

Discovery of two Einstein crosses from massive post-blue nugget galaxies at $z > 1$ in KiDS*

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ABSTRACT

We report the discovery of two Einstein Crosses (ECs) in the footprint of the Kilo-Degree Survey (KiDS): KIDS J232940-340922 and KIDS J122456+005048. Using integral field spectroscopy from MUSE@VLT, we confirm their gravitational-lens nature. In both cases, the four spectra of the source clearly show a prominence of absorption features, hence revealing an evolved stellar population with little star formation. The lensing model of the two systems, assuming a singular isothermal ellipsoid (SIE) with external shear, shows that: 1) the two crosses, located at redshift $z = 0.38$ and 0.24 , have Einstein radius $R_E = 5.2$ kpc and 5.4 kpc, respectively; 2) their projected dark matter fractions inside the half effective radius are 0.60 and 0.56 (Chabrier IMF); 3) the sources are ultra-compact galaxies, $R_e \sim 0.9$ kpc (at redshift $z_s = 1.59$) and $R_e \sim 0.5$ kpc ($z_s = 1.10$), respectively. These results are unaffected by the underlying mass density assumption. Due to size, blue color and absorption-dominated spectra, corroborated by low specific star-formation rates derived from optical-NIR spectral energy distribution fitting, we argue that the two lensed sources in these ECs are blue nuggets migrating toward their quenching phase.

Keywords: editorials, notices — miscellaneous — catalogs — surveys

1. INTRODUCTION

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* Based on observations with OmegaCam@VST and MUSE@VLT (Prog. ID: 0105.A-0253).

Strong gravitational lensing is a powerful tool to measure the distribution of Dark Matter (DM) in galaxies and study the properties of high-redshift sources. According to General Relativity, matter in the universe acts as a cosmic telescope deforming and magnifying the light of objects which would be hardly observable otherwise. Depending on the size of the source and the alignment of the foreground galaxy (lens or deflector) and the source, strong lensing events show-up as arcs or rings (when the source is extended, e.g. a galaxy) or as multiple images (when the source is a compact system, e.g. a quasar). Deformed images of background galaxies can be used, in combination with the dynamical and stellar population analysis of the deflector, to determine the lens total mass density profiles (e.g., Koopmans et al. 2006, Auger et al. 2010, Nightingale et al. 2019), to separate the dark from the luminous matter and to constrain the lens stellar initial-mass-function (IMF) slope (e.g., Treu et al. 2010, Spiniello et al. 2011). Furthermore, doubly (‘doublets’) or even quadruply-lensed (‘quads’) QSOs are particularly valuable for cosmology because they enable measuring the Hubble constant (H_0 , Suyu et al. 2013) via time-delays among the QSO light curves.

However, doublets and quads can also be produced by other compact sources, e.g. high-redshift, starforming, ultra-compact galaxies (e.g. Muzzin et al. 2012), which are fairly common at high- z . Using lensing forecasts from typical ground based surveys (Collett 2015) with a depth of the order of $r \sim 25$, the number of expected quads from compact galaxies ($R_e < 1$ kpc) at redshift $z \lesssim 4$, with an alignment sufficient to make a cross-like geometry (e.g. source misalignment $< 0.1''$), is of the order of half a dozen every 1000 deg² (see also §4). Unfortunately, only few of such systems have been observed so far: besides the Muzzin et al. (2012) system, only two Einstein Cross (EC) configurations from Ly- α emitters have been confirmed and fully analysed (Bolton et al. 2006, Bettoni et al. 2019). ECs are interesting *per se* as they are the rarest and most spectacular manifestation of quad systems, showing a distinctive symmetric cross pattern around the deflector, generated when the source and the lens are almost perfectly aligned. Generally, these systems have been found to be produced by distant quasars (e.g. Magain et al. 1988, Ostrovski et al. 2018) or supernovae (aka Refsdal system, Kelly et al. 2015).

Within the Kilo-Degree Survey (KiDS, de Jong et al. 2015), we have undertaken a systematic search for strong gravitational lenses, both arcs (Petrillo et al. 2017, P+17 hereafter, Petrillo et al. 2019a,b) and multiple images (Spiniello et al. 2018, 2019). In particular, in the process of improving the overall efficiency of the Convolutional Neural Network (CNN) finders, started with P+17, we have collected, in an area of ~ 1000 deg², a series of high quality quad candidates (Li et al. 2020, Li+20 hereafter), among which we found three clear EC configurations.

In this paper we report the results of the spectroscopic follow-up of the best two of them. We argue that these represent a new class of sources of EC configurations, i.e. high- z post-blue nugget systems, and discuss the possibility to systematically search for these objects in current and future ground and space surveys. For all calculations, we assume a Λ CDM cosmology with $(\Omega_M, \Omega_\Lambda, h) = (0.3, 0.7, 0.7)$.

2. CONFIRMATION AND LENSING MODEL

The first EC, KIDS J232940-340922 (KIDS-EC1, hereafter, see Fig. 1), has been found in the Southern KiDS patch. The deflector has a AB magnitude of $r \sim 19.8$ and red color, $g - i = 1.4$, while the average magnitude of the 4 lensed images of the source is $r \sim 22.6$ and their average color is $g - i = -0.21$. The second EC, KIDS J122456+005048 (KIDS-EC2, hereafter, Fig. 1), has been found in the Northern KiDS patch. The deflector has total magnitude $r \sim 19.7$ and color $g - i = 1.9$, while the 4 images have an average magnitude $r \sim 22.0$ and average color $g - i = 1.0$, i.e. bluer than the deflector but redder than KIDS-EC1 source. The two sources have obtained a high CNN probability and also high human visual score (see Li+20), hence they have been selected for the spectroscopic follow-up. Table 1 lists coordinates, relative positions of lens and source images and the optical and near-infrared (NIR) photometry in the *ugriZYZJK_s* bands, for both ECs. To minimize the relative contamination and derive homogeneous photometry for all sources, the 9-band photometry of lens and lensed images are derived by a simultaneous seeing convolved Sérsic plus 2D Gaussian fit of the objects, respectively, from KiDS-DR4 (Kuijken et al. 2019) and VIKING (Edge et al. 2013) calibrated images.

2.1. MUSE spectroscopy and lensing confirmation

Spectroscopic observations have been collected under ESO Directory Discretionary Time (program ID: 0105.A-0253, PI Napolitano) with MUSE at VLT, Cerro Paranal. Run A has been completed in November 2019 for KIDS J232940-340922 and Run B on February 2020 for KIDS J122456+005048. Observations have been taken in service mode, in wide-field non adaptive optic configuration, which allows a full $1' \times 1'$ field of view, in the wavelength range $\lambda = [4750, 9300]$ Å. The MUSE grating spectral resolution varies from 1750 to 3750, end-to-end, in the same interval.

The total exposure time for both targets is 130 minutes divided in 3 observing blocks (OBs). Every OB is split in $2 \times 1300s$ exposures with a 90deg position angle offset. The final seeing of the combined exposures is $0.93''$ for KiDS-EC1 and $0.84''$ for KiDS-EC2.

