


























The impact of human expert visual inspection on the discovery of strong gravitational lenses

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ABSTRACT

We investigate the ability of human ‘expert’ classifiers to identify strong gravitational lens candidates in Dark Energy Survey like imaging. We recruited a total of 55 people that completed more than 25 percent of the project. During the classification task, we present to the participants 1489 images. The sample contains a variety of data including lens simulations, real lenses, non-lens examples, and unlabelled data. We find that experts are extremely good at finding bright, well-resolved Einstein rings, while arcs with g -band signal to noise less than ~ 25 or Einstein radii less than ~ 1.2 times the seeing are rarely recovered. Very few non-lenses are scored highly. There is substantial variation in the performance of individual classifiers, but they do not appear to depend on the classifier’s experience, confidence or academic position. These variations can be mitigated with a team of 6 or more independent classifiers. Our results give confidence that humans are a reliable pruning step for lens candidates, providing pure and quantifiably complete samples for follow-up studies.

Key words: gravitational lensing; strong.

1 INTRODUCTION

The phenomenon of strong gravitational lensing has enormous power as a tool to study a variety of cosmological questions. For example, strong lenses enable a magnified view of the high-redshift Universe (Christensen et al. 2012; Stark et al. 2015; Shu et al. 2016; Ebeling et al. 2018; Shu et al. 2022), a direct probe of dark matter in galaxies, clusters, and substructures (Oguri et al. 2002; Vegetti et al. 2010; Jiménez-Vicente et al. 2015; Nierenberg et al. 2017; Gilman, Birrer & Treu 2020) and a geometrical probe of the cosmological parameters

(Collett & Auger 2014; Bonvin et al. 2017; Wong et al. 2020). Despite the potential of this tool, almost all applications of strong lensing are limited by sample size, but the era of deep wide area surveys offers an opportunity to grow strong lens samples a hundredfold (Collett 2015), and with that improve current studies and enable the exploration of novel ideas as lens supernovae or compounds lenses.

As astronomy enters the era of billion object surveys, sophisticated methods for discovering strong lenses have been developed (e.g. Lanusse et al. 2018; Avestruz et al. 2019) and applied (Jacobs et al. 2017; Petrillo et al. 2017, 2019; Jacobs et al. 2019a, b; Rojas et al. 2022; Savary et al. 2022). These methods have been extremely successful at identifying candidate lenses, but the rarity of lenses means that even classifiers with 99.99 per cent accuracy produce 100 false positives for every true lens. The gold standard for confirming a lens is spectroscopic confirmation of multiple redshifts,

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but reducing false positive rates is needed for a spectroscopic confirmation campaign to be viable. In most cases, a human expert step is used as the final stage filtering step to remove false positives.

Expert human classification has been very successful at identifying the best strong lens candidates. For example, Tran et al. (2022) recently targeted 79 lens candidates, spectroscopically confirming 53 and definitely ruling out only 4.¹ However, introducing a human into any classification task is likely to bring in selection biases: it is much easier to identify a bright arc that is well resolved from the lensing galaxy and significantly different in colour.

The primary purpose of this work is to calibrate and understand how introducing human experts biases lens searches. In addition, we aim to understand how the choice of ‘experts’ impacts the lens candidate sample selected and how search teams can mitigate the biases of their members. We set out to answer the following questions:

- (i) What are the properties of lensing systems that human experts identify reliably as lenses, and what do they miss?
- (ii) Do human experts confuse non-lenses for lenses?
- (iii) How does expert classification depend on the experience and confidence of the experts?
- (iv) How reliable are individual classifications?
- (v) When ranking lens candidates, what do the scores of teams of experts mean?
- (vi) How should lens searchers best build an expert team to classify their candidates?

In Section 2, we will lay out our experiment, data, and expert participants. In Section 3, we investigate how subsets of the lens candidates are scored by the ensemble of our users, enabling us to understand the selection biases of our experts. In Section 4, we investigate how individual users perform on the classification task. We summarize the conclusions of this work in Section 5.

2 THE EXPERIMENT

Our experiment is designed to understand human expert biases when performing visual inspection of strong lens candidates. With experts we refer to any person involved in strong lensing research, with an academic status from masters student to Professor (or similar). Additionally, we invited a small number of citizen scientists from outside the academic strong lensing community. Several of these are experienced users from the Spacewarps project. The details of our invitation to be part of this experiment can be found in Appendix A.

We used the citizen science web portal Zooniverse² to serve a sample of 1489 images for classification.

The users were asked to choose the best description for the object displayed from four options: (1) Certain lens (> 90 per cent), (2) Probable lens (50–90 per cent), (3) Probably not a lens (2–50 per cent), and (4) Very unlikely (< 1 per cent). We included percentages of confidence to be a lens to avoid semantic uncertainty.³

We designed our experiment to closely mimic a real strong lens classification task. In real lens searches, there are no tutorials, and

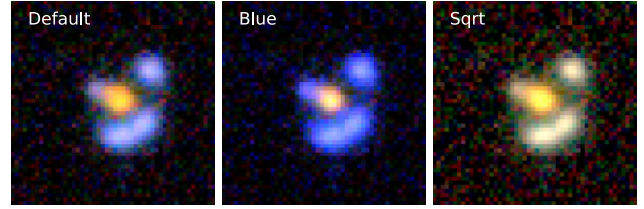


Figure 1. Example of a DES cutout of 50×50 pixels ($13 \text{ arcsec} \times 13 \text{ arcsec}$) of an object displayed in the three different scales presented to the users in the experiment.

there is limited prior knowledge of the completeness and purity of the sample to be classified. We therefore avoided offering further guidelines about the composition of the data sets to be classified. For the same reason, we did not offer a tutorial nor examples as would be usual in a citizen science project.

2.1 The data

The image cut-outs are from the Dark Energy Survey (DES). DES uses the Blanco 4-m telescope and the Dark Energy Camera (DECam; Honscheid & DePoy 2008; Flaugher et al. 2015) located at Cerro Tololo Inter-American Observatory (CTIO), Chile. The observations are performed in the optical *grizY* bands. We used *gri*-bands to produce colour composite 50×50 pixels ($\sim 13 \text{ arcsec} \times 13 \text{ arcsec}$) images centring the object of interest in the middle. The images have a typical 5σ depth of 23.72, 23.35, 22.88 in *gri*, respectively.

We simultaneously display three different colour scalings of each image to facilitate the recognition of the different features in the stamp (see Fig. 1). The three imaging scalings are Default, blue and sqrt, and they are described in Appendix B.

Since we aimed to assess the classification skills of experts, we required both a sufficiently large number of experts to participate and sufficient classifications per expert. This creates tension for experiment design since experts have difficulty engaging with the experiment if the classification task is too large. We decided that a sample size of around 1000 objects (around an hour of time assuming 2 s per classification) was small enough to get significant engagement and large enough to provide useful data.

