brightness than in a single-fibre spectrum. Hence, we can detect more numerous (though less spectacular) faint sources. By using SINFONI (the VLT Spectrograph for Integral Field Observations in the Near Infrared) to observe in the near-infrared (NIR), we open up a larger search volume for [O III] and Hα emission lines behind each lens, as compared to the optical range, further increasing the number of detectable lens systems.

The SLACS search method has the inherent advantage of using pre-existing archival survey data, and hence incurring no new observational cost (although HST imaging follow-up is needed to model the lenses). In contrast our method requires new targeted observations, so we maximise discovery efficiency by pre-selecting the most promising lens candidates based on velocity dispersion, σ, as lensing cross-section scales as $\sim \sigma^4$.

Taken in combination, the heightened contrast (from the IFU), the greater search volume (from working in the NIR) and the increased efficiency (from targeting high-σ galaxies) leads to a much larger survey "yield" than for the SLACS method. Calculating from the evolving Hα luminosity function of Sobral et al. (2013), we predicted that our survey would be able to discover one lens per ~10 observed candidates, per hour of total exposure with SINFONI.

Implementation in ESO Period 93

For Period 93 we compiled a target sample using velocity dispersion data from the SDSS (Abazajian et al., 2009) and the 6dF Fundamental Plane Survey (Campbell et al., 2014). Candidate lenses were selected to have $z < 0.055$ and $\sigma > 300$ km s^{-1}. All targets were vetted to exclude objects with strong emission lines, unusual morphology, etc. We also rejected central cluster galaxies, which have much larger halo dark matter contributions; they are poor systems from which to estimate the stellar masses and are hence less suitable for use in constraining the IMF.

From a proposed sample of 36 galaxies, observations were acquired in *J*- and *H*-bands for 27 targets, including the previously known lens, ESO325-G004. We use the largest SINFONI image scale, delivering an 8 by 8 arcsecond field of view (cf., the expected Einstein radii of 2–3 arcseconds). A complete observation consists of two pointings, offset by 2.3 arcseconds, in *J*-band and two in *H*-band, with a single 600-second exposure in each pointing, per band.

After standard data reduction with the SINFONI pipeline, we perform additional processing to suppress the signal from the lens galaxy, as well as from the sky airglow lines. We identify emission lines through visual inspection of a two-dimensional signal-to-noise spectrum in "unwrapped cube" format (see Figure 2). For objects where emission peaks are detected, we construct narrowband images from the datacube, to locate the source, and extract spectra to determine the redshift.

Two new lenses, and an old one

In three of the candidates observed so far, we recover multiple emission-line sources with identical wavelengths

