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## HIGH-QUALITY STRONG LENS CANDIDATES IN THE FINAL KILO-DEGREE SURVEY FOOTPRINT

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### ABSTRACT

We present 97 new high-quality strong lensing candidates found in the final  $\sim 350$  deg<sup>2</sup>, that completed the full  $\sim 1350$  deg<sup>2</sup> area of the Kilo-Degree Survey (KiDS). Together with our previous findings, the final list of high-quality candidates from KiDS sums up to 268 systems. The new sample is assembled using a new Convolutional Neural Network (CNN) classifier applied to  $r$ -band (best seeing) and  $g$ ,  $r$ ,  $i$  color-composited images separately. This optimizes the complementarity of the morphology and color information on the identification of strong lensing candidates. We apply the new classifiers to a sample of luminous red galaxies (LRGs) and a sample of bright galaxies (BGs) and select candidates that received a high probability to be a lens from the CNN ( $P_{\text{CNN}}$ ). In particular, setting  $P_{\text{CNN}} > 0.8$  for the LRGs, the 1-band CNN predicts 1213 candidates, while the 3-band classifier yields 1299 candidates, with only  $\sim 30\%$  overlap. For the BGs, in order to minimize the false positives, we adopt a more conservative threshold,  $P_{\text{CNN}} > 0.9$ , for both CNN classifiers. This results in 3740 newly selected objects. The candidates from the two samples are visually inspected by 7 co-authors to finally select 97 “high-quality” lens candidates which received mean scores larger than 6 (on a scale from 0 to 10). We finally discuss the effect of the seeing on the accuracy of CNN classification and possible avenues to increase the efficiency of multi-band classifiers, in preparation of next-generation surveys from ground and space.

*Subject headings:* gravitational lensing, galaxy, machine learning

### 1. INTRODUCTION

Strong gravitational lensing (SGL, hereafter) is the effect of deformation of the images of distant sources, induced by the gravitational field of massive, typically red and dead, galaxy lenses located along the line-of-sight of the observer to the source. According to general relativity, the light from the source is magnified and deflected by the curved space-time generated by the lens, or deflector, to form distinctive SGL features. If the source is a compact object like a quasar (e.g., Suyu et al. 2013, 2017) a supernova (e.g., Kelly et al. 2015) or an ultra-compact galaxy (e.g., Bolton et al. 2006a; More et al. 2017; Napolitano et al. 2020) its light is split into multiple images. If the source is an extended galaxy, it produces a stretched arc or full ring (e.g., Bolton et al. 2008; Brownstein et al. 2012; Sonnenfeld et al. 2013).

SGL is a powerful tool to infer both the distribution of dark matter (DM) of the lenses and the properties of high-redshift sources. Specifically, SGL allows one to measure the mass of the deflectors with much higher ac-

curacy than any other methods (e.g., Koopmans et al. 2006, 2009; Auger et al. 2009, 2010; Bolton et al. 2012; Shu et al. 2015; Li et al. 2018). SGL can further be used to constrain DM substructures (e.g., Vegetti et al. 2012; Li et al. 2017; Hsueh et al. 2020) and the expansion history of the Universe (e.g., Suyu et al. 2013, 2017; Bonvin et al. 2017; Sluse et al. 2019). Besides cosmology-related questions, SGL can also be used for galaxy formation and evolution studies. Indeed, acting as a gravitational telescope, it magnifies high-redshift objects, which otherwise would be difficult to observe, hence permitting the study of their internal structure and stellar populations (e.g., ALMA Partnership et al. 2015; Cornachione et al. 2018; Claeysens et al. 2019; Chen et al. 2019; Rydberg et al. 2020; Napolitano et al. 2020).

Unfortunately, SGL events are rare, since the strong lensing cross-section subtends only a small angular region around the lens center, typically a few tenths of an arcsec. For instance, we expect to find  $\sim 0.5$  arcs (Collett 2015) or  $\sim 0.025$  quadruple images per deg<sup>2</sup> (Oguri

& Marshall 2010) in typical ground-based surveys with  $r$ -band limiting AB magnitudes  $\sim 25$ . Hence, only by mapping large portions of the sky with deep multi-band photometric surveys, it is possible to build statistically large lens samples and span a large variety of deflectors and sources.

This opportunity is offered by ongoing programs like the Kilo-Degree Survey (KiDS, de Jong et al. 2013), the Hyper Suprime-Cam survey (HSC, Miyazaki et al. 2012), and the Dark Energy Survey (DES, The Dark Energy Survey Collaboration 2005), which are providing large databases of galaxies including millions of objects and thousands of lens candidates (e.g., Huang et al. 2021).

Next generation sky surveys (e.g., Vera Rubin/LSST survey, Ivezić et al. 2019; the *Euclid* mission, Laureijs et al. 2011; the Chinese Space Station Telescope, CSST, Zhan 2018) will offer even larger databases of billions of objects in the near future, where we expect to find hundreds of thousands of SGLs (see e.g., Collett 2015). The drawback is that the search for rare strong lensing events in such a gigantic number of galaxies cannot be done by visual inspection, but needs specialized tools.

Luckily, the combination of characteristic morphological patterns and different colors of lens and source images are distinctive features that can be used to identify these rare treasures among millions of galaxies. This feature recognition is a classical application for machine learning techniques, which can typically handle it with small computational times. For this reason, in the past years, a large effort has been made to develop machine learning-based algorithms to search for lenses in large sky surveys (e.g., Agnello et al. 2015; Ostrovski et al. 2017; Khramtsov et al. 2019; Speagle et al. 2019; Huang et al. 2020). In particular, Convolutional Neural Networks (CNNs) have proven to be very effective in finding lenses from imaging (e.g. Jacobs et al. 2019; Petrillo et al. 2019a; Li et al. 2020) and spectroscopic data (Li et al. 2019).

Indeed, many high-quality/reliability lens candidates have been already found among the higher-ranked candidates from CNNs by human inspection (see e.g., Li et al. 2020, also Metcalf et al. 2019 for a discussion), and a subsample of them has already been spectroscopically confirmed (see e.g., Spiniello et al. 2019a, Spiniello et al. 2019b Lemon et al. 2020, Nord et al. 2020, Napolitano et al. 2020). Hence, whereas CNNs are formidable tools to provide reliable candidates in the newly explored areas of the sky for follow-up observations, further improvement of CNN methods are needed to maximize the completeness and purity of the candidate lists (see e.g., Petrillo et al. 2019a), especially for medium/low signal-to-noise ratio arcs and multiple images.

In this work, we continue our effort, started in Petrillo et al. (2017), to develop CNN algorithms to identify strong gravitational lens candidates in high-quality multi-band optical images from the KiDS survey (de Jong et al. 2013). We make significant improvements both in the CNN architecture and in the preparation of its training sample. In Petrillo et al. (2019a), (Petrillo et al. 2019b, P+19 hereafter) and (Li et al. 2020, L+20 hereafter), we demonstrated that CNN classifiers can identify known lenses, and produced lists of high-quality SGL candidates from all publicly available KiDS Data Releases (DRs).

In this paper, we extend the search to the internal Data Release 5 (KiDS-iDR5). This is a partial data release, only made available to the KiDS consortium for science-driven tests. It includes the stacked images of 341 tiles in  $u, g, r, i$  optical bands, the weight maps, and the optical multi-band catalogs, containing aperture photometry of all detected sources in each tile. These are meta-products that are routinely produced by KiDS since the first data release (de Jong et al. 2015). The data reduction and calibration, as well as the image astrometry and photometry, are obtained with the same procedures of Data Release 4 (KiDS-DR4) described in Kuijken et al. (2019). Observational constraints and image quality are comparable to KiDS-DR4, while no photometric redshifts are available as the 9-band catalogs including Gaussianized aperture photometry (see Kuijken et al. 2019) are still under production. The official DR5 release will also contain multi-epoch imaging in the  $i$ -band, which is not yet available for the iDR5 and will be investigated in future analyzes.

Despite a number of new features implemented in the new classifier, we found some modules that need to be optimized, in particular, to improve the completeness and purity of the candidates. For this reason, our primary objective in this paper is to present a catalog of very high-quality (HQ) new strong lens candidates found in a yet unexplored sky area. We aim at providing a reference catalog to be used for the target selection of forthcoming spectroscopic surveys (e.g. 4MOST, de Jong et al. 2019), although we are aware that this new sample might not be fully complete nor entirely pure.

The paper is organized as follows. In Sect. 2, we describe the datasets used to train and test the classifiers. In Sect. 3, we apply our CNN classifiers to two predictive datasets, the luminous red galaxies (LRGs), and the bright galaxies (BGs) and discuss their performance. We present the new lens candidates and discuss the possible avenues to further improve the accuracy of the classifiers in Sect. 4, and summarize our main conclusions in Sect. 5.

## 2. NEW CONVOLUTIONAL NEURAL NETWORK CLASSIFIER

### 2.1. The CNN classifier

CNNs use convolution kernels as artificial neurons to capture the local features of input images. This makes them particularly suitable for feature recognition and hence for the identification of strong gravitational lenses.

In this work, we use ResNet (He et al. 2015). This is one of the most widely used CNN models in lens search analyzes, where it has been found to perform very efficiently (e.g., Lanusse et al. 2017; Petrillo et al. 2019a,b). Different from our previous work (Li et al. 2020), where we used the open-source `keras-resnet`<sup>1</sup> code, we here customize a new architecture with `Keras`<sup>2</sup> running on the backend of `TensorFlow`<sup>3</sup>.

We build up two different classifiers, although with the same architecture and the same number of convolutional layers (18). The first one (1-band CNN hereafter) uses only  $r$ -band images and thus searches for lens candidates based on morphological patterns. The second (3-band

<sup>1</sup> <https://github.com/raghakot/keras-resnet>

<sup>2</sup> <https://github.com/keras-team/keras>

<sup>3</sup> <https://github.com/tensorflow/tensorflow>

CNN) uses instead color-composite  $g$ ,  $r$ ,  $i$  images and hence is also sensitive to color contrast between the deflector and the source. In both cases, we use images of  $101 \times 101$  pixels (corresponding to  $20'' \times 20''$ ) as input, and we obtain the probability of a system to be a lensing event,  $P_{\text{CNN}}$ , as output.

A final technical note is related to the *data augmentation*. This is a standard strategy used in CNNs to avoid over-fitting and to improve the robustness of the classifier. As we will discuss in the next section, during the training of the CNN we provide a fresh supervised sample of “features”, i.e. images of true and false SGL events, and “labels”, i.e. true or false lens, at every training step. To virtually increase the training sample and generalize the features, we have customized the data augmentation, including randomly shift, flip, rotation, crop, and color vibrance (saturation, contrast, brightness, sharpness) of the images inputted to the CNN during the training phase.

## 2.2. The training and testing data

When building a CNN classifier, the principal step is network *training*. In this phase the CNN learns how to distinguish positive detections (“positives”, in short), i.e. galaxies with *true* lensing features, from negative detections (“negatives”, hereafter), i.e. contaminants. These latter are galaxies with features that can mimic gravitational arcs, such as spiral arms, polar rings, interactive systems, etc.