Given the rarity of real lenses on the sky, a random sample of ~ 1000 objects will not provide useful data. Instead, we designed a sample to have a broad variety of data including: simulated lenses; real lens candidates; non-lens examples; and unlabelled data. We also duplicated 105 cut-outs, 15 cut-outs from seven out of nine data sets excluding the eleven examples from SLACS, and the four lenses from Rojas et al. (2022). The idea is to investigate the level of consistency of individuals when classifying. In total, we had 1489 images to classify.

Below we describe the different data sets, which are in three main categories: lens simulations and lens candidates that are labelled as lenses; negative examples that are labelled as non-lenses; and unlabelled data. In Table 1, we present the name, number of objects, and category of each data set and in Fig. 2 we present as an example the image of four objects of each labelled data set, more details about these sets can be found in the following sections. Our sample is not actively selected to include common false positives such as spiral, irregular, interacting or ring galaxies, it also does not include lensing by disc galaxies or groups of galaxies. This is due to the sample size of 1500 objects

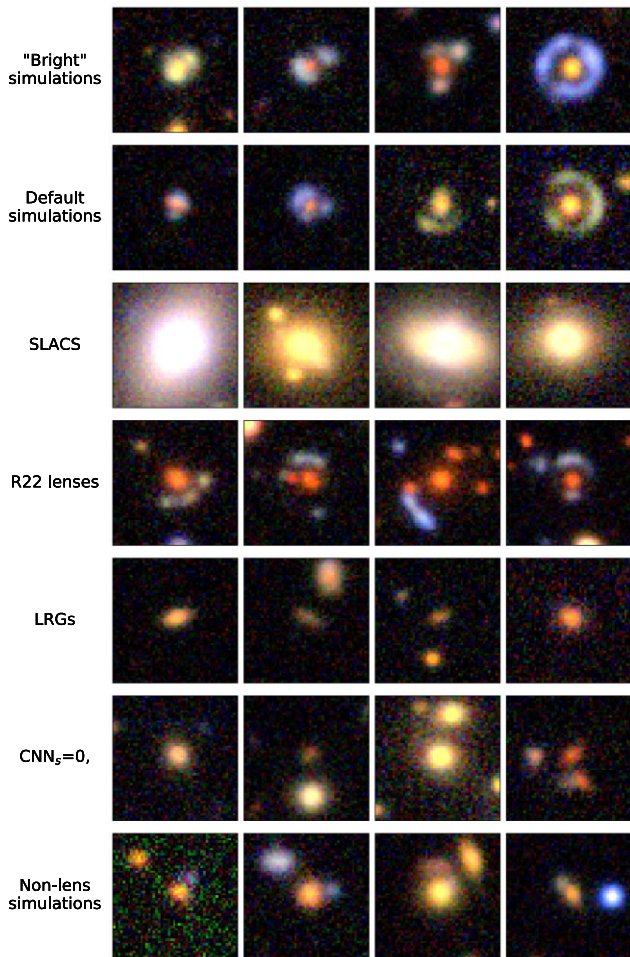
¹Twenty of the remaining objects are likely strong lenses but redshifts were not obtained for both lens and source in 20 of the systems. Twenty systems yielded no redshifts.

²<https://www.zooniverse.org/projects/krojas26/experts-visual-inspection-experiment>

³Formally, these percentages cannot be probabilities since we did not provide the users with prior information on the composition of the sample being classified.

Table 1. Data sets presented in the experiment.

Data set name	Number of objects	Category
'Bright' simulations	150	Lens data set
Default simulations	150	Lens data set
SLACS	11	Lens data set
R22 lenses	4	Lens data set
LRGs	150	Non-lens data set
$\text{CNN}_s = 0$	150	Non-lens data set
Non-lens simulations	150	Non-lens data set
CNN-best	300	Unlabelled data
Random	300	Unlabelled data

**Figure 2.** Example of objects presented in the different labelled data sets. 'Bright' simulations, Default simulations, SLACS and R22 lenses from Rojas et al. (2022) are examples of objects labelled as lenses, while LRGs, $\text{CNN}_s = 0$ and Non-lens simulations are examples of objects labelled as non-lenses. The cut-outs are 50×50 pixels and they are displayed in the default scale.

2.1.1 Lens simulations and additional lens examples.

We created two sets of simulations of strong lens systems. Each of them contains 160 images and both have a uniform Einstein radius distribution between $0.8 \text{ arcsec} < \theta_E < 3.0 \text{ arcsec}$.

The simulations were created using *Lenstronomy*.⁴ Birrer & Amara (2018) and Birrer et al. (2021) and are based on real images for the source and the lens. The full procedure is described in Rojas et al. (2022) and can be summarized as follows: We pair Luminous Red Galaxies (LRGs) from the DES and source galaxies from the *HST*/HSC combined catalogue compiled by Cañameras et al. (2020), here the galaxies have the *HST*/ACS F814W high resolution (Koekemoer et al. 2007; Leauthaud et al. 2007; Scoville et al. 2007) and the colour information from Hyper Suprime Cam (HSC) ultra-deep stack images (Aihara et al. 2018). We modelled the mass of the systems as a Singular Isothermal Ellipsoid (SIE), which has the following parameters: the Einstein radius (θ_E), position angle, the axis ratio, and the central position. The Einstein radius was calculated using the lens and source redshifts and the lens velocity dispersion. We inferred the lens galaxy redshift and velocity dispersion using a K-Nearest-Neighbours (KNN) algorithm, based on the assumption that galaxies with similar *gri* magnitudes will also have similar redshifts and velocity dispersion, this procedure is explained in detail in Rojas et al. (2022). The rest of the parameters are derived by fitting an elliptical Sérsic profile to the DES *r*-band image of the LRG. From this mass model, we calculate the deflection of light and trace rays back on to the source plane. The position of the source is randomly selected within a square that encloses the caustic curves. This process is done on a 0.03 arcsec pixel grid and then downsampled and PSF matched to the DES cut-out of the LRG, and the flux scaled to the DES zero-point. This simulated arc is then added to the DES LRG image to create a simulated lens.

The first data set is the 'Bright simulations'. This sample contains a selection of simulations used to train the Convolutional Neural Network (CNN) in Rojas et al. (2022), with the addition of smaller Einstein radius simulations in the range $0.8 \text{ arcsec} < \theta_E < 1.2 \text{ arcsec}$ that were not used to train the neural network in that work. In this data set, the magnitude of the sources is boosted by one magnitude brighter than the observed HSC sources. This gives a population of bright lensing features designed for the CNN to easily learn the properties of strong lenses. These simulations should be the easiest for experts of identifying as strong lenses.

The second data is the 'Default simulations'. These were created with the same procedure as in Rojas et al. (2022), but without boosting the magnitude of the source. In this set of simulations, we expect the systems to be harder to classify, since the signal-to-noise ratio (SNR) will be lower and the sources will stand out less brightly relative to the lensing galaxies.