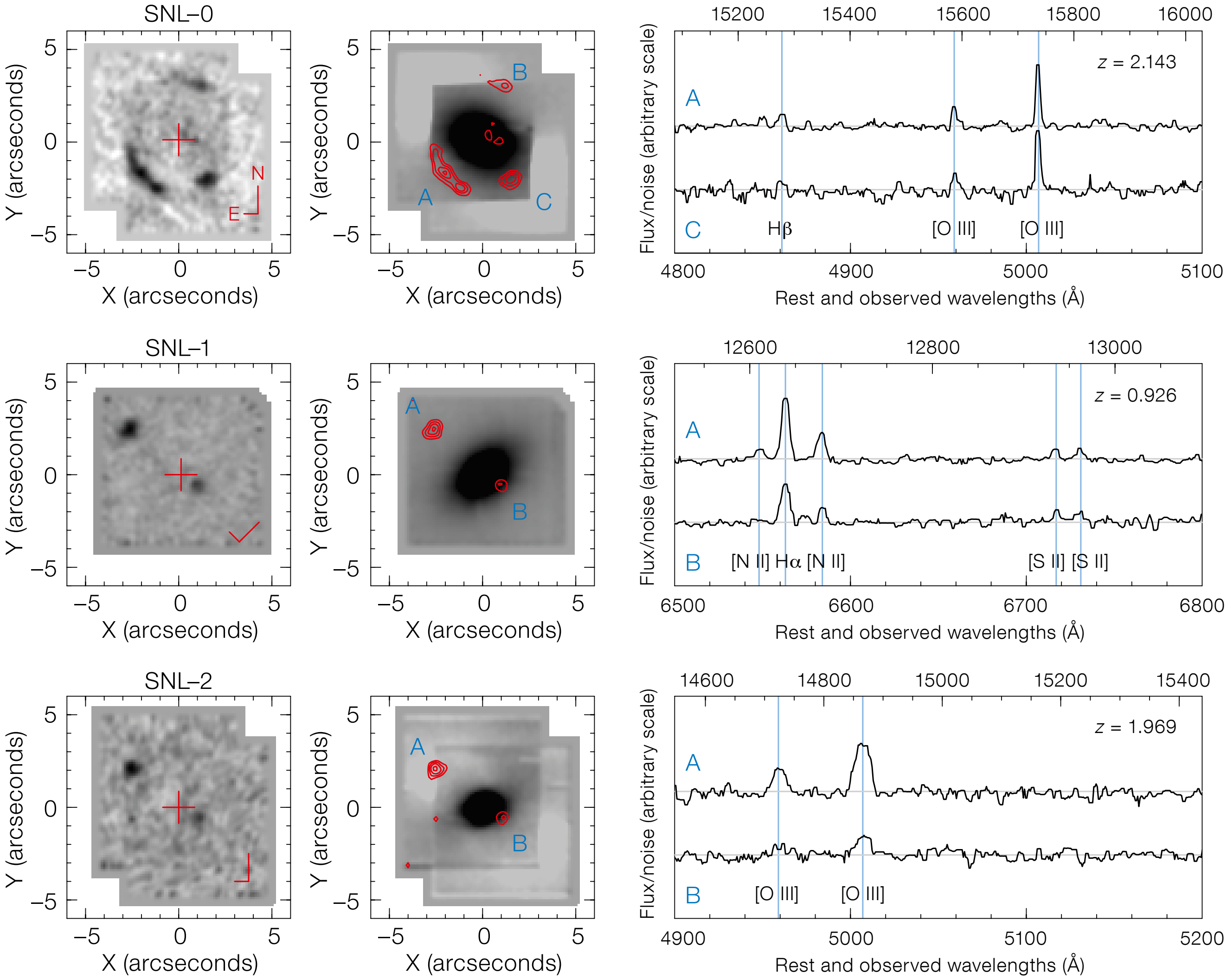

Figure 3. Source and lens images, and extracted spectra, (left to right) for the three SNELLS lens candidates. For each source, the first panel shows a narrowband, continuum-subtracted image extracted around the brightest line. (Hα for SNL-1, [O III] 5007 Å for SNL-0,2). The lens galaxy centre is marked by the red cross. The second panel shows the broadband image as greyscale, with contours indicating the narrowband flux, and source images identified. The third panel shows spectra extracted from the source (normalised by the errors to suppress sky subtraction residuals, hence strictly closer to signal-to-noise spectra). The strongest emission lines are indicated. From Smith et al. (2015).

(Figure 3). The interpretation of these systems as strong gravitational lenses is compelling. The delivered survey yield is thus consistent, so far, with our predicted "one-in-ten" discovery rate. Details of the three systems (SNL-0 to SNL-2) follow.

SNL-0 (ESO325–G004)

This system is the previously known low-redshift lensing elliptical, to which we assign the name SNL-0 within SNELLS. Although this galaxy was well studied in our earlier work, it was retained as a SINFONI target to test our search methods on a lens with known properties.

The SNELLS data for SNL-0 are shown in the top row of Figure 3. The emission-line image recovers most of the structure of the arc system as seen in HST images (compare with Figure 1, right), though some fidelity is lost through combining only two offset frames. The spectra show the strong [O III] 4959, 5007 Å doublet and weak Hβ line, as seen in X-shooter data (Smith & Lucey, 2013). No other lines were detected.

SNL-1 (ESO286–G022)

SNL-1 is an isolated, very compact galaxy, with an effective radius of only 2 kpc, but a total luminosity of ~1×10^{11} $L_\odot$ in the *J*-band. SuperCOSMOS and 2 Micron All Sky Survey (2MASS) images show an elongated but otherwise featureless morphology. The 6dF spectrum suggests an old passive stellar population, with weak Hγ and Hβ absorption, and no emission detectable at Hα or elsewhere.