A proper CNN training process requires the use of tens of thousands of positives and negatives with observational properties (e.g. seeing, noise, depth, etc) similar to the objects to be classified. However, even using all the existing confirmed lenses, their number would still be insufficient for this purpose.

To overcome this problem, a common approach is to produce mock positives. This can be done either by obtaining mock observations of fully simulated systems via ray-tracing of galaxies in hydrodynamical simulations (Lanusse et al. 2018; He et al. 2020) or by adding simulated arcs to images of real galaxies (e.g. Petrillo et al. 2019a; Cañameras et al. 2020). Here we follow this latter approach using KiDS images of galaxies to which we add simulated arcs, as already done in L+20. In this case, the quality of the training images matches that of the input images and the deflectors reproduce the real foreground light, in terms of color, size, and shape.

To simulate positives, we start by creating the multi-band arcs and multiple images in  $g$ ,  $r$ ,  $i$  bands with a ray-tracing method. We assume a Sérsic profile for the sources and a singular isothermal ellipsoid (SIE) mass model for the deflectors. We use the color information of the Rubin/LSST mock galaxies catalog (Connolly et al. 2010) to build a suitable source color library to obtain realistic colors of lensed images. This catalog has a photometric depth of  $r \sim 28$  and covers the redshift range  $0 < z < 6$ . It was generated from the Millennium Simulation (Springel et al. 2005), with superimposed galaxies based on a semi-analytical model for galaxy evolution (De Lucia et al. 2006) which includes gas cooling, star formation, and supernovae/AGN feedback, to reproduce the observed colors, luminosities, and clustering of galaxies. We select  $\sim 2600$  of these mock galaxies at redshift between 0.8 and 3 and with  $r$ -band AB magnitudes be-

tween 21 and 25. When building the ray-tracing images, the  $g$ ,  $r$ ,  $i$  band magnitudes of the Sérsic sources are randomly selected from this color library. The parameters of the SIE lens and Sérsic source profiles (e.g. Einstein radius, effective radius, Sérsic index, axis ratio, etc.), used to simulate the lensed images, are randomly generated from probability distributions, as reported in Table 1. For the parameter distributions, we have followed P+19 and L+20. The distributions of the Einstein radius ( $R_{\text{ein}}$ ) and the source effective radius ( $R_{\text{eff}}$ ) are exponential and normal, respectively. The distribution of the Sérsic index ( $n$ ), position angle and ellipticity of the lenses and sources are originally uniform. However, as we will describe below, we apply a further selection on signal-to-noise ratio and relative brightness of the lens galaxies and lensed images. We also perturb the magnitudes in all three bands by randomly adding a value between  $\pm 0.1$  to account for some scatter around the nominal Rubin/LSST mock colors. The final distribution for  $R_{\text{ein}}$ ,  $n$  and  $R_{\text{eff}}$ , together with the magnitude distribution in the three optical bands used by the CNNs are shown in Fig. 1.

The next step is to obtain lensed images in each band, and to convolve them with a simulated point spread function (PSF), assumed to have a Moffat profile. The range and distribution of the full width at half maximum (FWHM) of the adopted PSFs are chosen according to the seeing distribution of KiDS (Kuijken et al. 2019) and are shown in Table 1. This is a significant improvement over the use of an average PSF for all tiles, adopted in previous analyzes. In fact, the PSF variation leads to a large variance in the sharpness of the lensing features (see Sect. 4.2 for a detailed discussion). This might not particularly impact the  $r$ -band, which is the best image quality filter in KiDS with a narrow FWHM distribution ( $< 0.8''$ ), but it can strongly affect the classification in the 3-band CNN, since the seeing in the  $g$  and  $i$ -bands can be significantly worse than that of the  $r$ -band images. Hence, by accounting for the FWHM variance in all filters, we can improve the performance and robustness of the 3-band classifier.

Finally, as done in L+20, we also add (1) an external shear to account for the effect of different environments, and (2) simulated Gaussian random field (GRF) fluctuations with a power-law power spectrum to the lens potential to account for the effect of the sub-halos in the lens plane (Chatterjee & Koopmans 2018). The slope of the power-law is fixed to  $-6$  while the amplitude is determined using Parseval’s theorem, which is related to the variance of the GRF potential fluctuations inside the image via a normalization factor. Here, the variance for determining the amplitude is drawn by a logarithmic distribution between  $10^{-4} - 10^{-1}$ , about mean zero in the units of the square of the lensing potential (see also in P+19, and detail description in Chatterjee & Koopmans 2018). This yields both structured sources and lenses that are not perfect SIE.

Once the simulated lensed images are obtained, we add these to randomly selected LRGs to generate real-like lenses. In this process, we require the ratio of the peak of the  $r$ -band surface brightness of the arcs  $\alpha$  and the LRGs  $\beta$  to satisfy the condition  $\alpha/\beta \geq 0.05$ , or the local signal-to-noise ratio of the surface brightness peak of the arcs ( $3 \times 3$  pixels with the peak as center) to be  $\text{SNR} > 5$ .

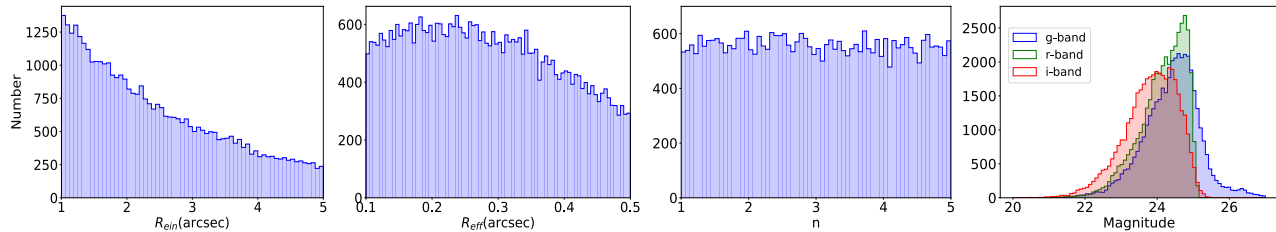


FIG. 1.— Distribution of the main input parameters in the lensing simulation. From left to right we plot the Einstein radius, the source effective radius, the source Sérsic index and the 3-band ( $g, r, i$ ) source magnitudes. See text for details.

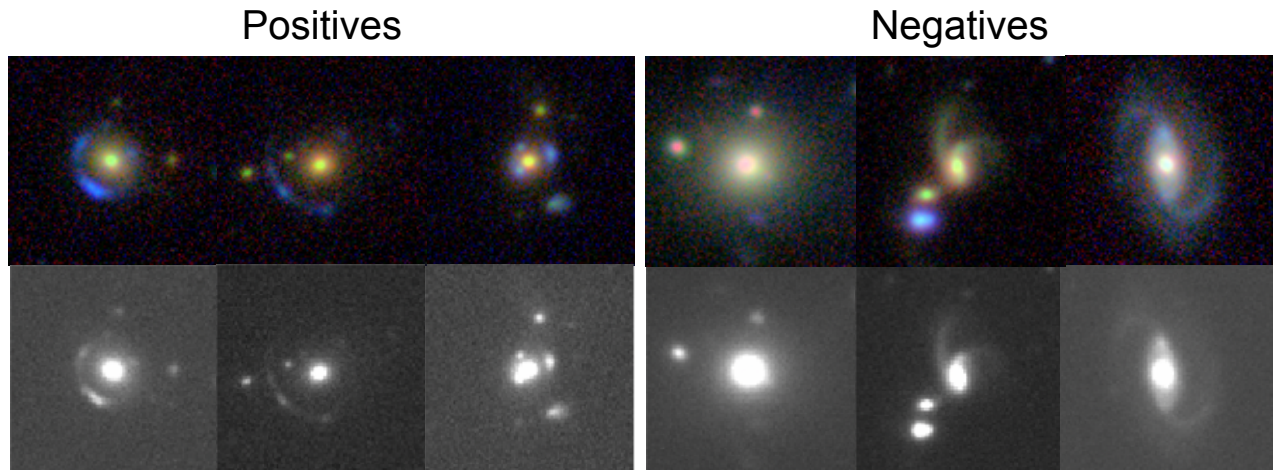


FIG. 2.— Examples of the training sample. The three panels on the left show three simulated lenses (‘positives’) generated by adding mock arcs to real LRGs. The three right panels show three real galaxies used as ‘negatives’. The first row shows the  $g, r, i$  color-composited images ( $20'' \times 20''$ ) while the second row shows the  $r$ -band images ( $20'' \times 20''$ ).

TABLE 1

| Parameter               | Range       | units  | Distribution                             |
|-------------------------|-------------|--------|--|
| lens (SIE)              |             |        |  |
| Einstein radius         | 1.0 – 5.0   | arcsec | exponential                              |
| Axis ratio              | 0.4 – 1.0   | –      | uniform                                  |
| Position angle          | 0 – 180     | degree | uniform                                  |
| External shear          | 0 – 0.1     | –      | uniform                                  |
| Angle of external shear | 0 – 180     | degree | uniform                                  |
| Source (Sérsic)         |             |        |  |
| Effective radius        | 0.1 – 0.5   | arcsec | normal<br>( $\mu = 0.2, \sigma = 0.3$ )  |
| Axis ratio              | 0.3 – 1.0   | –      | uniform                                  |
| Position angle          | 0 – 180     | degree | uniform                                  |
| Sérsic index            | 0.3 – 5.0   | –      | uniform                                  |
| PSF (Moffat)            |             |        |  |
| FWHM- $g$               | 0.60 – 1.2  | –      | normal<br>( $\mu = 0.85, \sigma = 0.1$ ) |
| FWHM- $r$               | 0.50 – 0.90 | –      | normal<br>( $\mu = 0.7, \sigma = 0.05$ ) |
| FWHM- $i$               | 0.55 – 1.2  | –      | normal<br>( $\mu = 0.80, \sigma = 0.1$ ) |
| $\beta$                 | 2.20        | –      | fixed                                    |
| Axis ratio              | 0.98 – 1.02 | –      | uniform                                  |
| Position angle          | 0 – 180     | –      | uniform                                  |

NOTE. — Range and distribution of parameter values used to simulate the lensed images.  $\beta$  is the shape parameter of the Moffat profile, here we fix it to be 2.2, according to our PSF modelling experience for KiDS images (e.g. Roy et al. 2018).  $\mu$  and  $\sigma$  are the mean value and standard Deviation of a normal distribution

This is a less conservative choice than in L+20, where we used  $0.02 \leq \alpha/\beta \leq 0.3$  to avoid the selection of extremely faint simulated arcs that would be undetectable by human inspection. However, this implies that the

trained CNN is intrinsically less complete because it is unable to discover faint or even small separation arcs. The CNN is also more accurate in recognizing mid-/high-contrast arcs with color information. Indeed, we stress that larger completeness is generally obtained at the cost of a larger contamination, as most of the “false positive” are concentrated at faint magnitudes. Hence, with the new training sample, we aim at dramatically reducing the number of these contaminants by inhibiting the CNN to guess in presence of low-contrast, faint features.