Reduced data have been provided by ESO as Internal Data Products, using the official MUSE pipeline (v2.8). For KiDS-EC1 we have also performed our own data-reduction to check consistency with the ESO Phase 3 data products, using the same pipeline. We have found very consistent spectral quality, in terms of flat fielding, signal-to-noise-ratio (SNR) and sky subtraction. A zoom-in of the field-of-views (FOVs) of the EC datacubes (i.e. the integrated flux over all wavelengths) are reported in Fig. 1, and clearly show all sources seen in the KiDS *gri* color images (also shown in the same figure). In Fig. 1, we also present the 1D spectra from the four lensed images, extracted from a single MUSE pixel, and the one of the corresponding deflector, extracted over an aperture of 3 pixels for KIDS-EC1 and 4 pixels for KIDS-EC2 respectively, corresponding to about half of the effective radius, $R_e/2$, see §2.2. We use these apertures because they allow us to minimise the contamination from the blue lensed sources. For both systems, the lensing nature is confirmed by the presence of identical spectral features in the four different images, all consistent with the same redshift, higher than the one of the lens. For KIDS-EC1, we infer a redshift of $z = 1.590 \pm 0.001$ from Fe and Mg absorption lines and faint [FeII] ($\lambda = 5650\text{\AA}$), [CII] ($\lambda = 6025\text{\AA}$) and [OII] ($\lambda = 6400\text{\AA}$) emissions. For KIDS-EC2, we calculate instead $z = 1.102 \pm 0.001$, from the spectrum at $\lambda > 7800\text{\AA}$, including Balmer absorption lines (H10 at $\lambda \sim 7980\text{\AA}$, H9 at $\lambda \sim 8060\text{\AA}$, H8 at $\lambda \sim 8180\text{\AA}$, H ϵ at $\lambda \sim 8350\text{\AA}$ and H δ at $\lambda \sim 8620\text{\AA}$), the Calcium K and H doublet (at $\lambda \sim 8360 - 8450\text{\AA}$), although with some sky contamination in H, and a clear [OII] doublet emission line at $\lambda \sim 7850\text{\AA}$. In this latter case Fe and Mg absorption lines are also present but look slightly blue-shifted, possibly due to some gas outflow from the source galaxy (see e.g. Rubin et al. 2014; Burchett et al. 2020), which we will investigate in a forthcoming paper.

The two deflectors reveal typical features of early-type galaxies (ETGs), in particular a strong rest-frame break at 4000\AA , faint Balmer lines in absorption, and Fe, Mgb and NaD lines, all characteristic of an old, metal rich stellar population. The inferred deflector redshifts are $z_1 = 0.381 \pm 0.001$ for KIDS-EC1, and $z_1 = 0.237 \pm 0.001$ for KIDS-EC2. The SNR and resolution of the spectra allow us to estimate the velocity dispersion of these two systems using the pPXF software (Cappellari 2017), yielding $\sigma_{R_e/2} = 192 \pm 4 \text{ km s}^{-1}$ for KIDS-EC1 and $\sigma_{R_e/2} = 248 \pm 2 \text{ km s}^{-1}$ for KIDS-EC2¹ (see also Table 2). The best-fit models are overlaid on the galaxy spectra in the same Fig. 1.

2.2. Lensing model, dynamical masses, dark matter fractions

The two ECs are modelled using the *lfit_gui* code (Shu et al. 2016). We use KiDS *r*-band images, with a pixel scale of $0.2''$ and seeing $0.8''$ for KIDS-EC1 and $0.7''$ for KIDS-EC2. The effect of the seeing is taken into account by convolving the lensing models with a point spread function (PSF) generated by nearby stars (see e.g., Roy et al. 2018). The *lfit_gui* code simultaneously models the deflector light, the lensed image positions and their magnification, and the best position and light distribution of the source galaxy. We assume a single Sérsic profile (Sérsic 1963) for the two deflectors, although for KIDS-EC2 we need to account also for the presence of two nearby galaxies (G1 and G2, respectively, see Fig. 1), as well as for the two sources. The deflector total mass distributions are modelled with a singular isothermal ellipsoid (SIE, Kormann et al. 1994) profile with a projected two-dimensional surface mass density profile described by:

$$\Sigma(x, y) = \frac{1}{2} \Sigma_c \sqrt{q} \theta_E (x^2 + q^2 y^2)^{-1/2}, \quad (1)$$

where θ_E is the lensing strength, equivalent to the Einstein radius, q is the minor-to-major axis ratio of the isodensity contours. $\Sigma_c = c^2 / (4\pi G) (D_s / D_d D_{ds})$ is the critical density, where D_s and D_d are the angular diameter distances from the observer of the lens and the source, respectively, and D_{ds} , the distance between deflector and source. The assumption of a SIE model is motivated by evidence pointing toward a logarithmic mass-density slope close to -2 for the total mass density around the Einstein radius (e.g. Koopmans et al. 2006), however the impact of this assumption is discussed in Appendix, while a full modeling with more general density profiles will be presented in future detailed analyses. We also include external shear, γ_{ext} , which approximates the influence of the surrounding environment on the lensing potential. After having initialized the model, with some test runs, the final best-fit of the two ECs are obtained via χ^2 minimization using the Levenberg–Marquardt algorithm (Moré 1978). These are shown in Fig. 2, and the corresponding parameters are reported in Table 2. From the Table, we can draw some first general results: 1) the

¹ We estimate that systematic errors from template mismatch and masked regions may amount to $\sim 20 \text{ km s}^{-1}$.

two ECs show similar Einstein radii, R_E , which are both very close to the lens effective radii, R_e (i.e. $R_E/R_e \sim 0.9$); 2) the stellar velocity dispersion measured from the spectrum of KIDS-EC1 is smaller than that inferred by the lens model, suggesting that the actual slope of the total density profile might deviate from -2 (see e.g. Auger et al. 2010 and the discussion in the Appendix), while the two values are consistent within 2σ for KIDS-EC2; 3) for both lenses, the total mass may be rounder than the starlight distribution (i.e. $b/a=0.91$ vs. 0.89 for KIDS-EC1 and $b/a=0.68$ vs. 0.59 for KIDS-EC2), but consistent within the errors, as earlier found in other studies (e.g. Shajib et al. 2020 and reference therein); 4) for KIDS-EC1 we measure a quite strong external shear ($\gamma_{\text{ext}} \sim 0.25$), compatible with a group/cluster potential which is confirmed by the presence of 12 more galaxies at a similar redshift as the lens within $30''$ distance in the MUSE FOV (Napolitano et al. in prep.); 5) both sources are aligned with the lens center of mass within $0.1''$, while the stellar and mass centers are consistent within the errors. In Appendix we discuss the impact of more general model density assumptions and show that these do not impact the main conclusions of this study. From the lens model parameters, we infer a projected mass within R_E of $\log M(R_E)/M_\odot = 11.28 \pm 0.02$ for KIDS-EC1 and $\log M(R_E)/M_\odot = 11.42 \pm 0.01$ for KIDS-EC2 (see also Table 2). Due to the underlying assumption of a SIE mass distribution, we can easily derive the mass inside $R_e/2$ (i.e., $M(R_e/2)$ in Table 2) to compare with the dynamical mass by the velocity dispersion measurements inside the same radius, derived above. We remark here that the adoption of $R_e/2$ as reference radius is consistent with previous strong lensing studies at the same scale (e.g. Auger et al. 2010).

For the dynamical masses, we use the projected solution of the Jeans Equation inside a circular aperture (e.g. Tortora et al. 2009), in order to take correctly into account the light profile of the lenses (i.e. n -index)². These projected masses, M_J in Table 2, are fully consistent with the equivalent lensing-derived masses, hence confirming the self-consistency of our mass estimates of the two systems.