Additionally to these two simulated sets of lenses, we added the eleven lenses from the Sloan Lens ACS Survey (SLACS; Auger et al. 2009) in the field of view of DES. These are spectroscopically confirmed, smaller Einstein radius systems, that are clear in Hubble Space Telescope imaging but represent a challenge to identify in ground-based resolution. Since small Einstein radius systems are expected to dominate in the real Universe (Collett 2015), we include the SLACS sample to see if there is any chance to identify these systems with visual inspection of ground-based telescopes. Finally, four lens candidates from Rojas et al. (2022) categorized with high scores in the 'sure lens' list were also shown to the participant to see if our classifiers agreed with the authors of Rojas et al. (2022), we call this data set 'R22 lenses'.

⁴<https://github.com/lenstronomy/lenstronomy>

2.1.2 Negative examples

We included three data sets with 150 objects each that contained non-lens examples. These samples test the classifiers' ability to reject non-lens systems. The first data set is a random sub-sample of the negative examples presented in the training set used to train the CNN in Rojas et al. (2022), we call this data set 'Non-lenses training set' and contains LRGs that were not used to create strong lens simulations.⁵ The second data set consisted of a random selection of objects that were classified by the CNN with scores near zero. We called this data set ' $\text{CNN}_s = 0$ ' and it contains stamps from the LRG selection that are highly improbable to contain any lens feature according to the CNN. The third data set is called 'Non-lens simulations': we follow the same procedure as for strong lens simulations, but we disable the lensing deflections. Instead, we paint the source nearby to the LRG. This is designed to mimic a 'source in front of LRG' alignment, which is the most potential false positive for lens classification. This sample allows us to evaluate if classifiers are able to distinguish between real compact lenses and unlensed blue galaxies close to LRGs.

2.1.3 Unlabelled data

We additionally included two data sets of unlabelled data, each set containing 300 objects. The first one contains the 300 best stamps graded by the CNN in Rojas et al. (2022), where 6 of them were flagged as 'Maybe lens' in that work. The objective of this data set is to re-do the visual inspection and compare the classifications of the authors of Rojas et al. (2022) with the participants in our experiment. We call this data set unlabelled as we do not have a confirmed classification of the objects displayed, and although this data set was previously inspected by another group we do not use this information as prior. The second set was created by selecting random objects with CNN scores distributed between 0.1 and 0.9 from the sample analysed in Rojas et al. (2022). The objective of this is both to see if CNN grades and expert grades are correlated and to see if a population of high-quality candidates are likely to be missed by CNNs.

2.2 Participants

We asked all the participants to complete a Google form requesting some basic and confidential information that we used to have a more deep analysis of this experiment. We asked three multiple choice questions. These questions and their options are as follows:

- (i) *How many years have you worked in the field of gravitational lensing?* (a) Less than 1 yr, (b) Between 1 and 4 yr, (c) Between 4 and 8 yr, (d) Between 8 and 12 yr, (e) More than 12 yr.
- (ii) *What is your research status?* (a) Master student, (b) PhD student, (c) Postdoc, (d) Professor/lecturer/similar, (e) Amateur enthusiast.⁶
- (iii) *How confident do you feel classifying lens systems?* (a) Very confident, (b) Confident, (c) A bit confident, (d) Not confident.

This information was asked so that we could search for correlations in the performance of the classifiers.

A total of 80 people filled in the Google form and a total of 69 592 classifications were made in the project. Some of the

⁵It is not impossible that this sample contains a real lens, but it is statistically unlikely.

⁶For better understanding, we call this group 'Citizen scientist' here.

Table 2. Number of participants split in the three different categories requested at the beginning of this experiment.

Academic status	Number of participants
Professors	16
Postdocs	13
PhD students	15
Master students	3
Citizen scientist	8
Years of experience in the field	
More than 12	11
8–12	8
4–8	10
1–4	17
Less than a year	9
Confidence	
Very confident	16
Confident	22
A bit confident	14
Not confident	3

users contributed only a small number of classifications and 15 per cent of them did not perform any classification – we discarded the classifications of such users. We included all classifications made by users that analysed more than 25 per cent of the sample (370 objects). This cut-off leaves 55 classifiers, where 51 per cent of them finished the whole project. Then we have a total of 66 835 classifications, with an average of 45 classifications per object.

The breakdown of the participants into the categories of academic position, years of experience, and confidence are listed in Table 2. A point of interest from the information compiled at this point is the correlation between confidence and experience. As is expected, classifiers with more experience (either a higher academic status or years working in the field) feel more confident performing the task as we can see in Appendix C.

3 RESULTS A: THE DISCOVERY OF LENSES WITH EXPERT VISUAL INSPECTION

In this section, we look at the performance of the ensemble of classifiers in identifying strong lenses.

3.1 Scoring objects

To compute a score for each object classified by our users, we translate the four different options into numbers as follows: 'Certain lens' = 1, 'Probable lens' = 2/3, 'Probably not lens' = 1/3, and 'Very unlikely' = 0. The score for each object is the mean value of all its classifications. This gives every object a score between 0 and 1: objects scoring 1 are universally considered to be a strong lens and objects scoring 0 are universally considered non-lenses.

In Fig. 3, we present the mean score histograms split into the various data subsets. Overall, we find that the scores of non-lenses are low and for many lenses the scores are high.

We investigated an alternative scoring system that up-weighted users with higher classification skill (Marshall et al. 2015), but this had no impact on our results (see Appendix D).

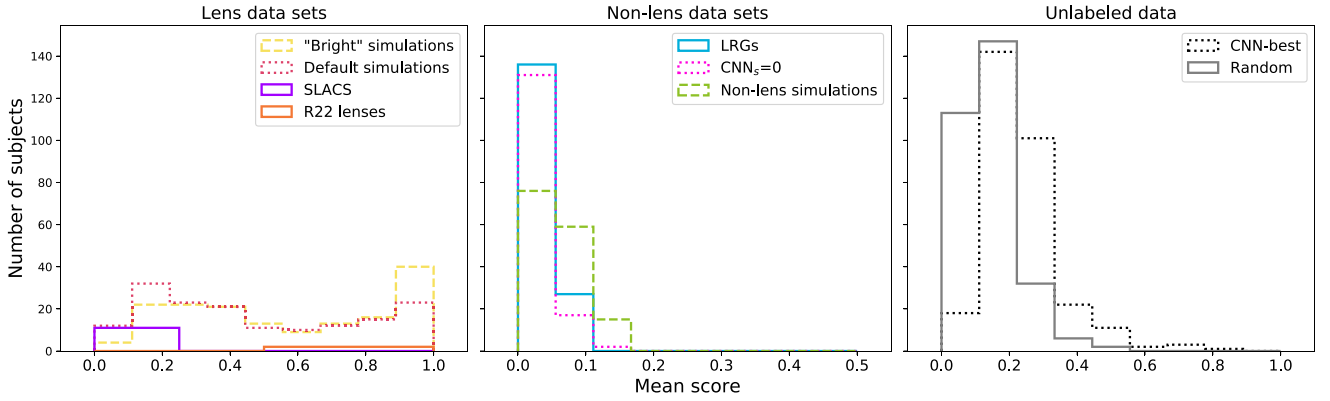


Figure 3. Mean score per object separated in each of the data sets presented in this work: lens examples (left-hand panel), non-lens examples (middle panel), and unlabelled data (right-hand panel). All the histograms have the same binning with the expectation of SLACS and R22 lenses data sets where the bin size is double for visualization purposes.