With these procedures, we finally build 43 000 mock lenses as positives, together with the 43 000 negatives, to train and test the CNNs. In Fig. 2 we show a sample of positives and negatives from the training sample.

This in turn reduces the number of “false positives” on the final predictive sample on which the visual inspection is carried out. Nevertheless, in Li et al. (2020) we have demonstrated that even without generalizing the training sample, the CNN can find high-quality lens candidates among the BGs sample. In fact, the majority of the HQ candidates found from the BGs sample are mainly identified thanks to the presence of sharp and bright *lensed* features, rather than the properties of the lens itself. Instead, by generalizing further the training sample, we would risk increasing the chance to add false negatives to the final list of HQ candidates.

Finally, during the training process, we optimize the CNNs with the Adam optimizer (Kingma & Ba 2014) by minimizing a ‘binary\_crossentropy’<sup>4</sup> loss.

<sup>4</sup> [https://keras.io/api/losses/probabilistic\\_losses/#binary\\_crossentropy](https://keras.io/api/losses/probabilistic_losses/#binary_crossentropy)

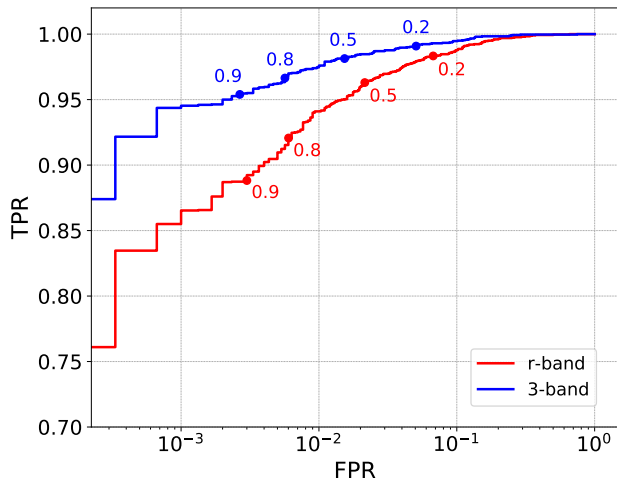


FIG. 3.— The ROC curve for the 1-band (red) and 3-band (blue) CNNs classifiers based on the 3000 simulated lenses and 3000 galaxies used as testing sample. On the curves, we also show the locations of 4 different values of probability threshold ( $P_{\text{CNN}} = 0.2, 0.5, 0.8, 0.9$ ) used to calculate the FPR and TPR.

### 2.3. Testing the CNN

In each epoch of the training, we test the performance of the networks using the validation sample. This is needed to measure the accuracy reached by the CNN at every training step. When the accuracy reaches an asymptotic value, then the training process can be stopped.

After completing the training, we can assess the overall performance of the two CNNs on the test sample, and evaluate the “false positive ratio” (FPR) vs. “true positive ratio” (TPR) curves, where the TPR and FPR are defined as:

- TPR: The fraction of **positives** that have also been identified as **positives** by the classifier (i.e. objects on which the classifier works properly).
- FPR: The fraction of **negatives** that have been wrongly classified as **positives** by the classifier.

This FPR-TPR curve, also called the receiver operating characteristic (ROC) curve, is useful to measure the contamination and accuracy of the classifiers. The ROC curves of the two CNNs are shown in Fig. 3. The introduction of the color information improves the accuracy of the 3-band over the 1-band CNN, as demonstrated by the higher number of true positives for the same false-positive ratios. This is particularly true towards higher  $P_{\text{CNN}}$ , where the 3-band CNN reaches even higher true-positive rates for similar false negative rates.

In Fig. 4 we show the  $P_{\text{CNN}}$  distribution for the 3000 positives (blue) and the 3000 negatives (grey) galaxies in the testing sample, obtained for the 1-band CNN (left panel) and the 3-band CNN (right panel).

In the ideal case, the positives should all be clustered around  $P_{\text{CNN}} = 1$ , while all negatives should peak at  $P_{\text{CNN}} = 0$ . The closer to the ideal case a CNN classifies

these two categories, the better it performs. In Fig. 4, both CNNs clearly identify the easiest cases as there is a peak of positives at  $P_{\text{CNN}} = 1$  and a peak of negatives at  $P_{\text{CNN}} = 0$ . However, the 3-band CNN shows a steeper decline of the distributions of both categories and has a small number of wrongly classified objects. This means that the 3-band CNN has a sharper ability to distinguish positives and negatives. As a consequence of that, the 3-band CNN concentrates most of the positives at higher  $P_{\text{CNN}}$  ( $> 0.5$ ), where there are only a few negatives, which possibly will end up to be false positives in the final catalog. This explains the better performance seen on the ROC curve, where a larger TPR is found for the 3-band CNN, especially at higher  $P_{\text{CNN}}$  values. Even if the 1-band CNN performs almost equally well in terms of false positives (i.e. few negatives with rather high probability), it spreads the true positives over a broader range of low  $P_{\text{CNN}}$ . This affects the completeness in the recovery of the “true lenses” since some of them would not pass the probability threshold. The completeness, defined as the fraction of recovered/simulated lenses, is shown in Fig. 6 as a function of the output probability  $P_{\text{CNN}}$  of the two classifiers. As expected, the 3-band classifier performs systematically better than the 1-band classifier, and reaches 90% completeness for a  $P_{\text{CNN}} = 0.98$ , while the 1-band CNN reaches the same completeness for  $P_{\text{CNN}} > 0.85$ . This shows that the colors of the lensing features add relevant information to correctly classify the positives and separate them from the negatives.

However, this over-performance of the 3-band CNN can be the consequence of the usage of rather ideal strong lensing configurations as the test sample, namely simulated arcs/multiple images (see Fig. 2). Hence, we should use caution by expecting a similar performance in real cases. This is a general problem of the true performance of CNNs trained on simulated datasets but then applied to real lenses. As a sanity check on the reliability of such performance, we apply the two CNNs to 179 high-quality lens candidates from Petrillo et al. (2019a) and Li et al. (2020). In Fig. 6, we overplot the completeness obtained for the “real candidates” to the one obtained for the test (simulated) sample. Overall, the two CNNs perform in a much more comparable way than they do on the test sample. The 3-bands CNN has a slightly higher completeness at  $P_{\text{CNN}} > 0.75$ , while the 1-band CNN does slightly better at lower probabilities.

However, the degradation of the performance of the 3-band CNN, from the mock lenses to the real ones, seems particularly worrisome, especially because this is not mirrored by the same effect on the 1-band. This might suggest a problem with the mock colors. To check that, in Fig. 7 we show some examples of “real candidates” with their probabilities ( $P_1$  for 1-band CNNs and  $P_3$  for 3-band CNN). In particular, in the first row, we show images of candidates that received very high scores from both CNNs. They all show clear blue and bright lensing features. In the second row, we show instead candidates for which  $P_3 \lesssim 0.5$  and  $P_1 > 0.98$ . They also have clear arcs but with either yellow/red colors or shallower bluer images, which return a low- $P_3$  because our training sample is tailored on bright bluer sources. These kinds of candidates which will be discarded since they received a low grade, can potentially reduce dramatically the com-

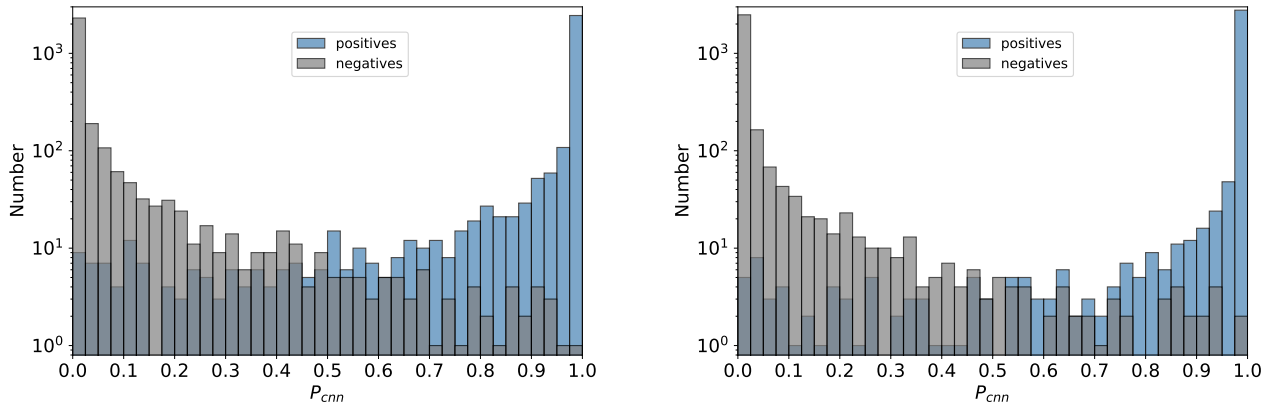


FIG. 4.— The probability distribution of the testing sample for both 1-band (left) and 3-band (right) CNNs. The blue histogram represents the probability distribution of the positives while the grey histogram shows that of the negatives.

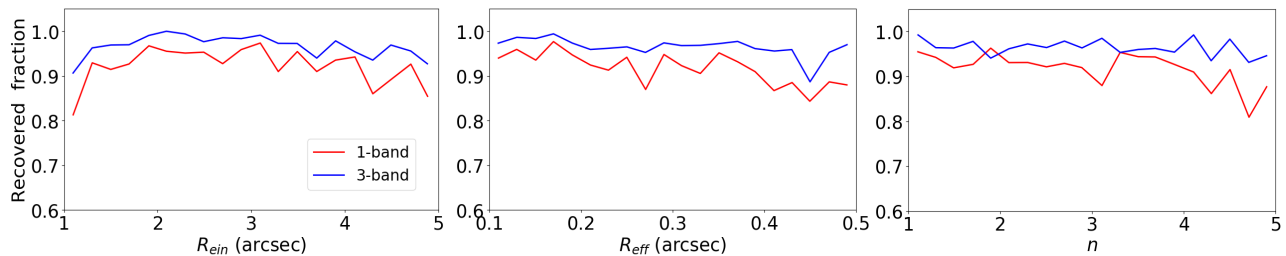


FIG. 5.—

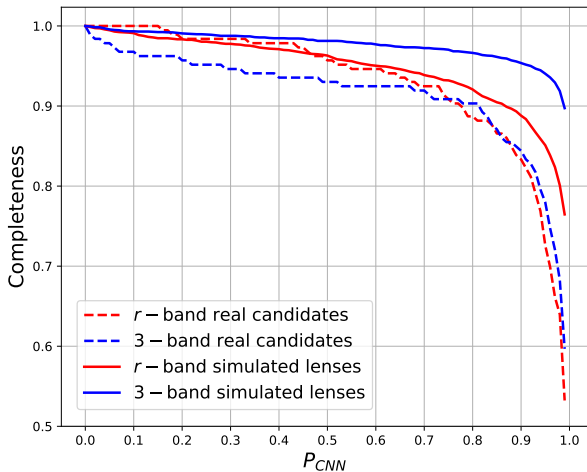


FIG. 6.— The completeness of the 1-band (red) and 3-band (blue) classifier at different probabilities based on 3000 simulated lenses (solid lines) and 179 real high quality lenses candidates (dash lines). The real lens candidates are collected from P+19 and L+20.

pleteness of the 3-band candidates when applied to real galaxies. This is a weakness of our multi-band design that we will study in future work.