We finally estimate the total stellar mass, M_* , of the two lens systems via SED fitting of the 9-band photometry, given in Table 1. We use the public SED fitting-Code Investigating GALaxy Emission (CIGALE v2018.0, Boquien et al. 2019). The M_* are used, in combination with the lensing masses, to derive the DM fraction inside $R_e/2$, $f_{\text{DM}} = 1 - M_*(R_e/2)/M(R_e/2)$. We assume solar metallicity, while all other parameters, such as the e-folding time, age of the main stellar population and internal extinction, $E(B-V)$, are free to vary. For the star formation rate (SFR), we adopt a delayed star formation history, which allows us to efficiently model both typical early-type and late-type galaxies (see Boquien et al. 2019). To double check the results we also use another independent code, LE PHARE (Ilbert et al. 2006), with a similar set-up and found consistent results for all the constrained parameters, within the errors. The stellar mass inside $R_e/2$ is derived assuming a constant stellar mass-to-light ratio for each lens Sérsic light profile, whose parameters have been inferred from the lensing model in Table 2. The final estimates of $M_*(R_e/2)$ are reported in the same Table, where we also list the final $f_{\text{DM}} = 0.60 \pm 0.07$ for KIDS-EC1 and $f_{\text{DM}} = 0.56 \pm 0.04$ for KIDS-EC2, and report the difference between the lensing and dynamical DM fractions (Δf_{DM}).

The inferred f_{DM} are typical of DM dominated systems and consistent with previous estimates based on lensing (Auger et al. 2010, Tortora et al. 2010, Schuldt et al. 2019) or dynamics of local (Tortora et al. 2009, Cappellari et al. 2012, Tortora et al. 2012) or higher redshift galaxies (Beifiori et al. 2014, Tortora et al. 2018) of similar stellar masses.

3. CHARACTERIZATION OF THE SOURCES

A striking outcome of the lensing model is the degree of compactness of the source galaxies in both ECs, that turned out to have effective radii smaller than $0.1''$. The lensing model also provides an estimate of the n -indexes (< 1 in both cases) and axis ratios (~ 0.9 and ~ 0.6 respectively), suggesting that the two sources might be disk dominated systems³. Only space or adaptive-optics imaging will provide accurate constraints for these parameters and confirm these findings, but meanwhile, to better assess the reliability of the ground-based inferences, we test the procedure using 20 mock ECs. We follow the same approach used to simulate the lensing systems centered on randomly selected red luminous galaxies used to train our CNN on KiDS ground-based images (see Li+20). In particular we produce quad configurations using a source effective radius varying between $R_e = [0.05'', 0.15'']$, n -index= $[0.05, 2]$, lens effective radius $R_e = [1.0'', 1.5'']$ and Einstein radius, $R_E = [1.0'', 1.5'']$. The ranges adopted are meant to cover the parameter space embracing the two crosses, and to demonstrate that the lens model tool can recover the parameters correctly. In particular we have tested the case of very small R_e and n -index of the source by modeling 4/20 mock lenses

² This is the most accurate way to determine the mass inside an aperture and avoid assumptions about the virial estimates for a non-de Vaucouleurs profile ($n \neq 4$), see e.g. Cappellari et al. 2006

³ The best-fit n -indexes are fairly small if compared to typical disks: however we have checked that fixing $n = 1$, the other parameters change within the errors and the reduced χ^2 is worsened, hence demonstrating that n -indexes are realistically $\lesssim 1$ (see e.g. former findings on lensed quenching galaxies by Geier et al. 2013).

with $R_e < 0.07''$ and $n\text{-index} < 0.6$. The simulated lenses are then convolved with a typical r -band PSF of KiDS observations and noise is finally added to produce realistic KiDS-like r -band EC images. We then run the *lfit_gui* using the same configuration file on these mock ECs and derived the lensing parameters like for the real ECs. The derived source R_e and $n\text{-index}$ fall on the one-to-one relation with the input ones. To quantify this we derive the following quantities: $\Delta R_e/R_e = (R_{e,\text{in}} - R_{e,\text{out}})/R_{e,\text{in}} = -0.01 \pm 0.06$ and $\Delta n/n = (n_{\text{in}} - n_{\text{out}})/n_{\text{in}} = -0.01 \pm 0.15$. The scatter is even smaller (~ 0.03 both in R_e and n) for the 4 most extreme cases. Since they are both consistent with zero and the (1σ) scatter is consistent with typical errors from the best-fit parameters in Table 2 ($\lesssim 20\%$), we are confident that the “compactness” of the sources as well as its “disk-like” nature are real, although for the latter there might be more freedom about the exact value of the $n\text{-index}$. We also remark that sub-pixel sizes of the sources are referred to the source plane, where *lfit_gui* maps the source model with a spatial resolution $10\times$ higher than the pixel scale of the lens plane, where the source images are observed ($0.2''$ for KiDS images). Hence sizes smaller than a single pixel are well within the reach of the tool we use. However, we have found that $0.04''$ is the lowest limit for our ground-based observations. In fact, mock lenses having sources with R_e in the range $[0.01, 0.04]$ are recovered with too large uncertainties.

As described in §2.1, the source spectra are dominated by absorption lines, which are typical of a relatively evolved population, and show only weak emission lines (see Fig. 1), somehow at odds with the blue colors produced by their continuum. In particular, KIDS-EC1 shows a low-SNR [OII] emission, while KIDS-EC2 shows [OII] and H ϵ , H δ and H γ Balmer lines in emission, although the latter are superimposed to absorption Balmer lines, which makes any modeling of their profile very degenerate (e.g. continuum level, velocity dispersion of the absorption and emission lines, age, metallicity). Using the [OII] line, after some careful continuum subtraction, we estimate a tentative SFR of $\sim 0.1 M_\odot/\text{yr}$ (using Eq. 3 in Kennicutt 1998). We stress that a $\text{SNR} \sim 6$ is not high enough for a robust estimate.

To better characterise the nature of the two sources, we thus exploit their 9-band photometry (Table 1) and run CIGALE, as already done for the deflectors. In order to increase the SNR of the source SEDs, we average the fluxes of the higher magnified lensed images (AB for KIDS-EC1 and AC for KIDS-EC2) and obtain the de-lensed (i.e. using the r -band magnification, μ_r , as in Table 2) SED in Fig. 3. We try two extreme metallicity scenarios: a standard solar metallicity and a largely sub-solar one ($Z = 0.0004$), being the latter suggested by the strength of the Balmer lines compared with the Calcium H and K of KIDS-EC2 (for EC1 these lines are too redshifted to fall in the MUSE wavelength range). For KIDS-EC1 we obtain a better fit with solar metallicity (reduced $\chi^2 = 1.7$, corresponding to a $\sim 10\%$ significance for 8 degree-of-freedom), while for EC2 the fit is better for the sub-solar metallicity ($\chi^2 = 0.7$, i.e. $\sim 70\%$ significance). The best fits, shown in Fig. 3, give for KIDS-EC1 an age of 4.0 ± 0.1 Gyr and a SFR of $9.1 \pm 1.2 M_\odot/\text{yr}$, while for KIDS-EC2, age= 3.8 ± 0.4 Gyr and SFR= $0.4 \pm 0.1 M_\odot/\text{yr}$ ⁴. Hence both systems have an old age for their redshift, but are still forming stars at a low rate, although we see only few emission lines in their spectra. In both cases the sources are quite massive: KIDS-EC1 has a stellar mass of $\log M_*/M_\odot = 11.08_{-0.05}^{+0.04}$ and KIDS-EC2 of $\log M_*/M_\odot = 10.21_{-0.02}^{+0.02}$, hence their specific star formation rate (sSFR) are $\log \text{sSFR}/\text{Gyr} = -1.12 \pm 0.07$ and $\log \text{sSFR}/\text{Gyr} = -1.61 \pm 0.03$ respectively, i.e. generally lower than the typical values expected for the main sequence (MS) of star-forming (SF) galaxies at $z > 1$ in the same mass range ($\log \text{sSFR}_{\text{MS}}/\text{Gyr} \sim 0.0 \pm 0.4$, see e.g. Johnston et al. 2015).