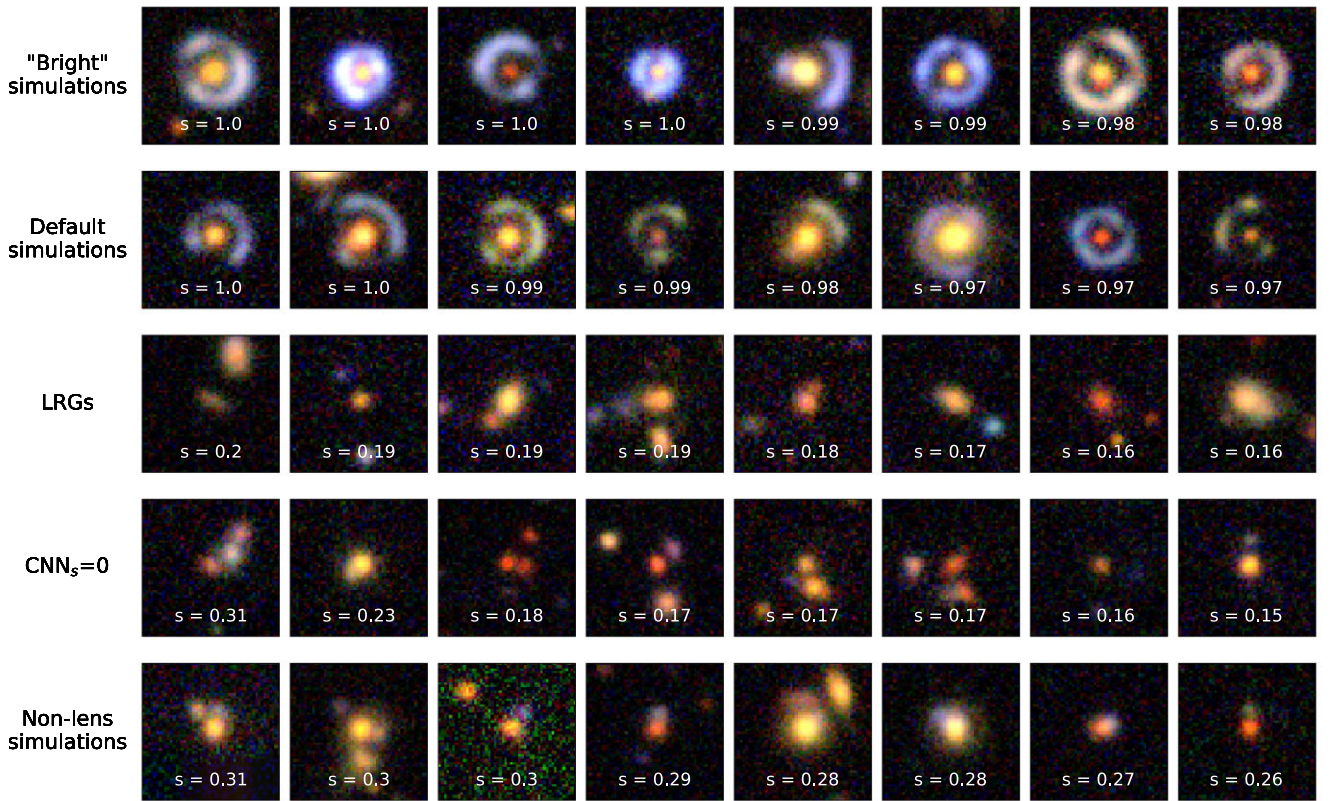


Figure 4. Examples of the eight objects with the highest mean score classified in the data sets: ‘Bright’ simulations, Default simulations, LRGs, $\text{CNN}_s = 0$, and non-lens simulations. The mean score is displayed at the bottom of each cut-out.

3.2 Scores for images known to contain lenses.

The left-hand panel in Fig. 3 shows the distribution of scores for the four data sets of objects labelled as lenses. Both simulated data sets have scores spanning the full range. This is not unsurprising: some of the simulations are bright arcs in textbook configurations, whereas others are extremely faint or are not easily resolved from the lensing galaxy. It is not a surprise that the ‘Bright’ simulation set contains a higher number of objects classified as lenses than in the ‘Default’ one: the brightest arcs stand out more from the lenses. In Fig. 4, we present the 8 cut-outs with the best

scores for each of the lens simulation samples on the two top panels.

The simulated lenses also give us an insight into the selection function of lens discovery with visual inspection. Since our sample is relatively small, we can only gain a coarse understanding of the selection function. In Figs 5 and E1, we compare the recovery fraction of simulated lenses and its standard deviation as a function of signal-to-noise ratio in the g band, the magnitude of the Arc in the g band, and the Einstein radius of the lens. Since all of our images are simulations of the approximately uniform depth Dark Energy Survey,