Finally, in the third row of the same figure, we show the candidates with high  $P_3$  but low  $P_1$ , which instead demonstrated why higher completeness of the 3-band CNN is reached at higher  $P_{CNN}$ . In this case the 3-band CNN tends to select also arcs or multiple images that

the 1-band CNN ranks lower. This is because the 3-band CNN has been trained to search for sharpness features in the bluer bands, due to the varying FWHM in Table 1, as discussed in Section 2.2. Instead, the 1-band CNN returns a low  $P_{CNN}$  because the lensing features are fainter and less defined in the  $r$ -band. Overall, Fig. 7 demonstrates that the two CNNs are complementary to each other, as there are good candidates that received very high probability in one case but very low probability in the other, and vice-versa. This “complementarity” mainly resides in the different features/information the two CNN are based on.

To further quantify that, in Fig. 8 we compare the probability distribution of the “real” lenses (blue dots) obtained from the 1-band CNN versus the ones obtained from the 3-band CNN. Encouragingly, most of the 60% of the lens candidates are located in the high  $P_{CNN}$  ( $> 0.95$ ) corner, meaning that the SGL features have both clear morphology and color contrast, with the lensed images being bluer than the lens.

For  $P_1, P_3 < 0.9$ , the scatter between the probabilities of the two CNNs becomes large. More importantly, the points are not distributed around the 1-to-1 relation, which would imply a consensus between the two classifiers. Instead, there is a number of lenses that are highly ranked by one CNN but received a very low score from the other one. In particular, if we use a threshold of  $P_{CNN} = 0.8$  for both CNNs, 21 objects will be discarded from the 1-band CNN and 18 will be discarded from the 3-band CNN. But only 6 of them would be discarded by both. This means that there are 33 HQ candidates (i.e. 18% of the total sample) which represent a “comple-

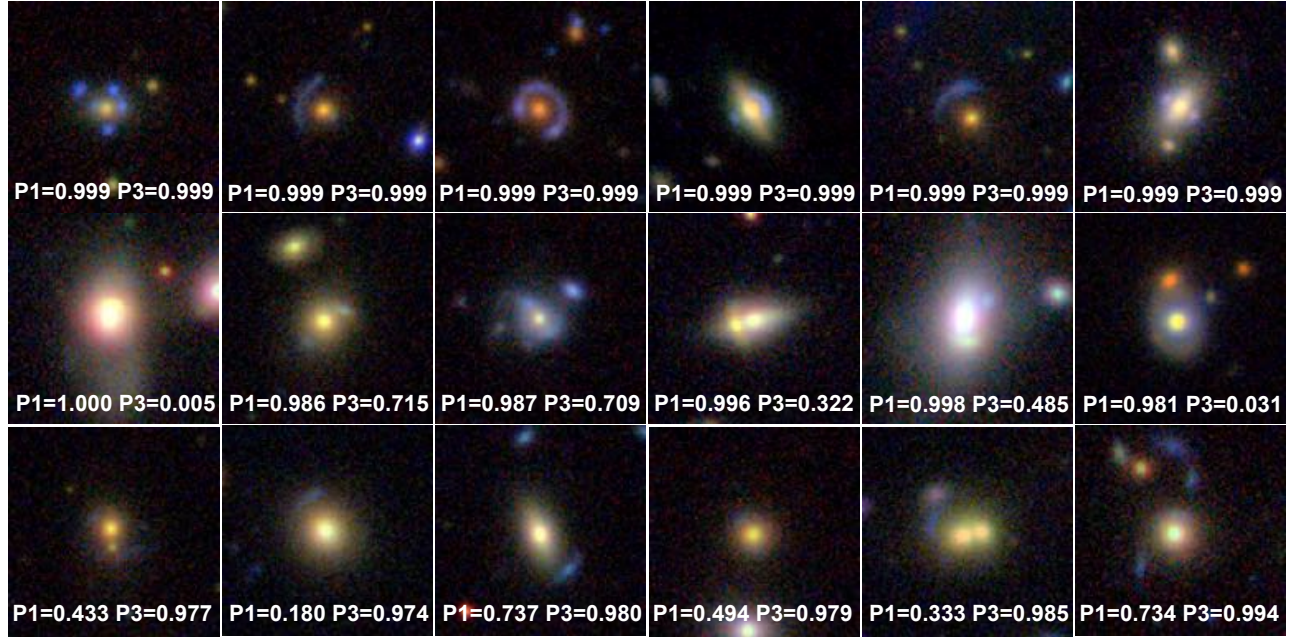


FIG. 7.— HQ candidates from P+19 and L+20 that received different predictions from the 1-band classifier and 3-band classifier. Candidates in the first row obtained high probabilities from both the 1-band and 3-band classifier ( $P_1 > 0.99$  and  $P_3 > 0.99$ ). In this group of objects there are almost no ‘false positives’. Candidates in the second row obtained higher probability from the 1-band classifier but a lower one from the 3-band classifier ( $P_1 > 0.95$  and  $P_3 < 0.8$ ). Candidates shown in the third row obtained lower probability for the 1-band classifier but a higher probability for 3-band classifier ( $P_1 < 0.8$  and  $P_3 > 0.95$ ). The stamps ( $2'' \times 2''$ ) are obtained by combining  $g$ ,  $r$ , and  $i$  KiDS images.

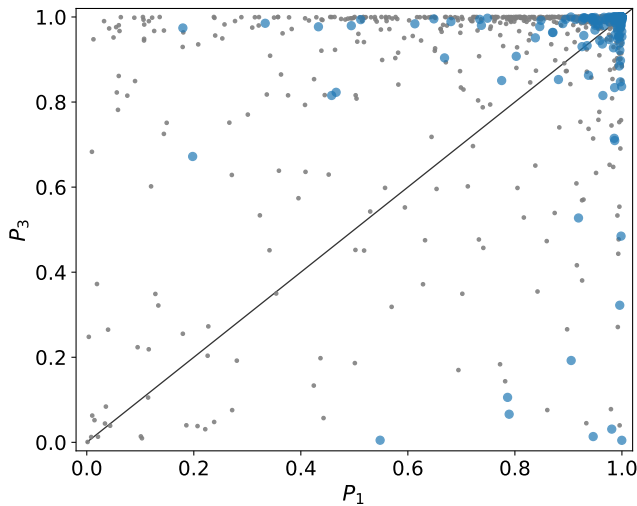


FIG. 8.— Probability of the real lens candidates (blue) and 3000 mock lenses (grey) for the 1-band versus the probability for the 3-band CNN. The two probability look uncorrelated, suggesting a large complementarity between the two methods if applied to ground based observations. See discussion in the text.

ment” sample that would be selected by only one CNN<sup>5</sup>. In Fig. 8 we also show the same comparison for the test

<sup>5</sup> We remark that this “real sample” has been selected by different CNNs: a pure 1-band CNN (L+20) and a mix of 1-band and 3-band CNNs (P+19), and visually inspected. Hence, the lack of predicted objects along the 1-to-1 relation is a consequence of the human inspection that tend to “select” candidates either toward higher  $P_1$  or high  $P_3$ .

sample (grey dots) of LRGs, which corresponds to the majority of systems the “real sample” has been selected from. Here we clearly see the only small correlation between the output  $P_{\text{CNN}}$  of the two classifiers, confirming the strong complementarity of the two approaches. However, a large number of points are visible with  $P_3 > 0.95$  at almost all  $P_1$ . We also see a fair number of  $P_1 > 0.95$  at  $P_3 < 0.8$ . If we choose to select candidates which are above a conservative threshold on both classifiers, we would lose a lot of these two tails, which are mirrored by the distribution of the “real lenses”. On the other hand, we can take advantage of the segregation toward the tails in high  $P_1$  and  $P_3$  to optimize the candidate selection and the overall completeness of the two CNNs together. In conclusion, the best strategy to take full advantage of their complementarity is to select LRG candidates above a given threshold for one *or* the other CNN. In Section 3.2 we will introduce a more conservative approach to the BG sample.

### 3. APPLYING THE CLASSIFIERS TO KIDS-IDR5

KiDS-iDR5 includes a total of 1347 tiles, of these 1006 have been publicly released as data release 4 (DR4) and searched for strong lenses in P+19 and Li+20. In this paper, we therefore analyze the remaining 341.

#### 3.1. Selection of the predictive samples

We define two “predictive samples”, in which we expect to find SGL events, using the method described in Petrillo et al. (2017, 2019a) and Li+20. We first define the larger sample of BGs as those objects with KiDS star-galaxy separation parameter  $2DPHOT = 0$  (La Barbera et al. 2008; de Jong et al. 2015) and



$r$ -band Kron-like magnitude (Bertin & Arnouts 1996)  $mag_{auto} \leq 21$ .

Then, we define the LRG sample, that is selected from the BGs by setting two further criteria: 1)  $r_{auto} \leq 20$ , 2) the colors satisfy a slightly adapted LRG color-magnitude selection (see also in Eisenstein et al. 2001, P+19 and Li+20):

$$\begin{aligned} r_{auto} &< 14 + c_{par}/0.3, \\ |c_{perp}| &< 0.2, \end{aligned} \quad (1)$$

where

$$\begin{aligned} c_{perp} &= (r - i) - (g - r)/4.0 - 0.18, \\ c_{par} &= 0.7(g - r) + 1.2[(r - i) - 0.18]. \end{aligned} \quad (2)$$

### 3.2. 1-band and 3-band CNN predictions

We first apply the CNNs described in Section 2 to the LRG sample. In order to achieve  $\gtrsim 90\%$  completeness, we set the threshold probability to be  $P_{CNN} > 0.8$  for both CNNs (see Fig. 6). We retrieve candidates passing one or the other classifier, to take advantage of the complementarity between the two CNNs, as demonstrated in Section 2.3. The number of candidates is 1213 (1.67% of the LRGs) and 1299 (1.80% of the LRGs) from the 1-band classifier and 3-band classifier, respectively, with an overlap of 442 systems ( $\sim 30\%$ ). This overlap is smaller than what was found for the “test sample” in Section 2.3. This is because in the testing phase we could exclude contaminants, which we cannot do on real data. As shown in Fig. 2, we expect some spurious candidates also at the high-end of the  $P_{CNN}$  distribution. The final list of candidates, after removing duplicates, comprises 2070 automatically selected galaxies.