Also for the lensed images we have performed a double check with LE PHARE and we have found slightly lower masses (0.1 and 0.2 dex for KIDS-EC1 and EC2, respectively) but consistent or even lower $\log \text{sSFR}/\text{Gyr}$ (-1.3 and -1 respectively), hence confirming the quenching status of the two systems.

Are these systems special? They are for their sizes, as they are both outliers of the typical size–mass relation of SF systems by ~ 0.5 dex in effective radius. Allen et al. (2017), for instance, found a mean $\log R_e/\text{kpc} \sim 0.6$ and 0.5 in the redshift bin $1 < z < 1.5$ for $\log M_*/M_\odot \sim 11.1$ and ~ 10.2 respectively, while we have $\log R_e/\text{kpc} = -0.06$ for KIDS-EC1 and -0.34 for KIDS-EC2. This means that they deviate significantly from normal galaxies at their redshift, while they are closer to typical sizes of SF galaxies at $z \gtrsim 5$. On the other hand, they also show very low sSFR, deviating from the MS by $\Delta_{\text{MS}} = \log \text{sSFR}_{\text{MS}} - \log \text{sSFR} \sim -1.1$ and -0.4 . Simulations from Tacchella et al. (2016) have shown that these low sSFR, together with sizes of $\log R_e/\text{kpc} < 0$, are typical of a “post–blue nugget” (BNs, hereafter) phase, i.e. systems having gone through compaction and entering their quenching phase. Huertas-Company

⁴ For completeness, the results obtained for KIDS-EC1 assuming a sub-solar metallicity are age= 4.0 ± 1.0 Gyr and SFR= $0.4 \pm 0.1 M_\odot/\text{yr}$ and the results for KIDS-EC2 with solar metallicity are age= 1.2 ± 0.2 Gyr and SFR= $5.5 \pm 0.3 M_\odot/\text{yr}$. Note that full spectro-photometric stellar population analysis of the sources is beyond the purpose of this letter and will be addressed in a separate paper.

et al. (2018) have also found that most of the massive, compact systems at $z > 1$ ($\log M_*/M_\odot \gtrsim 10.3$) tend to be in such a post-BN phase.

4. CONCLUSIONS AND PERSPECTIVES

We have presented the confirmation and modelling of two Einstein Crosses found in the KiDS footprint. The confirmation is based on MUSE spectroscopy, unequivocally showing the strong-lensing nature of the systems. We have detected the same spectral features in the four images of the two crosses and inferred a redshift of $z_s \sim 1.59$ for KIDS-EC1 and $z_s \sim 1.10$ for KIDS-EC2, both higher than their respective deflector galaxies, i.e. two old early-type galaxies at $z_1 \sim 0.38$ (KIDS J232940-340922) and $z_1 \sim 0.24$ (KIDS J122456+005048).

The discovery is exceptional as we only inspected $\sim 1000\text{deg}^2$ so far and Einstein Crosses (ECs) are very rare phenomena. However, general predictions on the number of expected quads (of which ECs are a special case) are based on the assumption that these are generated by quasars (see e.g. Oguri & Marshall 2010). For the two ECs presented here, we have shown that they are produced by ultra-compact, blue, quenching galaxies. In particular:

1. to reproduce the cross configuration, the best lensing model (see Table 2), assuming a singular isothermal ellipsoid (SIE) with external shear, predicts that the sources have very compact sizes: $R_e \sim 0.9$ kpc for KiDS-EC1 and $R_e \sim 0.5$ kpc for KiDS-EC2, i.e. $> 10\sigma$ off the typical size-mass relation of normal SF galaxies at the same redshifts (see Allen et al. 2017);
2. the spectra of the sources show a dominance of absorption lines, typical of a quite evolved stellar population, which has been confirmed by SED fitting of the 9-band photometry performed on the average of the two highest magnified images of each system. We inferred old ages (4 Gyr and 3.8 Gyr for KIDS-EC1 and KIDS-EC2, respectively) and moderate star formation (9.1 and $0.4 M_\odot/\text{yr}$, respectively). However, the inferred stellar masses ($\log M_*/M_\odot \sim 11.08$ and 10.21 , respectively) imply very low specific star-formation rates ($\log \text{sSFR} = -1.1$ and -1.6 Gyr^{-1} , respectively), typical of quenching galaxies at $z > 1$ (see e.g. Tacchella et al. 2016, Newman et al. 2018).

In §3, we have argued that the combination of an extremely compact size and the low sSFR is compatible with the sources being two massive post-BNs. These are compact massive galaxies having almost exhausted their star-forming phase and currently undergoing quenching. As such, these systems are important to understand the transformation of primordial disks into the compact cores (“red nuggets”, see Dekel & Burkert 2014) of today’s large elliptical galaxies in the first phase of their evolution, before they enter their subsequent merging phase (e.g. Oser et al. 2012). These systems have been predicted to be very numerous in simulations (e.g. Zolotov et al. 2015, Tacchella et al. 2016) and their census at $z > 1$ has just started, including the confirmation of their abundance and physical properties (see e.g. Huertas-Company et al. 2018). Having observed two of such systems in a peculiar lensing configuration, might suggest that, indeed, they are not uncommon at $z > 1$. To make a rough estimate of the expected numbers of such EC events from compact post-BN systems, we can use predictions based on a size-luminosity relation compatible with high- z studies calibrated over compact star-forming galaxies from Collett (2015), reproducing typical ground based surveys with seeing $\leq 1''$. We estimate ~ 1 EC over 1000deg^2 (assuming $< 0.1''$ alignment between source and deflector), generated by a slightly flattened mass distribution like the one estimated for our ECs ($q = [0.7, 0.9]$) by a compact source (size $\lesssim 1$ kpc) at $z < 1.7$, with sufficient SNR (> 10) to be identified as a sure lens around bright deflectors ($r < 21$, according to our selection in Li+20). This rough prediction can be likely an upper limit because we are assuming that all sources aligned within $0.1''$ produce an EC, but using mock lenses we have checked that most of them should look as such (see §3). The two ECs reported here are possibly slightly overabundant with respect to the expectation for standard star-forming systems. This is a first interesting indication that this population of post-BNs might be particularly abundant at $z > 1$. According to the same predictions, releasing any limitation on the brightness of the lens (i.e. $r < 25$), the expected EC/quad configurations are \sim half a dozen for sources at $z < 4$ (see also §1). Hence we expect to confirm other systems in KiDS, in the future. More importantly we can expect that for next generation surveys like LSST, EUCLID or CSST, we can discover 4000 to 7000 similar quad-like configurations. This will represent a unique opportunity to perform systematic studies of this population of compact systems in great

⁵ We have used the pre-compiled predictions for the Dark Energy Survey (DES), with seeing $1''$ in github.com/tcollett/LensPop. These simulations are consistent with KiDS in terms of depth ($r \sim 25$, 5σ within $2''$), hence giving access to a similar lens luminosity distribution, and only slightly worse in image quality ($\sim 1''$ for DES vs $0.7''$ for KiDS and a pixel size $0.26''$ vs $0.21''$). Furthermore the adoption of a slightly larger seeing allows us to better account for the selection function introduced by the visual inspection, as the human eye tends to give a lower grade to arcs or multiple images that are too close to the lens center as they look diluted/confused in the lens starlight.

details using lensing as a “gravitational telescope”, which will be prohibitive to observe without lensing magnification (see e.g. [Toft et al. 2017](#)) before extremely large telescopes will be online.