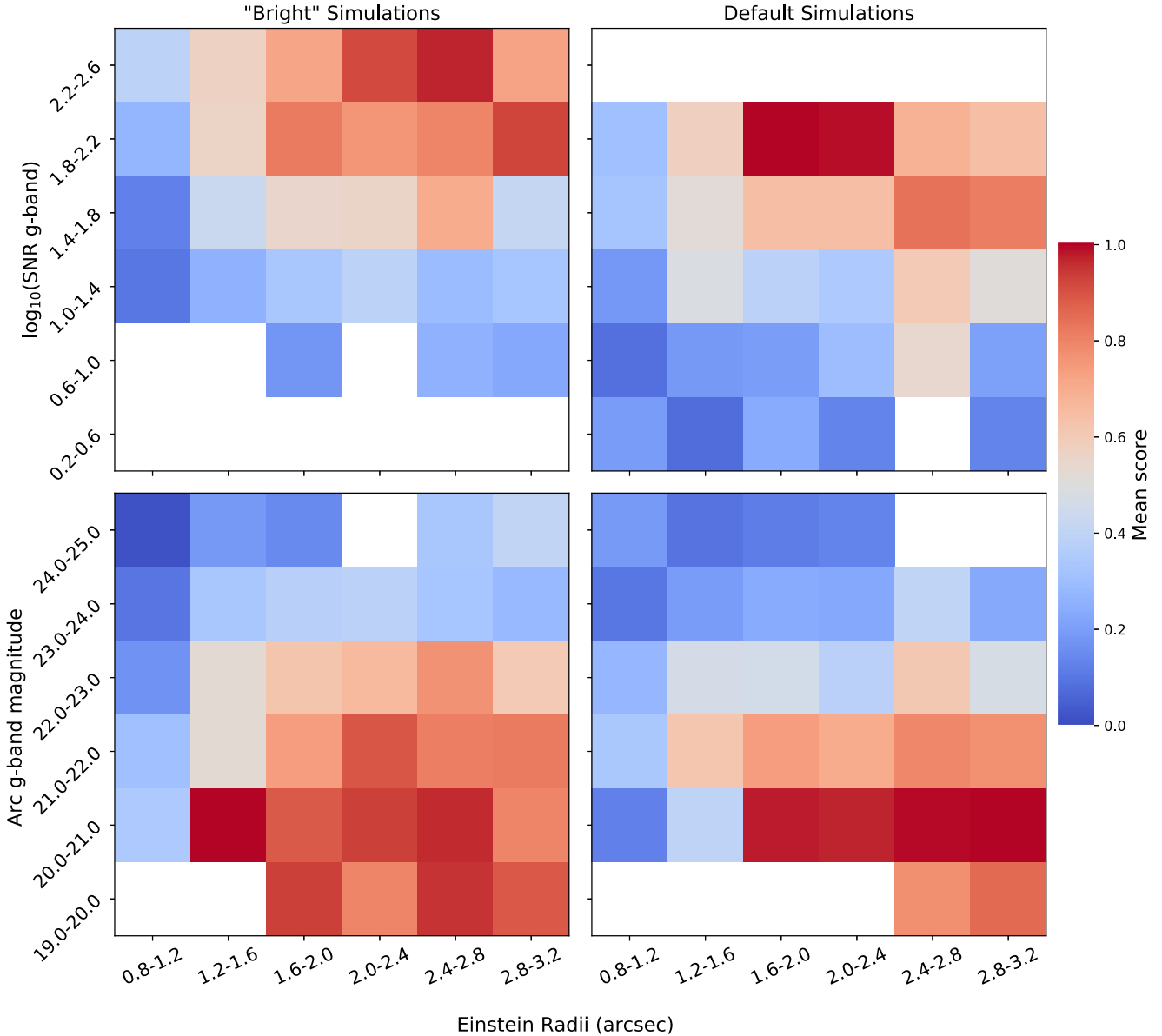


Figure 5. Heat maps with the average mean score per bins for the objects in the simulated lenses data sets. The left-hand panels correspond to the ‘Bright’ simulations, while the right-hand panels to the ‘Default’ simulations. In the top panels, we display the logarithm of the SNR in *g* band, while in the bottom panels we present the magnitude of the arc in the *g* band. The colour bar was selected with the purpose to more easily identify the bins, where the simulations can be recognized as lens systems (in red) and where they are not identified (blue).

the first two quantities are tightly correlated. It is clear from the heat maps of Fig. 5 that there is a fairly sharp cut-off in recovery fraction for each quantity. Arcs fainter than ~ 23 rd magnitude (corresponding to a total SNR less than about 25), or with Einstein radius less than ~ 1.2 arcsec are not discoverable by human eye in DES-like imaging. On the other hand, from the standard deviation of the scores we do not see any trend that allows us to get further information.

In the same way, when we analysed the SLACS sample we found that they were classified as ‘Non-lenses’. The selection function of these systems drives them to have very bright lens galaxies and Einstein radii below 1.0 arcsec in most of the cases (Dobler et al. 2008). Given the results on similar simulated lenses, it is therefore not surprising that the human experts struggled to classify these

systems as lenses. This is almost certainly because of the challenge to visually deblend the lens and source in DES imaging. The eleven SLACS systems in DES are shown in Fig. 6, in the three different colour scales along with the score that they obtained from the visual inspection.

On the other hand, the ‘R22 lenses’ received scores between 0.6 and 1.0, i.e. the classifiers consider them to probably be lenses. These R22 lenses were discovered using a visual inspection of the same DES data, so it is not surprising that these lenses remain discoverable for our classifiers. Although, as we can see in Fig. 7, the visual inspection scores obtained in Rojas et al. (2022) are somewhat different to those of our classifiers. We attribute this to human factors that we will discuss further in Section 4.3.