We also apply the two classifiers to the BG sample. Considering that the CNNs have been trained only on LRGs. This implies higher contamination for BGs with respect to LRGs, at any given predicted  $P_{CNN}$ . Hence, with the aim of maximizing the number of HQ candidates passing the threshold, while minimizing the number of possible contaminants, we use a higher threshold, selecting only candidates with  $P_1 > 0.9$  and  $P_3 > 0.9$ . Such a strategy was proved to be successful in L+20, where we found very HQ candidates within this galaxy selection. This returns 3740 new lens candidates from the BG sample.

### 3.3. Visual inspection and selection of HQ candidates

The number of candidates that have survived this process is 487, among which 192 from the LRG sample and 295 from the BG sample. We define this as the “good quality” sample.

Seven inspectors<sup>6</sup> visually grade the “good quality” sample, according to an *ABCD* quality letter scheme where *A* is a sure lens, *B* is maybe a lens, *C* is maybe not a lens and *D* is not a lens. We subsequently associate to each letter a mark of 10, 7, 3, 0 respectively, to convert the quality flags into a score (see L+20). Furthermore, to reduce the impact of biased judgment from any of the inspectors on the final visual inspection score, we decided to remove the highest and the lowest scores

<sup>6</sup> These are RL, NRN, CS, CT, LL, WS, GC.

for each candidate, and compute the average scores,  $s_{ave}$ , from the remaining 5 inspectors.

In Fig. 11 we show the 97 candidates that have received  $s_{ave} \geq 6$ , which we define as HQ lens candidates. In Table 2 we list the “KiDS.ID”, coordinates,  $r$ -band magnitudes, probabilities from CNNs, and scores from human inspection

Among these, we identify some interesting systems. J234804.98–302855.45 is a new Einstein cross, that, based on the color and size of the quadruple images, seems to be a lensed blue nugget system like the ones we have found in Napolitano et al. (2020). J112610.75+033847.89 is a large arc around a close pair of galaxies.

The CNN has also identified strong lenses in galaxy clusters/groups, e.g., J020706.67–272644.71, J124159.31–021756.09, J014320.63–271746.99, and J021227.44–284258.00. These show clearly visible arcs around a few bright galaxies in a crowded field, suggesting a cluster environment. These systems are just a demonstration of the variety of deflectors and sources accessible with the new data, and the science one can pursue with extended spectroscopic follow-ups. Indeed, the collection of large numbers of HQ candidates provides statistical samples for DM studies in the lenses in isolation and in denser environments, as well as interesting targets to address galaxy formation issues at high redshift with lensing magnification effect. Spectroscopic confirmation remains the only missing information for these targets.

## 4. DISCUSSION

In this section, we discuss in more detail the two major outcomes from this work: the discovery of new HQ lens candidates, which we make publicly available; and the comparison between the performance of the 1-band versus the 3-band classifiers on ground-based observations.

### 4.1. The first KiDS catalog of HQ lens candidates

Putting together the new HQ candidates presented in this work with the ones previously found in KiDS (Petrillo et al. 2017, 2019a, L+20), the number of HQ candidates in the survey has reached 268. This first catalog of strong lens candidates in the final KiDS footprint is made available at this link xxxxxx.

These HQ definition candidates have a very high probability of being confirmed, as demonstrated by the follow-up observations performed so far, that generally return a  $\gtrsim 70\%$  confirmation rate (see e.g., Spiniello et al. 2019a, Lemon et al. 2020, Nord et al. 2020, Napolitano et al. 2020). The “good candidates”, instead, generally have a confirmation rate of the order of 40% or lower, making them suitable as “filler” targets for large sky spectroscopic surveys.

Our new KiDS findings are meant to contribute to the ongoing effort of the scientific community to collect the best candidates needed for the planning of large-scale spectroscopic follow-up, e.g., with 4-metre Multi-Object Spectroscopic Telescope (4MOST, de Jong et al. 2019).

Indeed, the majority of currently available candidates recently found in multi-band wide-sky surveys (e.g., Cañameras et al. 2020; Jacobs et al. 2019; Huang et al. 2021), is yet to be confirmed, thereby limiting the scientific outcome of these lens samples. Instead, large

samples of confirmed SGL events are utterly required. First, it would make process on a variety of science cases, from astrophysics to cosmology (see Section 1). Second, a large database of confirmed SGL systems is necessary to optimize the training of CNNs for future large sky surveys. In future space missions (e.g. Euclid or CSST) and ground-based observations (e.g. Rubin/LSST) we will face the challenge of selecting up to  $10^5$  lenses out of tens of million of candidates, and for this we will need highly accurate classifiers to make both the search and the spectroscopic follow-up feasible, efficient and accurate.

In this context KiDS candidates offer unique advantages. Compared with existing lens samples imaged by the Hubble Space Telescope (e.g., SLACS, Bolton et al. 2008; BELLS, Brownstein et al. 2012, BELLS GALLERY, Shu et al. 2016), KiDS, combined with the twin NIR VIKING survey (Edge et al. 2013), provides us photometry images in 9 bands ( $u, g, r, i, Z, Y, J, H, K_s$ ), which can be used for accurate stellar mass establishment of both deflectors and sources (see e.g. Napolitano et al. 2020). This is a crucial ingredient to derive unbiased DM estimates of the lenses and characterize the physics of the high redshift galaxies in the background.

KiDS lenses have a wider stellar mass coverage, which can be used, in particular, to push the study of the DM content of galaxies toward the sub- $L^*$  regime, where a transition of the DM properties has been observed (e.g., Tortora et al. 2019; Cappellari et al. 2013). This can be seen in Fig. 9, where we plot the stellar mass versus photometric redshift (photo- $z$ ) of 174<sup>7</sup> HQ lens candidates used to test the CNNs in Section 2.3 (grey dots). The photo- $z$  of KiDS lens candidates are derived from the 9-band photometry using METAPHOR, a machine learning tool for photometric redshifts (Amaro et al. 2017, 2021). Stellar masses are obtained by spectral energy distribution (SED) fitting of the 9-band photometry using Lephare (Ilbert et al. 2006). For the latter, we adopt the Bruzual & Charlot (2003) stellar population synthesis models and assume a Chabrier (2003) stellar Initial Mass Function. As uncertainties on the stellar masses, we consider a 0.2 dex mean error, which reasonably accounts for modeling methods, and photometry and redshift uncertainties (see Wright et al. 2019 for details).

In the same figure, in red and blue we overplot confirmed gravitational lenses from the Sloan Lens ACS Survey (SLACS, Bolton et al. 2006b) and the Survey of Gravitationally-lensed Objects in HSC Imaging (SuGOHI, Sonnenfeld et al. 2019), respectively. SLACS objects cover a lower redshift range and have a mass distribution which is more biased toward high stellar masses, whilst are restricted to  $z \geq 0.4$  and do not cover the lowest mass bins. Compared to both datasets, KiDS shows a more extended distribution both in redshift and stellar masses.

Moreover, the 9-band photometry offers a unique opportunity to exploit the use of accurate photo- $z$ s of both lenses and sources (Li et al. in preparation). These can be used to have a first photometric solid indication of the true lensing nature of the system, hence providing an ultra-refined sample for deeper spectroscopic follow-up. Finally, (unbiased) photo- $z$ s can be used in the ray-

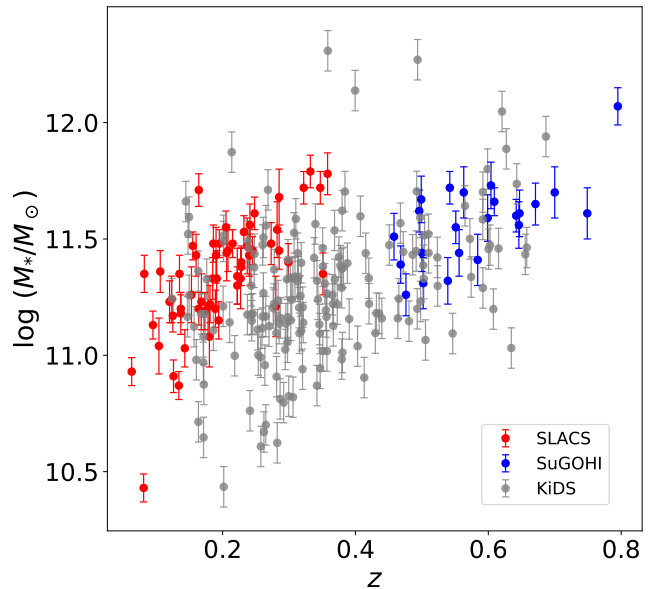


FIG. 9.— Stellar mass versus redshift for KiDS HQ lens candidates (grey dots), and confirmed lenses from SLACS (red symbols) and the SuGOHI (blue symbols). For KiDS candidates we use photometric redshifts determined by machine learning method (Amaro et al. 2021) and stellar mass from 9-band photometry SED fitting.

tracing models to derive (unbiased) mass estimates with low but reasonable accuracy ( $\sim 20 - 30\%$ ), which might be mitigated if large statistical samples are gathered.

Hence, the KiDS sample offers the possibility to enhance both detection techniques and mass modeling techniques. The optical+NIR multi-band photometry will also be available in combined datasets from future facilities (e.g. Rubin/LSST or CSST in the optical + Euclid in NIR).

#### 4.2. 1-band vs. 3-band CNN performance

An important result of this work is the comparison of the performance of the CNN that uses only high-quality  $r$ -band images (seeing  $\lesssim 0.8''$  in KiDS) and the one using color information. In Section 2.3 we have shown that the two CNNs are complementary because they recognise lenses based on different features. The 1-band case focuses on the morphology of the strong lensing features, the 3-band classifier on the color contrast between the red lens and the bluer arcs or multiple images. Ideally, one expects that the color information should improve the detection of lensing features.

However, although colors do improve the performances on simulated data, there is no corresponding increase in completeness in the real data (see Fig. 6). Here we discuss in more detail two possible reasons behind this result.

The first reason is empirical and related to the color library used to create multi-band images. This has been created from LSST simulations, which could reproduce a different color distribution with respect to that covered by KiDS galaxies, thus biasing the efficiency of the 3-band CNN when applied to KiDS data. In order to explore this possible effect, we have tested a different color library, based on COSMOS models in Lephare (Ilbert et al. 2006), as previously done to simulate arc colors in P+19. From the COSMOS library, we selected

<sup>7</sup> 5 candidates are removed because of the lack of photometry in the NIR that prevented the photo- $z$  inferences.