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REFERENCES

- Allen, R. J., Kacprzak, G. G., Glazebrook, K., et al. 2017, *ApJL*, 834, L11
- Auger, M. W., Treu, T., Bolton, A. S., et al. 2010, *ApJ*, 724, 511
- Beifiori, A., Thomas, D., Maraston, C., et al. 2014, *ApJ*, 789, 92
- Bettoni, D., Falomo, R., Scarpa, R., et al. 2019, *ApJL*, 873, L14
- Bolton, A. S., Moustakas, L. A., Stern, D., et al. 2006, *ApJL*, 646, L45
- Boquien, M., Burgarella, D., Roehlly, Y., et al. 2019, *A&A*, 622, A103
- Bruzual, G., & Charlot, S. 2003, *MNRAS*, 344, 1000
- Burchett, J. N., Rubin, K. H. R., Prochaska, J. X., et al. 2020, *arXiv:2005.03017*
- Cappellari, M., Bacon, R., Bureau, M., et al. 2006, *MNRAS*, 366, 1126
- Cappellari, M., McDermid, R. M., Alatalo, K., et al. 2012, *Nature*, 484, 485
- Cappellari, M. 2017, *MNRAS*, 466, 798
- Chabrier, G. 2003, *ApJL*, 586, L133
- Collett, T. E. 2015, *ApJ*, 811, 20
- de Jong, J. T. A., Verdoes Kleijn, G. A., Boxhoorn, D. R., et al. 2015, *A&A*, 582, A62
- Dekel, A., & Burkert, A. 2014, *MNRAS*, 438, 1870
- Edge, A., Sutherland, W., Kuijken, K., et al. 2013, *The Messenger*, 154, 32
- Geier, S., Richard, J., Man, A. W. S., et al. 2013, *ApJ*, 777, 87
- Huertas-Company, M., Primack, J. R., Dekel, A., et al. 2018, *ApJ*, 858, 114
- Johnston, R., Vaccari, M., Jarvis, M., et al. 2015, *MNRAS*, 453, 2540
- Kelly, P. L., Rodney, S. A., Treu, T., et al. 2015, *Science*, 347, 1123
- Kennicutt, R. C. 1998, *ARA&A*, 36, 189
- Koopmans, L. V. E., Treu, T., Bolton, A. S., et al. 2006, *ApJ*, 649, 599
- Kormann, R., Schneider, P., & Bartelmann, M. 1994, *A&A*, 284, 285
- Kuijken, K., Heymans, C., Dvornik, A., et al. 2019, *A&A*, 625, A2
- Ilbert, O., Arnouts, S., McCracken, H. J., et al. 2006, *A&A*, 457, 841
- Li, R., Napolitano, N. R., Tortora, C., et al. 2020, *ApJ*, 899, 30 (Li+20)
- Magain, P., Surdej, J., Swings, J.-P., et al. 1988, *Nature*, 334, 325
- Moré, J. J. 1978, *Lecture Notes in Mathematics*, Berlin Springer Verlag, 105
- Muzzin, A., Labbé, I., Franx, M., et al. 2012, *ApJ*, 761, 142
- Newman, A. B., Belli, S., Ellis, R. S., et al. 2018, *ApJ*, 862, 125
- Nightingale, J. W., Massey, R. J., Harvey, D. R., et al. 2019, *MNRAS*, 489, 2049
- Oser, L., Naab, T., Ostriker, J. P., et al. 2012, *ApJ*, 744, 63
- Petrillo, C. E., Tortora, C., Chatterjee, S., et al. 2017, *MNRAS*, 472, 1129
- Petrillo, C. E., Tortora, C., Vernardos, G., et al. 2019, *MNRAS*, 484, 3879
- Petrillo, C. E., Tortora, C., Chatterjee, S., et al. 2019, *MNRAS*, 482, 807
- Oguri, M., & Marshall, P. J. 2010, *MNRAS*, 405, 2579

- Ostrovski, F., Lemon, C. A., Auger, M. W., et al. 2018, *MNRAS*, 473, L116
- Roy, N., Napolitano, N. R., La Barbera, F., et al. 2018, *MNRAS*, 480, 1057
- Rubin, K. H. R., Prochaska, J. X., Koo, D. C., et al. 2014, *ApJ*, 794, 156
- Sérsic, J. L. 1963, *Boletin de la Asociacion Argentina de Astronomia La Plata Argentina*, 6, 41
- Shu, Y., Bolton, A. S., Mao, S., et al. 2016, *ApJ*, 833, 264
- Schuldt, S., Chirivì, G., Suyu, S. H., et al. 2019, *A&A*, 631, A40
- Shajib, A. J., Treu, T., Birrer, S., et al. 2020, *arXiv:2008.11724*
- Spiniello, C., Koopmans, L. V. E., Trager, S. C., et al. 2011, *MNRAS*, 417, 3000
- Spiniello, C., Agnello, A., Napolitano, N. R., et al. 2018, *MNRAS*, 480, 1163
- Spiniello, C., Agnello, A., Sergeev, A. V., et al. 2019, *MNRAS*, 483, 3888
- Suyu, S. H., Auger, M. W., Hilbert, S., et al. 2013, *ApJ*, 766, 70
- Tacchella, S., Dekel, A., Carollo, C. M., et al. 2016, *MNRAS*, 457, 2790
- Tessore, N., Bellagamba, F., & Metcalf, R. B. 2016, *MNRAS*, 463, 3115
- Toft, S., Zabl, J., Richard, J., et al. 2017, *Nature*, 546, 510
- Tortora, C., Napolitano, N. R., Romanowsky, A. J., et al. 2009, *MNRAS*, 396, 1132
- Tortora, C., Napolitano, N. R., Romanowsky, A. J., et al. 2010, *ApJL*, 721, L1
- Tortora, C., La Barbera, F., Napolitano, N. R., et al. 2012, *MNRAS*, 425, 577
- Tortora, C., Napolitano, N. R., Roy, N., et al. 2018, *MNRAS*, 473, 969
- Treu, T., Auger, M. W., Koopmans, L. V. E., et al. 2010, *ApJ*, 709, 1195
- Zolotov, A., Dekel, A., Mandelker, N., et al. 2015, *MNRAS*, 450, 2327