As the first new discovery from SNELLS, the original data were supplemented with deeper Director's Discretionary Time (DDT) observations to confirm this galaxy definitively as a lens. SINFONI reveals a doubly imaged emission-line source in the *J*-band; additional lines confirm the source is Hα at a redshift of z = 0.926 (Figure 3, second row). The emission line sources are spatially unresolved in the SINFONI data. With $z_{\rm lens}$ = 0.031, SNL-1 is now the closest confirmed galaxy-scale strong lens.

SNL-2 (2MASX J01414232–0735281)
This object, with z_{lens} = 0.052, is part of a galaxy pair, with a fainter companion 7 arcseconds to the north (beyond the SINFONI field of view). SDSS imaging shows a faint outer envelope around both galaxies. SNL-2 itself has very regular morphology; its effective radius (6 kpc) and total luminosity (~ 3×10^{11} $L_{\odot}$ in *J*-band) are comparable to those of SNL-0. The 6dF spectrum is consistent with a pure passive stellar continuum.

The SNELLS data reveal emission in two noticeably broad emission lines consistent with the [O III] 4959, 5007 Å doublet, at a redshift of z = 1.969 (Figure 3, bottom row). The lines form two spatially unresolved images, quite similar to the case of SNL-1. No counterpart to the emission-line source is visible in the SDSS imaging.

IMF constraints

We apply simple lensing models for each galaxy to determine the Einstein radius, R_{Ein}, and the corresponding total projected mass, M_{Ein}. The total lensing masses have estimated precision of 5 % for SNL-0 and SNL-1, and 10 % for SNL-2, the latter being larger due to uncertainty in the shear from the companion galaxy.

To derive an estimate for the stellar mass within R_{Ein}, we estimate the dark matter contribution based on the projected halo mass profiles of similarly massive galaxies in the EAGLE cosmological hydrodynamical simulations (Schaller et al., 2015). Through this method, the dark matter fractions within R_{Ein} are estimated to be 16–26 %. With the stellar mass-to-light ratio in hand, we compare against the predictions from stellar population synthesis models to determine the deviation of the IMF from a fiducial Kroupa (2001) case. We quantify the IMF constraint through the mass excess factor α, which is the ratio of measured $M_{\star}/L$ to the value expected under the fiducial IMF. This step requires knowledge of the stellar population age. Our "default" assumption is that these very massive ellipticals formed all their stars at early epochs, with an age 10 ± 1 Gyr (formation redshift $1 < z < 4$, at two standard deviations).

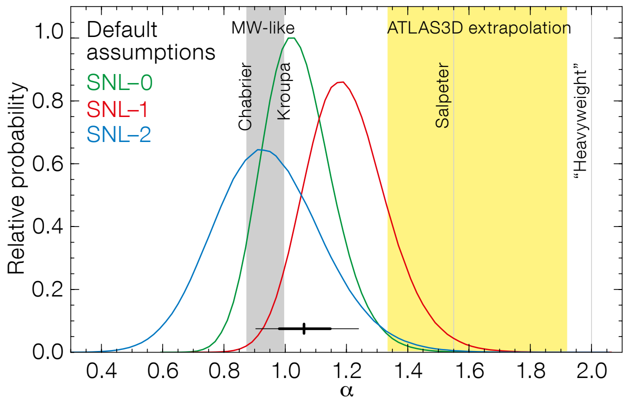

Figure 4. Constraints derived from the three SNELLS lenses for our "default" assumptions (see text). α is the mass excess factor, relative to a Milky Way IMF. The heavy/light bar below shows the $1\sigma/2\sigma$ intervals for the mean of the three SNELLS galaxies. All three galaxies have a mass-to-light ratio consistent with a Kroupa IMF. For comparison, the yellow shading indicates $\pm 1\sigma$ in α expected at the mean velocity dispersion of our sample, 345 km s^{-1}, based on the trend reported by Cappellari et al. (2013). From Smith et al. (2015).