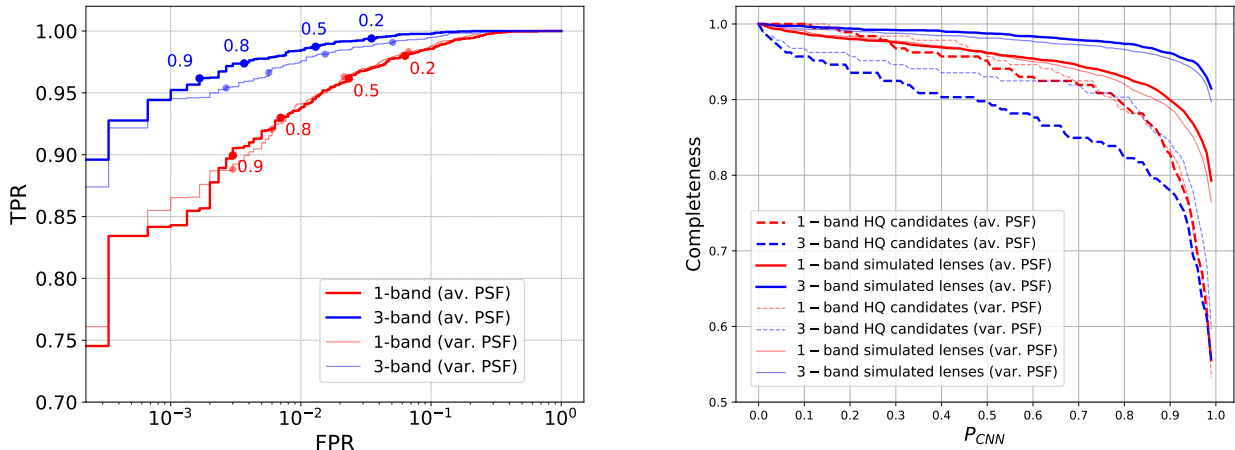


FIG. 10.— ROC curve (left) and completeness (right) of the CNNs for average PSFs (thick lines) and variable PSFs (thin lines, equivalent to Figs 3 and 6, respectively). In both panels, the red lines show the results obtained for the 1-band CNN and the blue lines these obtained for the 3-band CNN. The completeness on HQ candidates for the 3-band CNN improves using a variable PSF. All the other curves show only minimal changes.

models with galaxy types later than S0 and calculated the observed-frame magnitudes in the KiDS  $g, r, i$  bands for redshifts from 1 to 3 in steps of 0.02. From these, we produced a new color library to create the lensed images and repeated the training, validation and testing of the 3-band CNN. We have finally applied the new “COSMOS-color” CNN to both the simulated data and the real data and found no significant difference in terms of  $P_{\text{CNN}}$  with respect to the results obtained with the LSST library. However, we need to remark that the majority of the arcs simulated from these two color libraries are blue, which means that the 3-band CNN is expected to have a limited capability to identify lenses with “non-blue” arcs. In Section 2.3 we have anticipated this lower sensitivity to red or yellow arcs, compared to the 1-band classifier. In the future, we plan to extend the color library also to redder colors, to improve the completeness of the 3-band CNNs on real data.

The second reason behind the degradation of the 3-band CNN performance on the real data is methodological related to the matching of the PSFs adopted for the simulated arcs and the actual PSF of the hosts. Unlike in previous studies (P+19 and L+20) where we used an average PSF in each band, we have accounted for the observed distribution of the PSFs in each band when creating the simulated arcs with simulated PSFs.

To demonstrate that this produces a clear advantage in the final completeness, we show in Fig. 10 the ROC (left panel) and completeness curves (right panel) that we obtain adopting an average (thick lines) PSF and a variable one (thin lines). The thin lines, colored in blue for the 3-band and red for the 1-band CNN, reproduce the ones shown in Figs. 3 and 6. Interestingly, the PSF does not produce significant differences in terms of TPR/FPR (i.e. contamination). The same happens for the completeness on simulated lenses, for both CNNs. In other words, the CNNs “get out what is put in”. On real HQ lens candidates, the adoption of the average PSFs does not change significantly the completeness of the 1-band CNNs be-

cause the KiDS  $r$ -band images have a narrow seeing distribution. However, it heavily reduces the completeness of the 3-band CNN, because of the wider distribution of the real PSF of the images.

This test gives a visual idea of the impact of using an appropriate PSF when producing  $P_{\text{CNN}}$  predictions. However, the step of accounting for a realistic PSF variation has been done only for the sources but not yet for the lenses, which would impact the final completeness of real candidates. Ultimately, to improve the realism of the simulated systems, one should use the same PSF for the arcs and deflectors while, when making predictions for each individual lens, one should take into account the observed PSF of each system. Neither of these aspects have been included yet in the CNNs presented here and, together with the color optimization discussed above, represent the next developments of our work. In particular, we plan to accurately model the PSFs in different bands from stars close to the galaxies belonging to the predictive samples. These will be input in a new CNN that has been trained with pairs of images including the simulated arcs and the corresponding PSFs. Then, during the classification, the CNN will be able to weight the probability of an object to be a lens using appropriate information about the PSFs.

Finally, we list other possible sources of bias in the lens simulation, that might further reduce the predictive ability of our CNNs: 1) the distributions of the lens mass parameters (e.g. Einstein radius, axis ratios) and source parameters (magnitudes, colors, etc). If these do not cover the entire real parameter space, the predictive power of the CNNs on outliers will be affected (e.g. lenses with Einstein radius smaller than 1” or larger than ”); 2) the assumptions of the SIE profile and the “single lens” can be too simple. Some real lenses will have more than one foreground galaxies, so that both the light profile and the gravitational potential of the system will be different from the one obtained from a single galaxy. Although we have many candidates in cluster environ-

ments and pairs of galaxies in the current HQ sample, we cannot be sure that the completeness of these particular classes of system is optimized by the current CNNs. Some lenses with multi-deflectors could be missed.

## 5. CONCLUSIONS

We have built two new CNN classifiers to search for strong gravitational lenses in both 1-band (*r*) and 3-band (*gri*) color-combined images in the KiDS internal Data Release 5. The classifiers have been tested on both simulated data, made of real KiDS galaxies with artificial arcs following an empirical color distribution, and HQ candidates identified in previous KiDS releases.

We have found different performances in terms of completeness of the recovered lenses when using mock data and real HQ candidates. However, this difference is much smaller for real data, especially at higher threshold probabilities ( $P_{\text{cnn}} > 0.7$ ). On simulated data, the 3-band classifier performs much more efficiently (e.g. it reaches  $\sim 95\%$  above a CNN probability  $P_{\text{CNN}} = 0.9$ ) than the 1-band classifier (which reaches  $\sim 88\%$  at the same  $P_{\text{CNN}} = 0.9$ ). On real data, the difference is almost cancelled because of a strong degradation of the 3-band CNN performances. This has been mainly tracked to a combination of a too blue color definition of the arcs, and the impact of the non-uniform seeing in different KiDS bands.

We have demonstrated the presence of a clear complementarity between the 1-band and the 3-band CNNs, residing on the different features they are able to detect, at least in ground-based observations with sparse seeing distribution among the different filters. The 1-band focuses on the morphology of the strong lensing features, the 3-band on the color contrast between the red lens and the bluer arcs or multiple images. As a consequence, some lenses receiving a very high score from the 3-band CNNs might obtain a low probability for the 1-band one, and vice-versa. For this reason, at least for one of the “predictive samples”, we have decided to take advantage of the best capabilities of both classifiers to optimize the completeness and collect the best candidates selected from the two CNNs separately.

We have applied the new classifiers to two “predictive samples” selected from KiDS-iDR5: the luminous red galaxies (LRGs) and the bright galaxies (BGs). Using as probability thresholds  $P_1 > 0.80$  “or”  $P_3 > 0.80$  for the 1-band and 3-band CNN respectively on the LRGs and a more conservative combination of  $P_1 > 0.90$  “and”  $P_3 > 0.90$  for the BGs, the classifiers have retrieved a total of 5810 candidates. After a first visual cleaning carried out by a single inspector, we have defined a “good sample” of 487 potential lenses. These objects were fur-

ther inspected by 7 co-authors. Setting a threshold on the mean score obtained by 5 of them, after removing the highest and lowest scores, we finally collected a HQ sample of 97 lenses. These HQ lens candidates show a variety of different arcs or point-like configurations around central galaxies. Due to the high  $P_{\text{CNN}}$  and human score, these are ideal candidates for follow-up spectroscopical observations.

We have finally discussed the avenues to improve the current classifiers, related 1) to the color definition of SGL sources used to produce realistic arc/multiple image colors and 2) to the way the PSF is accounted for both for arc simulation and for lens classification. In particular, we plan to implement the PSF modeling in different bands from stars close to the galaxies belonging to the predictive samples. This information will be used as an additional “label” to be input into the next generation of classifiers. We expect this to produce a significant leap in the accuracy of our methods and to optimize the number of HQ candidates in future large sky surveys (Rubin/LSST, Euclid, CSST) while minimizing the number of false positives.

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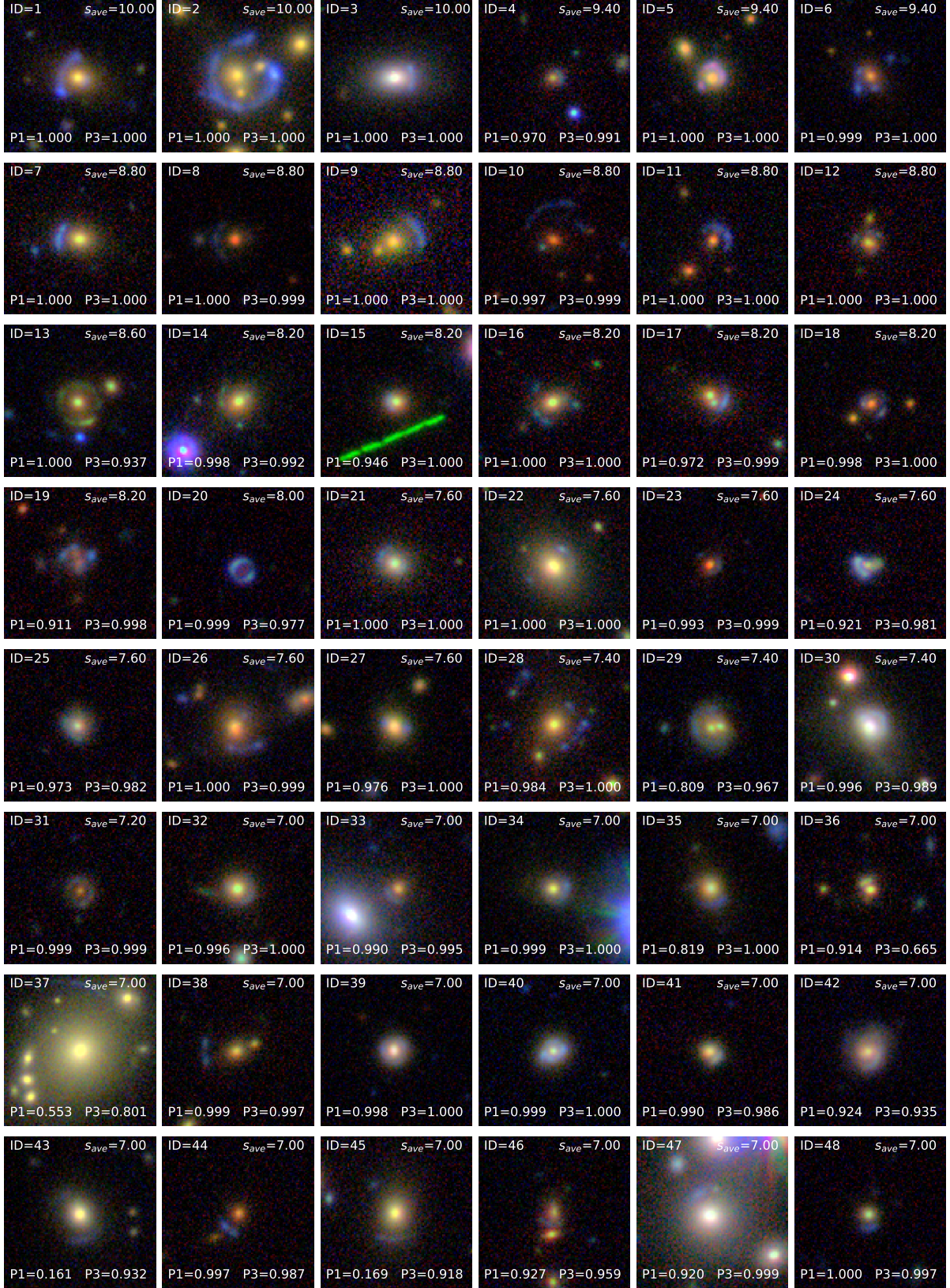


FIG. 11.— Colored stamps of the best candidates. The stamps ( $20'' \times 20''$ ) are obtained by combining  $g$ ,  $r$  and  $i$  KiDS images.