APPENDIX

IMPACT OF THE SIE ASSUMPTION AND THE FITTING TOOL

The mismatch between the stellar velocity dispersion measured from the spectrum and the lensing dispersion of KIDS-EC1 found in §2.2 suggests that the assumption of a SIE mass density might be inappropriate. To investigate the impact of this assumption and check the reliability of the main parameters derived by *lfit_gui* and reported in Table 2, we use a different lens model tool, *LENSED* (Tessore et al. 2016). We stress that a full comparison of different fitting techniques is beyond the purpose of this paper, however we can use the relevant outputs of an independent tool to validate the main results of this paper. First, as *LENSED* allows a free slope for the mass density profile (i.e. an Elliptic Power Law, EPL, model), we can check how this deviates from SIE (3D slope= 2). For KIDS-EC1 we find the best-fit 3D slope= -1.75 ± 0.06 , which is consistent with the Auger et al. (2010) formula ($\gamma' - 2 = 2.67(f_{\text{SIE}} - 1) + 0.20$, where γ' is the 3D slope and $f_{\text{SIE}} = \sigma_{e/2}/\sigma_{\text{SIE}}$) for the mismatch between stellar velocity dispersion measured from the spectrum and the lensing dispersion for the SIE model. For EC2 we have a 3D slope= 2.04 ± 0.01 , which is instead very close to the 3D slope predicted for a SIE. Due to the different slopes, we derive different 2D mass extrapolation at $R_e/2$: for KIDS-EC1 we have $\log M(R_e/2)/M_\odot = 10.99 \pm 0.07$, for KIDS-EC2 we have $\log M(R_e/2)/M_\odot = 11.20 \pm 0.02$. The inferred dark matter fractions are $f_{\text{DM}} = 0.54 \pm 0.11$ for KIDS-EC1 and $f_{\text{DM}} = 0.58 \pm 0.05$ for KIDS-EC2, i.e. fully consistent with the SIE results within 1σ . This shows that the inner slope does not impact significantly our inference on the DM content of the galaxies, as well as the overall conclusions related to the lensing parameters in Table 2, hence the use of the SIE in the rest of the paper is fairly justified.

Another central result of the paper is the compactness of the source, which, as discussed in §3, is challenging to assess from ground based imaging and might depend, e.g., on the way a given tool samples the model at the sub-pixel scale, performs the convolution with the PSF and re-bins the model. We have double checked the results of *lfit_gui* against *LENSED* and confirmed both compactness and the pseudo-exponential light profiles of the sources, even though the central values are consistent only within $\sim 2\sigma$. In fact, from *LENSED* we found that the source sizes of KIDS-EC1 is $R_e = 0.05'' \pm 0.01''$ while its n -index is $n = 1.2 \pm 0.3$; for KIDS-EC2, we found instead $R_e = 0.03'' \pm 0.01''$ and $n = 1.58 \pm 0.07$. Finally, source axis ratios and magnitudes are fairly similar to *lfit_gui* inferences: for KIDS-EC1, *LENSED* gives $(b/a, r) = (0.24, 23.54)$, for KIDS-EC2 $(0.64, 23.80)$. As comparison, *lfit_gui* gives $(0.5, 23.78)$, $(0.7, 23.69)$ for KIDS-EC1 and KIDS-EC2, respectively.

Table 1. Einstein Cross Optical-NIR photometry

| ID | Δ RA | Δ DEC | u | g | r | i | Z | Y | J | H | K_s |
|--|------------------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| | (arcsec) | (arcsec) | (mag) | (mag) | (mag) | (mag) | (mag) | (mag) | (mag) | (mag) | (mag) |
| KIDS-EC1: KIDS J232940-340922 RA= 352.417753 DEC= -34.156375 | | | | | | | | | | | |
| G | 0.00 ± 0.03 | 0.00 ± 0.03 | 21.44 (0.22) | 20.69 (0.09) | 19.77 (0.04) | 19.29 (0.04) | 19.05 (0.12) | 18.48 (0.06) | 17.90 (0.08) | 17.19 (0.08) | 16.48 (0.04) |
| A | -1.04 ± 0.06 | -0.75 ± 0.05 | 22.57 (0.17) | 21.97 (0.15) | 22.29 (0.11) | 22.27 (0.17) | 21.16 (0.11) | 21.14 (0.14) | 20.46 (0.12) | 19.70 (0.12) | 19.39 (0.12) |
| B | 0.87 ± 0.08 | 0.99 ± 0.05 | 22.65 (0.19) | 21.98 (0.11) | 22.36 (0.12) | 22.10 (0.15) | 21.32 (0.13) | 21.29 (0.17) | 20.24 (0.10) | 19.60 (0.10) | 19.44 (0.12) |
| C | -0.58 ± 0.09 | 0.67 ± 0.07 | 24.06 (0.79) | 22.24 (0.17) | 22.62 (0.29) | 22.23 (0.37) | 21.31 (0.24) | 21.18 (0.21) | 20.38 (0.16) | 20.14 (0.23) | 20.32 (0.39) |
| D | 0.61 ± 0.19 | -0.72 ± 0.16 | 25.44 (1.65) | 22.80 (0.39) | 23.14 (0.38) | 23.24 (0.51) | 21.86 (0.39) | 21.81 (0.71) | 21.32 (0.42) | 20.23 (0.43) | 19.57 (0.18) |
| KIDS-EC2: KIDS J122456+005048 RA= 186.233401 DEC= +0.846682 | | | | | | | | | | | |
| G | 0.00 ± 0.01 | 0.00 ± 0.01 | 20.94 (0.09) | 19.30 (0.03) | 18.10 (0.03) | 17.48 (0.04) | 17.20 (0.03) | 17.04 (0.05) | 16.67 (0.06) | 16.24 (0.02) | 15.98 (0.38) |
| A | -1.24 ± 0.05 | 0.78 ± 0.05 | 23.13 (0.14) | 22.52 (0.16) | 21.90 (0.17) | 21.57 (0.13) | 20.74 (0.08) | 20.51 (0.09) | 20.34 (0.11) | 20.33 (0.08) | 19.82 (0.42) |
| B | 0.50 ± 0.07 | 1.29 ± 0.08 | 23.25 (0.11) | 23.14 (0.33) | 22.01 (0.21) | 21.79 (0.21) | 21.05 (0.09) | 20.97 (0.11) | 20.66 (0.12) | 20.56 (0.09) | 19.87 (0.42) |
| C | 1.27 ± 0.06 | -0.96 ± 0.06 | 23.44 (0.15) | 22.63 (0.16) | 21.97 (0.15) | 21.65 (0.13) | 20.73 (0.08) | 20.62 (0.11) | 20.43 (0.11) | 20.08 (0.08) | 19.96 (0.44) |
| D | -0.73 ± 0.09 | -1.14 ± 0.09 | 23.36 (0.18) | 22.77 (0.29) | 22.11 (0.22) | 21.93 (0.27) | 21.22 (0.15) | 21.12 (0.16) | 20.94 (0.19) | 20.69 (0.10) | 20.34 (0.46) |