Under our standard assumptions, we derive IMF mass excess factors of α = 1.04 ± 0.11, 1.20 ± 0.13 and 0.94 ± 0.17, for SNL-0, SNL-1 and SNL-2, respectively (see Figure 4). After a small correction for selection bias caused by the SINFONI field of view, the estimated mean is $\langle\alpha\rangle$ = 1.06 ± 0.08 (the quoted error is statistical; there is also a ± 0.10 systematic component which applies to all results here). Hence, individually, and on average, the lensing constraints for these three very massive ellipticals are consistent with a Milky Way IMF, old stellar populations and EAGLE dark matter profiles.

We have explored various modifications to our methodology and assumptions, finding that the preference for a standard IMF is quite robust. For example, if the stellar age of each galaxy is fit directly from the optical spectrum, instead of being assumed "old", we recover $\langle\alpha\rangle$ = 1.19 ± 0.15 after bias correction. This average is still consistent with the Kroupa (2001) IMF. Alternatively, if we assign all of the lensing mass to the stars, i.e., assume negligible dark matter, we find a mass excess of $\langle\alpha\rangle$ = 1.31 ± 0.09, still smaller the value of 1.55 expected for a Salpeter power law IMF.

These results are surprising, given the accumulated evidence for "heavy" IMFs in massive ellipticals from other studies. For example, to reproduce the gravity-sensitive spectral features in such galaxies, Conroy & van Dokkum (2012) require an IMF with an excess of cool dwarf stars, implying a large $M_{\star}/L$, and $\alpha \sim 2$ in the most massive galaxies. From the SLACS lenses, Treu et al. (2010) derived $\alpha \sim 2$ at $\sigma > 300$ km s^{-1}; from dynamical modelling of galaxies in the ATLAS3D survey, Cappellari et al. (2013) recover $\alpha \sim 1.5$ on average at high σ.

The causes of these apparent discrepancies are not yet understood; intercomparison between the various methods applied to the same set of galaxies will be crucial to resolving this puzzle. The SNELLS lenses provide a unique benchmark sample, for which the various methods (spectroscopic, dynamical and lensing) can all be applied, in bright nearby galaxies where excellent data quality can be obtained.

Ongoing work and prospects

The SNELLS lens search programme is continuing in Period 95, with an enlarged sample of candidates at $z_{lens} < 0.06$. Our aim is to double the number of low-redshift lenses, enabling us to: (a) provide tighter limits on the average α in very massive ellipticals; (b) determine the galaxy-to-galaxy scatter in α among such galaxies; and (c) test for correlations of α with other parameters (metallicity, compactness, etc.).

In parallel with the search programme, follow-up observations are underway to obtain uniform high-quality supporting data for the three lenses SNL-0, SNL-1 and SNL-2. With FORS2 we will acquire deeper and higher-resolution optical imaging than currently available for the three systems. Meanwhile, X-shooter will provide high-S/N spectroscopy over the full optical and NIR range, which will improve the direct constraints on stellar ages (obviating the need to assume old populations). The X-shooter observations will also yield measurements for the IMF-sensitive spectral features (e.g., Na I, FeH, etc.) in the far-red and NIR, for direct comparison against the lensing results for the same galaxies.

SINFONI is currently the only near-infrared integral field unit, on any large telescope, with sufficient contiguous field of view to perform this kind of survey efficiently. In the long term, we anticipate that with HARMONI on the European Extremely Large Telescope, it should be possible to detect faint lensed line-emitters behind any chosen massive elliptical, opening up the prospect of measuring strong-lensing masses "to order", rather than as a matter of luck.

Further details

A full description of the Period 93 lens search and our IMF results can be found in Smith, Lucey & Conroy (2015).

Acknowledgements

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Composite image (FORS1 *V*, *R* and *I* filters and Hubble Space Telescope *B*, *V*, *I*) of the galaxy cluster Abell 2744 (redshift 0.31), one of the Hubble Frontier Fields clusters. Abell 2744 is one of the most actively merging galaxy clusters and shows evidence of several merger events with prominent X-ray and dark matter substructures. Many background high redshift galaxies amplified by the gravitational lensing of the cluster have been identified.