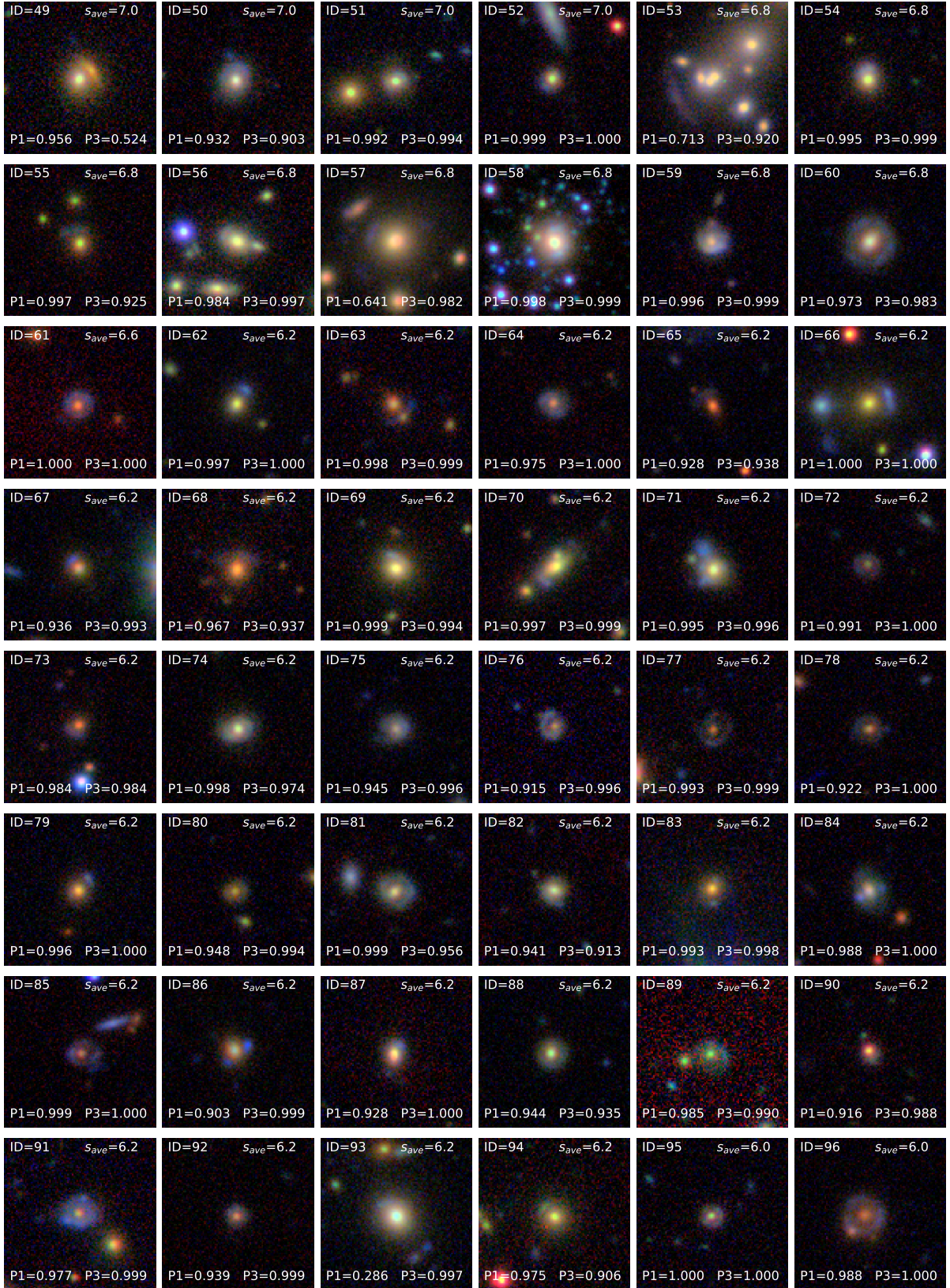


FIG. 11.— Continued

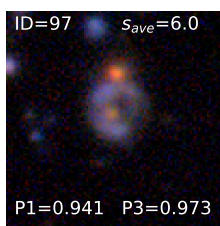


FIG. 11.— Continued



TABLE 2  
 PROPERTIES OF THE BEST 97 LENS CANDIDATES

| ID | KiDS_ID              | RAJ2000   | DECJ2000  | $r_{\text{auto}}$ | $P_1$ | $P_3$ | $s_{\text{ave}}$ | RMS  |
|----|----------------------|-----------|-----------|-------------------|-------|-------|------------------|------|
| 1  | J125808.27+033208.86 | 194.53446 | 3.53579   | 18.4582           | 1.000 | 1.000 | 10.00            | 0.00 |
| 2  | J020706.67-272644.71 | 31.77778  | -27.44575 | 17.6572           | 1.000 | 1.000 | 10.00            | 0.00 |
| 3  | J124727.77+035701.16 | 191.86571 | 3.95032   | 17.6281           | 1.000 | 1.000 | 10.00            | 0.00 |
| 4  | J124350.11+031434.75 | 190.95879 | 3.24299   | 20.4942           | 0.970 | 0.991 | 9.40             | 1.20 |
| 5  | J111826.56-033739.06 | 169.61066 | -3.62752  | 18.5258           | 1.000 | 1.000 | 9.40             | 1.20 |
| 6  | J234804.98-302855.45 | 357.02074 | -30.48207 | 19.8429           | 0.999 | 1.000 | 9.40             | 1.20 |
| 7  | J124952.79+030933.21 | 192.46998 | 3.15923   | 18.7408           | 1.000 | 1.000 | 8.80             | 1.47 |
| 8  | J020317.64-353056.15 | 30.82351  | -35.5156  | 20.4508           | 1.000 | 0.999 | 8.80             | 1.47 |
| 9  | J020526.09-353947.36 | 31.35873  | -35.66315 | 18.8324           | 1.000 | 1.000 | 8.80             | 1.47 |
| 10 | J133134.96+033139.35 | 202.89568 | 3.5276    | 20.805            | 0.997 | 0.999 | 8.80             | 1.47 |
| 11 | J142822.48+031800.06 | 217.09365 | 3.30002   | 20.5881           | 1.000 | 1.000 | 8.80             | 1.47 |
| 12 | J130004.86+014450.56 | 195.02023 | 1.74738   | 20.0374           | 1.000 | 1.000 | 8.80             | 1.47 |
| 13 | J104724.45-031242.50 | 161.85186 | -3.21181  | 19.3084           | 1.000 | 0.937 | 8.60             | 2.80 |
| 14 | J151737.38+024235.06 | 229.40577 | 2.70974   | 18.5053           | 0.998 | 0.992 | 8.20             | 1.47 |
| 15 | J105559.06+022249.79 | 163.99607 | 2.3805    | 19.0038           | 0.946 | 1.000 | 8.20             | 1.47 |
| 16 | J130526.14-035438.01 | 196.35892 | -3.91056  | 18.9711           | 1.000 | 1.000 | 8.20             | 1.47 |
| 17 | J125505.51-032459.20 | 193.77294 | -3.41644  | 20.8538           | 0.972 | 0.999 | 8.20             | 1.47 |
| 18 | J143354.72+030014.06 | 218.478   | 3.0039    | 20.474            | 0.998 | 1.000 | 8.20             | 1.47 |
| 19 | J014907.97-313738.93 | 27.28322  | -31.62748 | 20.953            | 0.911 | 0.998 | 8.20             | 1.47 |
| 20 | J023341.29-344759.24 | 38.42204  | -34.79979 | 20.7505           | 0.999 | 0.977 | 8.00             | 2.76 |
| 21 | J120143.00-035815.58 | 180.42918 | -3.97099  | 18.589            | 1.000 | 1.000 | 7.60             | 1.20 |
| 22 | J134404.67-030629.89 | 206.01944 | -3.1083   | 17.5325           | 1.000 | 1.000 | 7.60             | 1.20 |
| 23 | J143018.63+034441.30 | 217.57761 | 3.74481   | 20.8596           | 0.993 | 0.999 | 7.60             | 1.20 |
| 24 | J115351.61-033558.18 | 178.46503 | -3.59949  | 19.534            | 0.921 | 0.981 | 7.60             | 1.20 |
| 25 | J121631.22-035304.15 | 184.13008 | -3.88449  | 19.3739           | 0.973 | 0.982 | 7.60             | 1.20 |
| 26 | J224120.79-272937.60 | 340.33662 | -27.49378 | 18.5693           | 1.000 | 0.999 | 7.60             | 1.20 |
| 27 | J014319.43-321914.54 | 25.83097  | -32.32071 | 18.9009           | 0.976 | 1.000 | 7.60             | 1.20 |
| 28 | J124157.98+034721.94 | 190.49158 | 3.78943   | 17.9694           | 0.984 | 1.000 | 7.40             | 2.58 |
| 29 | J112610.75+033847.89 | 171.54477 | 3.64664   | 19.4704           | 0.809 | 0.967 | 7.40             | 2.58 |
| 30 | J122203.54+030743.20 | 185.51474 | 3.12867   | 17.351            | 0.996 | 0.989 | 7.40             | 2.58 |
| 31 | J115247.36+034255.18 | 178.19734 | 3.71533   | 20.3757           | 0.999 | 0.999 | 7.20             | 3.43 |
| 32 | J003639.79-342535.61 | 9.16581   | -34.42656 | 18.7459           | 0.996 | 1.000 | 7.00             | 0.00 |
| 33 | J130021.54-035610.71 | 195.08977 | -3.93631  | 19.2234           | 0.990 | 0.995 | 7.00             | 0.00 |
| 34 | J001011.07-270046.47 | 2.54611   | -27.01291 | 17.433            | 0.999 | 1.000 | 7.00             | 0.00 |
| 35 | J014658.63-264616.68 | 26.74428  | -26.7713  | 18.978            | 0.819 | 1.000 | 7.00             | 0.00 |
| 36 | J124100.73+031802.65 | 190.25303 | 3.30074   | 19.6761           | 0.914 | 0.665 | 7.00             | 0.00 |
| 37 | J143821.90+034013.28 | 219.59123 | 3.67036   | 16.3782           | 0.553 | 0.801 | 7.00             | 0.00 |
| 38 | J004919.61-352730.58 | 12.33172  | -35.4585  | 19.8968           | 0.999 | 0.997 | 7.00             | 0.00 |
| 39 | J231852.22-273759.16 | 349.71757 | -27.6331  | 18.9433           | 0.998 | 1.000 | 7.00             | 0.00 |
| 40 | J145605.71+033707.02 | 224.0238  | 3.61862   | 18.9394           | 0.999 | 1.000 | 7.00             | 0.00 |
| 41 | J004419.36-350407.80 | 11.08066  | -35.06883 | 19.5136           | 0.990 | 0.986 | 7.00             | 0.00 |
| 42 | J230502.92-264517.15 | 346.26215 | -26.75476 | 18.7199           | 0.924 | 0.935 | 7.00             | 0.00 |
| 43 | J120813.61+035444.17 | 182.0567  | 3.91227   | 18.301            | 0.161 | 0.932 | 7.00             | 0.00 |
| 44 | J004838.52-351355.91 | 12.1605   | -35.2322  | 20.5841           | 0.997 | 0.987 | 7.00             | 0.00 |
| 45 | J122455.77+031337.92 | 186.23238 | 3.2272    | 18.2486           | 0.169 | 0.918 | 7.00             | 0.00 |
| 46 | J123129.73+034716.39 | 187.87387 | 3.78789   | 20.1557           | 0.927 | 0.959 | 7.00             | 0.00 |
| 47 | J133221.82-031517.42 | 203.0909  | -3.25484  | 16.5788           | 0.920 | 0.999 | 7.00             | 0.00 |
| 48 | J014538.40-305936.15 | 26.40999  | -30.99338 | 20.1657           | 1.000 | 0.997 | 7.00             | 0.00 |
| 49 | J103244.87+035608.11 | 158.18696 | 3.93559   | 18.5431           | 0.956 | 0.524 | 7.00             | 0.00 |
| 50 | J132731.02+033655.73 | 201.87927 | 3.61548   | 18.8195           | 0.932 | 0.903 | 7.00             | 0.00 |
| 51 | J122917.55+031330.57 | 187.32312 | 3.22516   | 19.0799           | 0.992 | 0.994 | 7.00             | 0.00 |
| 52 | J120355.23-033218.89 | 180.98013 | -3.53858  | 19.8452           | 0.999 | 1.000 | 7.00             | 0.00 |
| 53 | J015148.40-323715.86 | 27.95167  | -32.62107 | 17.9265           | 0.713 | 0.920 | 6.80             | 2.23 |
| 54 | J125632.39-021600.64 | 194.13498 | -2.26684  | 19.0053           | 0.995 | 0.999 | 6.80             | 2.23 |
| 55 | J013336.28-321114.42 | 23.40117  | -32.18734 | 19.8008           | 0.997 | 0.925 | 6.80             | 2.23 |
| 56 | J134223.83-035645.69 | 205.59929 | -3.94603  | 18.5063           | 0.984 | 0.997 | 6.80             | 2.23 |
| 57 | J014320.63-271746.99 | 25.83596  | -27.29639 | 17.6511           | 0.641 | 0.982 | 6.80             | 2.23 |
| 58 | J024000.80-341812.44 | 40.00335  | -34.30346 | 17.6939           | 0.998 | 0.999 | 6.80             | 2.23 |