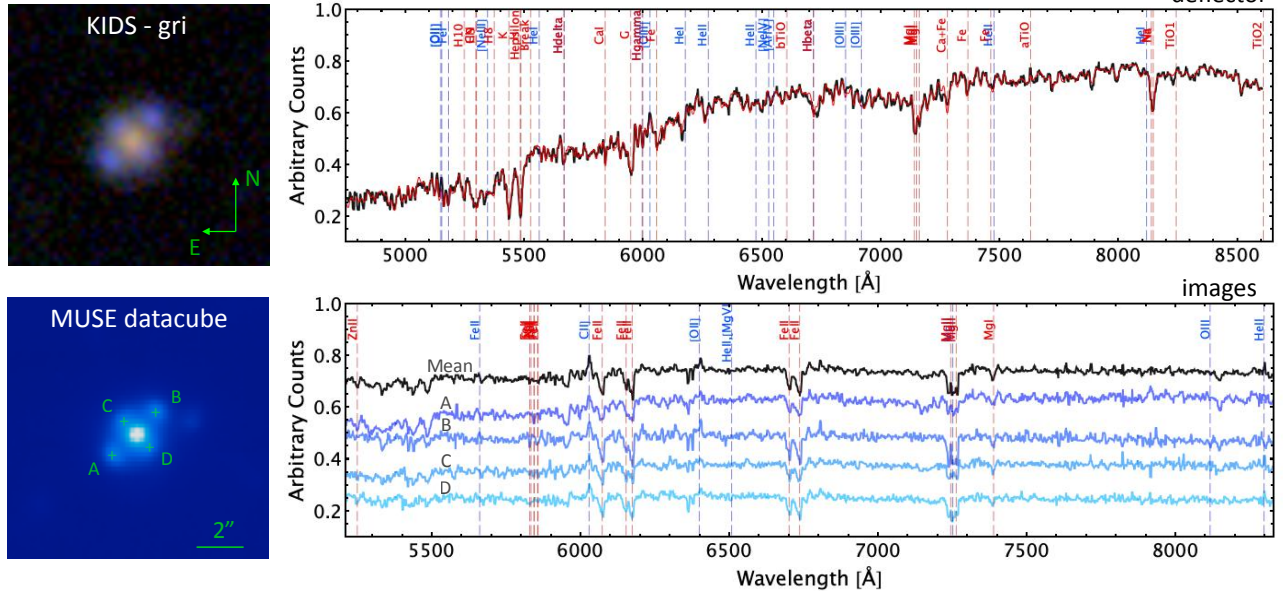
NOTE—Objects coordinates are in degree, errors on magnitudes in different bands are given in brackets. Magnitudes of the lensed images (A, B, C, D) are total magnitudes obtained by Gaussian fit after the central galaxy G has been removed. Galaxy magnitude are total Sérsic magnitudes.

Table 2. Summary of the Einstein cross main parameters

| Parameter | KIDS-EC1 | KIDS-EC2 |
|---|----------------------|----------------------|
| MUSE spectroscopy | | |
| z_l | 0.3810 ± 0.001 | 0.2372 ± 0.0005 |
| z_s | 1.59 ± 0.01 | 1.10 ± 0.01 |
| $\sigma_{R_e/2}$ (km s ⁻¹) | 192 ± 4 | 248 ± 5 |
| Lensing model | | |
| θ_E (arcsec) | 0.99 ± 0.02 | 1.42 ± 0.01 |
| R_E (kpc) | 5.2 ± 0.1 | 5.4 ± 0.1 |
| σ_E (km s ⁻¹) | 226 ± 8 | 260 ± 5 |
| lens b/a | 0.91 ± 0.07 | 0.68 ± 0.07 |
| lens PA | 1 ± 56 | 148 ± 2 |
| μ_r (A, B, C, D) | (3.6, 3.4, 2.7, 1.7) | (5.6, 5.1, 5.3, 4.6) |
| lens PA | 1 ± 56 | 148 ± 2 |
| star n -index | 2.8 ± 0.3 | 3.43 ± 0.08 |
| star b/a | 0.89 ± 0.03 | 0.59 ± 0.01 |
| star PA | 107 ± 9 | 146 ± 1 |
| star R_e (arcsec) | 1.12 ± 0.10 | 1.63 ± 0.05 |
| star R_e (kpc) | 5.8 ± 0.5 | 6.2 ± 0.2 |
| R_E/R_e | 0.90 ± 0.08 | 0.87 ± 0.03 |
| star ΔRA | -0.02 ± 0.02 | 0.01 ± 0.01 |
| star ΔDEC | 0.02 ± 0.02 | 0.01 ± 0.01 |
| source n -index | 0.4 ± 0.1 | 0.2 ± 0.1 |
| source b/a | 0.5 ± 0.1 | 0.7 ± 0.1 |
| source R_e (arcsec) | 0.10 ± 0.02 | 0.06 ± 0.01 |
| source R_e (kpc) | 0.87 ± 0.14 | 0.46 ± 0.04 |
| source ΔRA | -0.03 ± 0.02 | 0.04 ± 0.01 |
| source ΔDEC | -0.07 ± 0.02 | 0.05 ± 0.01 |
| external shear γ_{ex} | 0.25 ± 0.03 | 0.01 ± 0.01 |
| Mass estimates | | |
| $\log M(R_E)/M_\odot$ | 11.28 ± 0.02 | 11.42 ± 0.01 |
| $\log M(R_e/2)/M_\odot$ | 11.04 ± 0.03 | 11.18 ± 0.01 |
| $\log M_J(R_e/2)/M_\odot$ | 10.95 ± 0.05 | 11.21 ± 0.02 |
| $\log M_*/M_\odot$ | 11.18 ± 0.04 | 11.33 ± 0.03 |
| $\log M_*/M_\odot(R_e/2)$ | 10.65 ± 0.04 | 10.81 ± 0.03 |
| $f_{DM}(R_e/2)$ | 0.60 ± 0.07 | 0.56 ± 0.04 |
| $\Delta f_{DM} = f_{DM, len} - f_{DM, J}$ | 0.09 ± 0.10 | -0.02 ± 0.07 |

NOTE—Einstein cross parameters. Muse spectroscopy: redshift of the lens and source and velocity dispersion of the lens calculated at $R_e/2$. Lensing models: Einstein radius in arcsec (θ_E) and kpc (R_E) and the model SIE velocity dispersion, σ_E , followed by self-explaining parameters related to the total mass (labelled by ‘lens’), stellar mass parameters (labelled by ‘star’) and source parameters (labelled by ‘source’) light distribution. Offsets (ΔRA , ΔDEC) are calculated with respect to the lens center. Mass estimates: summary of the mass estimates from lensing model (M), Jeans model (M_J), and stellar population M_* (see text for details) together with the projected DM fractions (f_{DM}) and difference between lens ($f_{DM, len}$) and Jeans ($f_{DM, J}$) analyses.