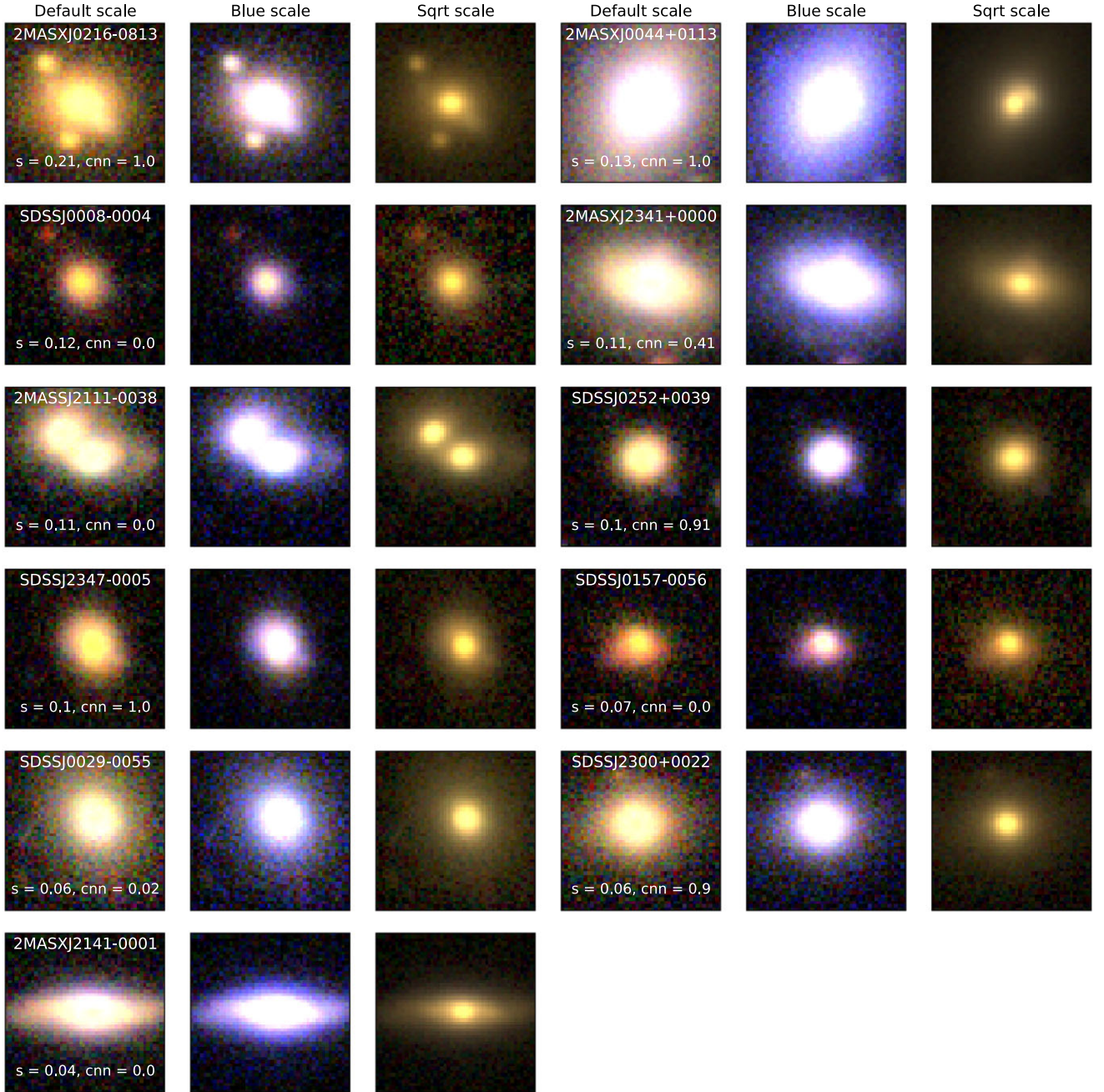


Figure 6. Mosaic of the SLACS sample in the DES. We displayed the cut-outs of each system in the same three different scales presented in the experiment: Default, Blue, and Sqrt. On the cut-out with the Default scale, we added on the top the name of the system and on the bottom the visual inspection mean score obtained in this search and the score given by the CNN trained in Rojas et al. (2022).

3.3 Performance in negative examples

Our Non-lens examples are divided in three different data sets, the distribution of scores of their objects are shown in the middle panel of Fig. 3. Here, we see that most of them were classified with scores between 0 and 0.3, meaning they are very unlikely to be lenses. The ‘Non-lens simulations’ (mimicking a chance non-lensing alignment) data set shows a broader distribution towards higher values these objects were potentially false positives, but they clearly do not particularly confuse our expert classifiers.

Even though most of the objects are correctly identified as non-lenses, in Fig. 4 we present the eight cut-outs of each sample with higher scores. Here, we can see that most of the objects in the ‘LRGs’ and ‘ $\text{CNN}_s = 0$ ’ data sets have little blue or redish companions around the central galaxy that could be mistaken for signs of lensing. In the same way, the cut-outs of the ‘Non-lens simulations’ set can be easily mistaken by very compact (low Einstein radii) lens systems, producing that some users gave a higher score to these objects. Strictly speaking, the LRG and ‘ $\text{CNN}_s = 0$ ’ sets could contain a lens, though the probability of this is $\ll 1$ per cent.

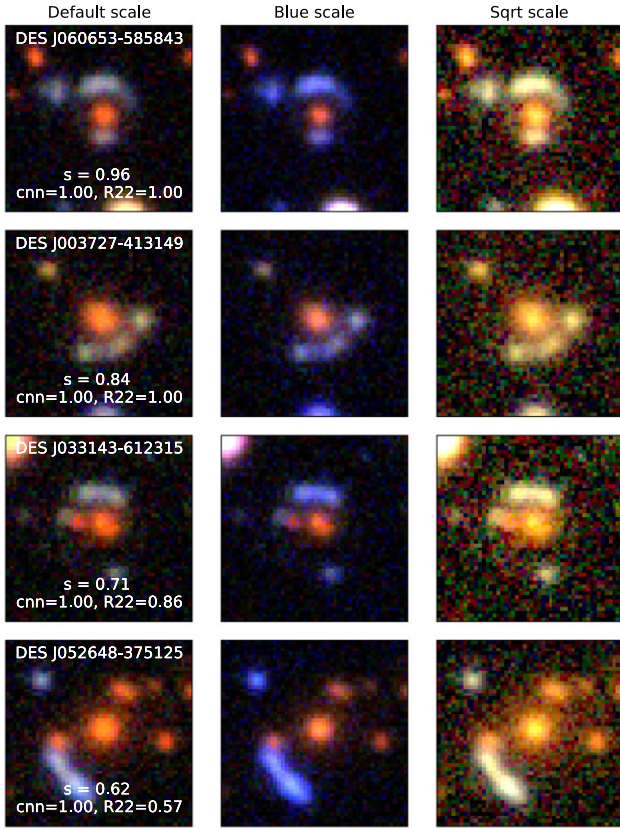


Figure 7. Mosaic of the four systems in Rojas et al. (2022) classified in their category ‘Sure lens’ displayed in the three different scales presented in this experiment. On the cut-out with the Default scale, we added on the top the name of the system, and on the bottom the mean score (s) from our visual inspection, the CNN (cnn) and visual inspection score ($R22$) from Rojas et al. (2022).

3.4 Performance in unlabelled data

We have two unlabelled data sets, ‘CNN-best’ and ‘Random’. Intuitively, we should hope that the CNN-selected sample should contain more lens candidates than the random sample. All of the CNN-best lenses have been inspected in Rojas et al. (2022). In the right-hand panel of Fig. 3, we see that the CNN-best objects are distributed between 0.0 and 0.8 (0.5 in the case of the Random sample), but the peak of these distributions are around 0.2, with most of the objects classified as Non-lenses and only a few of them have a score above 0.5.

In Fig. 8, we present the 16 cut-outs with the highest scores for each of the samples. In the ‘CNN-best’ data set, we find that five of the objects were also recognized as candidates in Rojas et al. (2022), all of them classified in their ‘Maybe lens’ catalogue. There are also seven objects with scores above 0.5 that were not classified as potential candidates in Rojas et al. (2022). In the case of the ‘Random’ sample, none of the cut-outs was classified as a potential lens candidate, although some get close to a score of 0.5. We can see some of them were highly graded by the CNN, this means that they went through the visual inspection steps in Rojas et al. (2022) but were not selected as lenses by those authors.

3.5 Comparison between CNN and visual inspection scores

We compare the classification scores given by the CNN trained in Rojas et al. (2022) with our visual inspection scores. Fig. 9 shows the scatter graph of aggregated expert scores against the CNN scores of Rojas et al. (2022). These two scores are not strongly correlated, indicating that the CNN and the experts are likely responding to different features in the images.

Since none of the objects in the Random data received a human score of 0.5 or more, we see no evidence of the CNN missing good candidates, however, this cannot be a definitive conclusion given the small sample size and the lack of correlation between the CNN and human scores. We cannot draw definitive conclusions from the CNN’s strong performance on simulations, since the CNN was trained on simulations constructed in the same way.