NOTE. — We list from Column 1 to 4, the ID, the KiDS name and the coordinates (in degrees) of the candidates, respectively. Column 5 lists the total magnitudes ( $r_{\text{auto}}$ ) obtained by from SExtractor. Column 6 and 7 list the probability to be a lens from 1-band CNN and 3-band CNN. Column 8 and 9 list the average scores from human inspection and the corresponding RMS.).

TABLE 2  
 PROPERTIES OF THE BEST 82 LENS CANDIDATES

| ID | KiDS_ID              | RAJ2000   | DECJ2000  | $r_{\text{auto}}$ | $P_1$ | $P_3$ | $s_{\text{ave}}$ | RMS  |
|----|----------------------|-----------|-----------|-------------------|-------|-------|------------------|------|
| 59 | J111401.10-033323.54 | 168.50457 | -3.55654  | 19.0885           | 0.996 | 0.999 | 6.80             | 2.23 |
| 60 | J222201.35-273614.23 | 335.50565 | -27.60395 | 18.7133           | 0.973 | 0.983 | 6.80             | 2.23 |
| 61 | J023206.32-352923.41 | 38.02635  | -35.48984 | 20.0357           | 1.000 | 1.000 | 6.60             | 3.14 |
| 62 | J000651.87-271357.05 | 1.71611   | -27.23251 | 19.591            | 0.997 | 1.000 | 6.20             | 1.60 |
| 63 | J031418.60-284156.45 | 48.57751  | -28.69901 | 20.0205           | 0.998 | 0.999 | 6.20             | 1.60 |
| 64 | J003118.07-350132.27 | 7.82531   | -35.02563 | 20.0741           | 0.975 | 1.000 | 6.20             | 1.60 |
| 65 | J102839.00-030048.13 | 157.16251 | -3.01337  | 20.6399           | 0.928 | 0.938 | 6.20             | 1.60 |
| 66 | J234124.17-271145.14 | 355.35073 | -27.19587 | 19.1013           | 1.000 | 1.000 | 6.20             | 1.60 |
| 67 | J023517.89-271129.01 | 38.82454  | -27.19139 | 17.9813           | 0.936 | 0.993 | 6.20             | 1.60 |
| 68 | J002342.53-350534.93 | 5.9272    | -35.09304 | 19.3053           | 0.967 | 0.937 | 6.20             | 1.60 |
| 69 | J125940.84-032637.29 | 194.92017 | -3.44369  | 18.418            | 0.999 | 0.994 | 6.20             | 1.60 |
| 70 | J020518.38-273743.38 | 31.32657  | -27.62872 | 18.6231           | 0.997 | 0.999 | 6.20             | 1.60 |
| 71 | J014535.28-313235.48 | 26.39699  | -31.54319 | 18.7319           | 0.995 | 0.996 | 6.20             | 1.60 |
| 72 | J003617.62-343420.56 | 9.07342   | -34.57238 | 20.9532           | 0.991 | 1.000 | 6.20             | 1.60 |
| 73 | J021203.87-270653.29 | 33.01613  | -27.1148  | 20.2011           | 0.984 | 0.984 | 6.20             | 1.60 |
| 74 | J000654.69-283746.64 | 1.72787   | -28.62962 | 19.1697           | 0.998 | 0.974 | 6.20             | 1.60 |
| 75 | J002823.72-265957.95 | 7.09883   | -26.99943 | 19.6856           | 0.945 | 0.996 | 6.20             | 1.60 |
| 76 | J134604.91-032322.36 | 206.52046 | -3.38954  | 20.5645           | 0.915 | 0.996 | 6.20             | 1.60 |
| 77 | J132205.60-014938.03 | 200.52334 | -1.82723  | 20.7019           | 0.993 | 0.999 | 6.20             | 1.60 |
| 78 | J132326.60+033701.12 | 200.86085 | 3.61698   | 20.5082           | 0.922 | 1.000 | 6.20             | 1.60 |
| 79 | J120913.95+031014.33 | 182.30813 | 3.17065   | 19.9832           | 0.996 | 1.000 | 6.20             | 1.60 |
| 80 | J110322.38-010726.73 | 165.84325 | -1.12409  | 20.5388           | 0.948 | 0.994 | 6.20             | 1.60 |
| 81 | J112307.43-032628.80 | 170.78097 | -3.44133  | 19.3007           | 0.999 | 0.956 | 6.20             | 1.60 |
| 82 | J110256.69-011831.10 | 165.73622 | -1.30864  | 19.4852           | 0.941 | 0.913 | 6.20             | 1.60 |
| 83 | J124914.12-033404.02 | 192.30883 | -3.56778  | 18.814            | 0.993 | 0.998 | 6.20             | 1.60 |
| 84 | J014403.02-321237.07 | 26.01258  | -32.2103  | 19.7753           | 0.988 | 1.000 | 6.20             | 1.60 |
| 85 | J012246.67-273322.09 | 20.69444  | -27.55613 | 20.8031           | 0.999 | 1.000 | 6.20             | 1.60 |
| 86 | J014603.78-264457.39 | 26.51576  | -26.74927 | 19.7145           | 0.903 | 0.999 | 6.20             | 1.60 |
| 87 | J111500.11-025804.30 | 168.75047 | -2.96786  | 19.2168           | 0.928 | 1.000 | 6.20             | 1.60 |
| 88 | J143738.88-031635.12 | 219.41199 | -3.27642  | 19.7014           | 0.944 | 0.935 | 6.20             | 1.60 |
| 89 | J133214.79-005719.17 | 203.06162 | -0.95533  | 19.8245           | 0.985 | 0.990 | 6.20             | 1.60 |
| 90 | J125935.77-024708.16 | 194.89906 | -2.7856   | 20.4277           | 0.916 | 0.988 | 6.20             | 1.60 |
| 91 | J115735.71+034500.96 | 179.39877 | 3.75027   | 19.0632           | 0.977 | 0.999 | 6.20             | 1.60 |
| 92 | J145209.65+034947.22 | 223.04023 | 3.82978   | 20.6841           | 0.939 | 0.999 | 6.20             | 1.60 |
| 93 | J112440.94+030347.95 | 171.17057 | 3.06332   | 17.9943           | 0.286 | 0.997 | 6.20             | 1.60 |
| 94 | J125148.11+034128.43 | 192.95046 | 3.69123   | 18.9286           | 0.975 | 0.906 | 6.20             | 1.60 |
| 95 | J122932.16+033726.90 | 187.38402 | 3.62414   | 20.4791           | 1.000 | 1.000 | 6.00             | 2.68 |
| 96 | J232142.07-271318.88 | 350.42531 | -27.22191 | 19.6246           | 0.988 | 1.000 | 6.00             | 2.68 |
| 97 | J010552.76-352030.92 | 16.46984  | -35.34192 | 19.5707           | 0.941 | 0.973 | 6.00             | 3.95 |

NOTE. — continued.