KIDS J232940-340922



KIDS J122456+005048

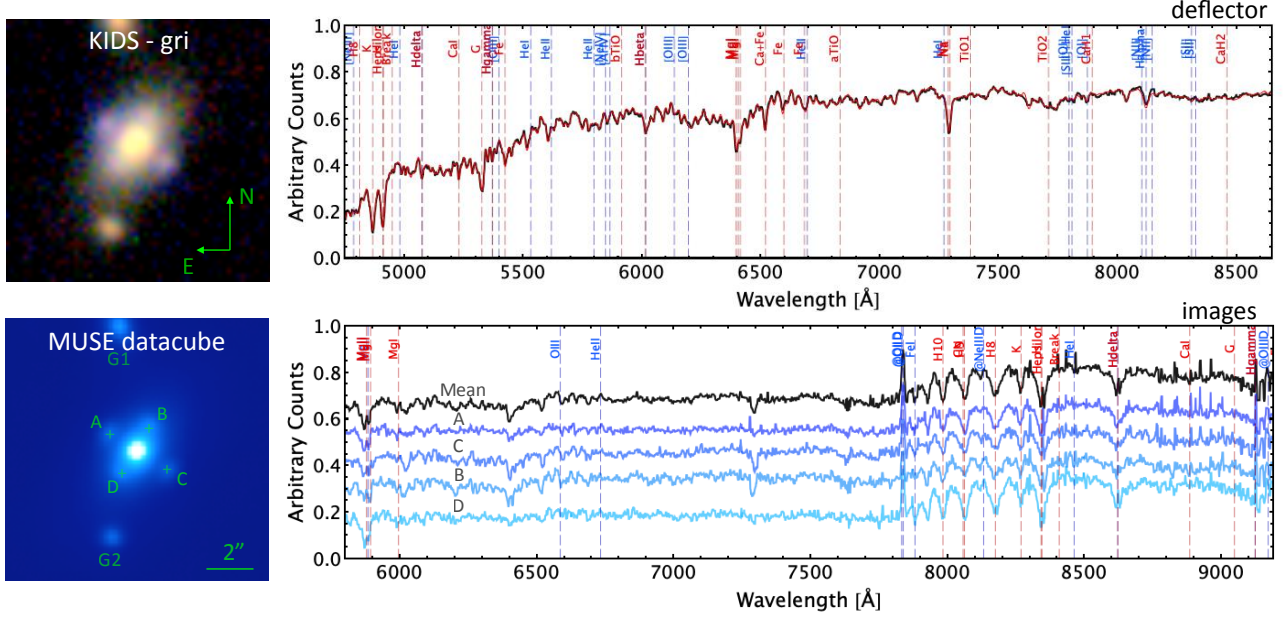


Figure 1. Detection and confirmation of the Einstein crosses: KIDS J232940-34092 (top), KIDS J122456+005048 (bottom). Left column: for each cross we show the KIDS (*gri*) color image (top) and the MUSE white light image (bottom). Right column: for each cross we plot the MUSE spectrum of the deflector, in black, with the best fit model for the velocity dispersion estimate with PPXF, in red, (top) and of the 4 individual images, in blue tones, and the mean spectrum, in black (bottom). Over-plotted on all spectra, are the main absorption lines (in red) and emission lines (in blue), shifted to the estimated redshift of the represented object (see Table 2).

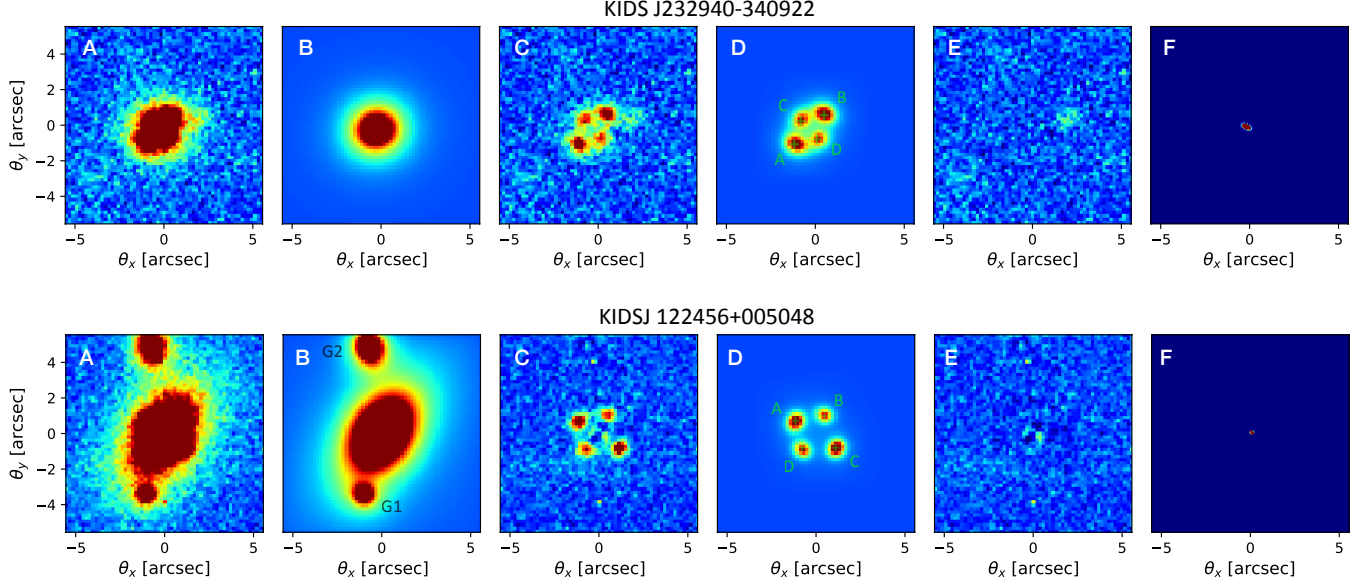


Figure 2. Lensing models for KIDS J232940-34092 (top), KIDS J122456+005048 (bottom). From left to right we show the r -band KiDS image used for the model (A), the foreground light-subtracted image (B), the Einstein cross images with the foreground light subtracted (C), the reconstructed Einstein crosses, the residual image ($E=A-B-D$), and the reconstructed background source (F). We use a singular isothermal ellipsoid to model the deflector mass model and a Sérsic model for foreground and source light. For KIDS J122456+005048, to model the foreground light, we also account for the light of the two nearby galaxies marked as G1 and G2 (see panel B). They are also visible in the KiDS and MUSE images (see Fig. 1) and found to have a similar redshift as the lens.

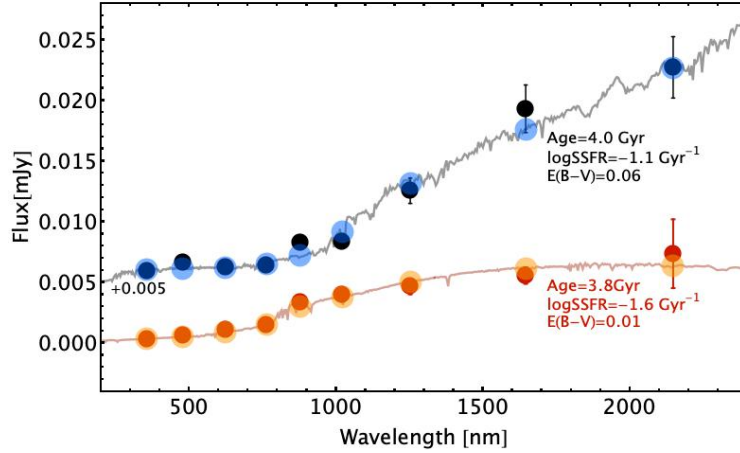


Figure 3. SED fitting of the mean optical+NIR photometry obtained from averaging the de-lensed fluxes of the most magnified images in Table 1. KIDS J232940-34092 photometry (black points with error bars) is plotted together with the best fit template model (gray solid line), corresponding to the parameters reported in the figure (see text for more details) and solar metallicity. Dark blue points show the corresponding photometry from the model used to fit the observations. KIDS J122456+005048 photometry (red points with error bars), is plotted against the best fit model (light red line) and integrated photometry (yellow points), as well as model parameters for the sub-solar metallicity case (see text for details). Data from KIDS J232940-34092 have been shifted +0.005 upward for clarity.