In the non-lens data sets, we see that most of the scores are well below 0.5, although a few non-lens simulations did manage to confuse the CNN. In a similar way, the CNN fails to recognize a subset of the lens simulations, often with a score even lower than given by the humans. In both simulated data sets, the CNN correctly classifies around 1.6 times more images as lenses than humans, with the difference mostly coming from systems where the Einstein radii are below 1.2 arcsec (Fig. 10). Similarly, some of the SLACS lenses obtained high scores by the CNN, despite being missed by the humans classifiers.

Jacobs et al. (2022) showed that, for CNN lens finders, parameters like colour, PSF, occlusion, and source magnitude play a major role in the CNN’s scoring. We clearly see in that the source magnitude of plays a major role (see Fig. 10, left-hand panel), with sources fainter than 24.5 mag not being detected by either the CNN and humans: fainter arcs are not detectable in DES-like imaging. We also see that the CNN gives higher scores to simulations with blue features, although it does reject other objects across the range of $g-i$ space. As such it appears that the CNN is correctly learning that most lensed sources are blue, rather than incorrectly assuming that most blue objects are lensed sources.

To understand cases where humans and the CNN gave contradictory scores, we compare the Einstein radii and SNR in g -band distributions for those systems (Fig. 10, right-hand panel). Several objects with high CNN scores but low visual inspection scores have small Einstein radii and/or low SNR, suggesting that the completeness of the CNN pushes further into this regime. A mosaic with examples of the simulations with mismatched scores is presented in Fig. F1.

4 RESULTS B: UNDERSTANDING EXPERT CLASSIFICATION

In this section, we investigate how individual users performed when executing the classification task.

4.1 How accurately do individuals classify our sample?

In order to evaluate the classification performed by each user we used the labelled data where we know the underlying truth: objects are either Lens or Non-lens. In our labelled category, we find 58 per cent of all the classifications (38 432 in total). Knowing the true label of each object and the classification given by each user we can compute confusion matrices to compare user performance when classifying the objects.

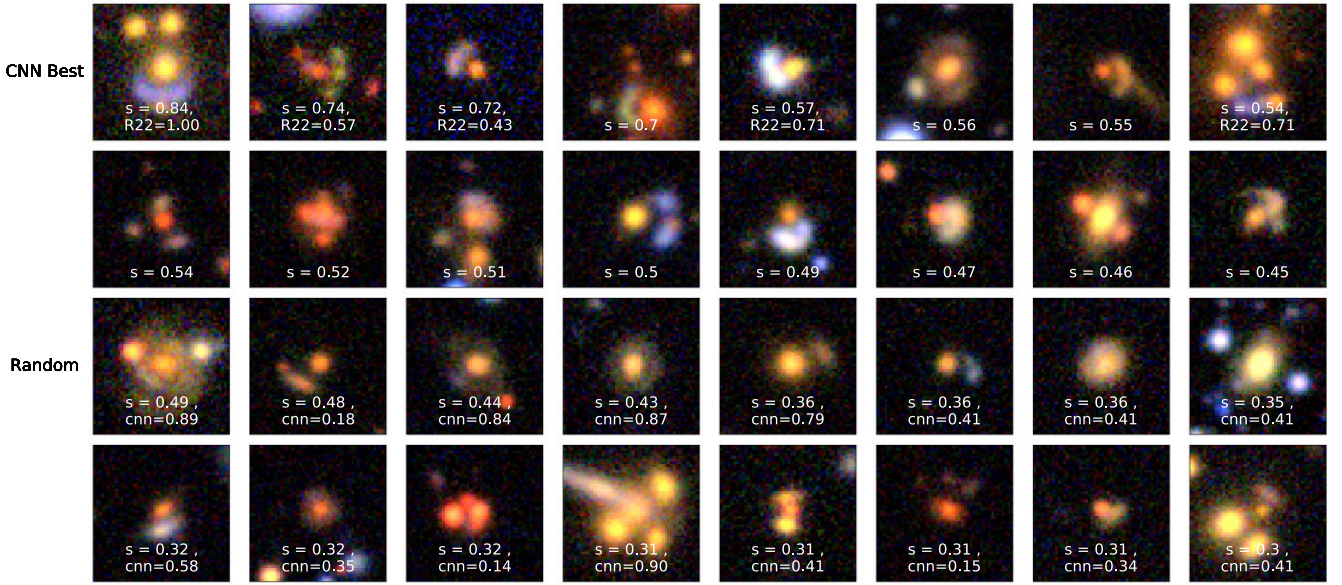


Figure 8. Examples of the 16 highly graded cut-outs in the unlabelled data sets. The CNN-best data set is displayed in the two top panels, on the bottom of the cut-outs we present the mean score (s) from this experiment, and visual inspection score (R22) from Rojas et al. (2022) in case they were part of the final catalogues presented in that work. The CNN score for all these objects is CNN = 1.00. The Random sample is shown in the two bottom panels, on the bottom of each cut-out we display the mean score (s) from this experiment, and the CNN score (cnn) from Rojas et al. (2022).

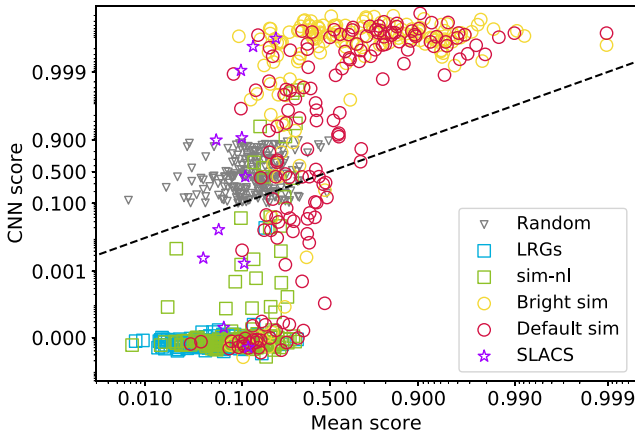


Figure 9. Comparison between the human expert scores from our classifiers and the CNN scores given by the model in Rojas et al. (2022). The dashed black line is the one-to-one line. Grey triangles are from the unlabelled 300 randomly drawn DES images. Squares are non-lens labelled data sets, in blue LRGs and in green the simulated non-lenses. Circles are simulated lenses, in yellow the bright data set and in red the default data set. Purple Stars are the SLACS lenses.

Aggregating all of the classifiers and classifications, we computed a confusion matrix displaying the four different classification options. In Fig. 11, we see the percentage of classifications that are in agreement or disagreement with the original label of the object. From here we can see that objects voted in the options ‘Certain lens,’ ‘Probable lens,’ and ‘Very unlikely’ are in general well classified, achieving overall a 99 per cent, 83 per cent, and 80 per cent of objects correctly labelled. On the other hand, the classification ‘Probably not lens’ is evenly split between labelled lenses and labelled non-lenses.

To see in more detail, the performance for each of the labelled data sets, we calculated a confusion matrix displaying the percentage of classifications according to the four different options for each

data set. From Fig. 12, we can see that the three data sets labelled as ‘Non-lenses’ obtained a very high percentage of votes in the option ‘Very Unlikely’. However, there is confusion when classifying the simulated strong lens systems. SLACS lenses are mostly not recognized as lenses and only the four ‘R22 lenses’ get a high amount of classifications in the categories ‘Certain lens’ and ‘Probable lens’.

From the classifications of the labelled data, we compute confusion matrices for each user. In this section, we call objects Lenses if they are classified as either ‘Certain lens’ or ‘Probable lens’. Systems classified as ‘Probably not lens’ or ‘Very unlikely’ are considered Non-lenses. In that way, we build a 2×2 confusion matrix that will tell us what it is the probability that a user classifies an object as ‘Lens’ or ‘Non-lens’ given that the true label is ‘Lens’ or ‘Non-lens’, this means the true positive and true negative rates in the confusion matrix.

Following Marshall et al. (2015), we plotted these probabilities in Fig. 13, where we can see that most of the classifiers have very low false positive rates. This makes these classifiers extremely good at identifying easy lenses, but there is a significant range in their ability to identify challenging lenses. Some classifiers manage completeness of ~ 60 per cent at high purity, whilst more pessimistic classifiers are identifying half as many lenses.

A handful of the classifiers are more optimistic, classifying more marginal systems as lenses. This comes at the cost of more false positives, which is not desirable in a real search where lenses are intrinsically rare.

Additionally, we computed the same 2×2 confusion matrix joining all the classifications of the users among the different groups separated by academic status, years of experience and confidence in performing the classification. This gives a confusion matrix for each grouping. To derive the error bars for these values, we use the standard deviation of the individual true positive and true negative rates of each user in the group. Fig. 14 shows these results: overall the results are very similar. That is to say that, regardless of academic status, years of experience and confidence, each grouping produces a very similar average classification. There are very significant differences between

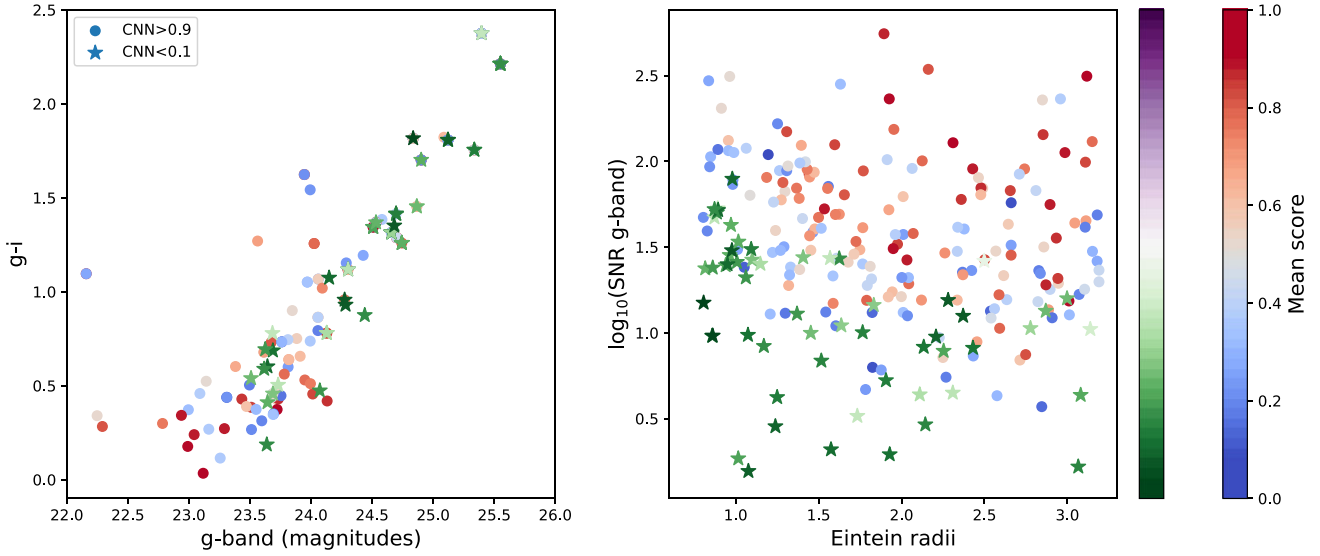


Figure 10. Scatter plots comparing source colour ($g - i$) and g -band source magnitude (left) and Einstein radii and the logarithm of the SNR in g band (right) for simulated lenses. Circular blue-red markers have a CNN score above 0.9, star-shaped green-purple markers have a CNN score below 0.1. The markers are coloured according to the mean visual inspection score.

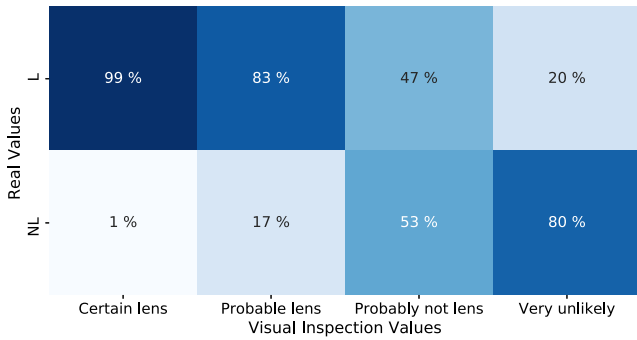


Figure 11. Confusion matrix of the four different classification options: ‘Certain lens,’ ‘Probable lens,’ ‘Probably not lens,’ and ‘Very unlikely’ contrasted with the real labels L: lens and NL: no lens. The percentages shown are the number of lenses (non-lenses) classified in a determined option.

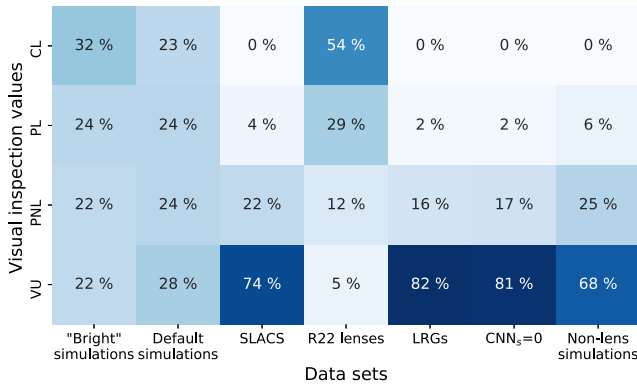


Figure 12. Confusion matrix of the seven different labelled data sets analysed in this experiment contrasted with the classification options CL: Certain lens, PL: Probable lens, PNL: Probably not lens and VU: Very unlikely. The percentages represent the amount of classifications made in each category.

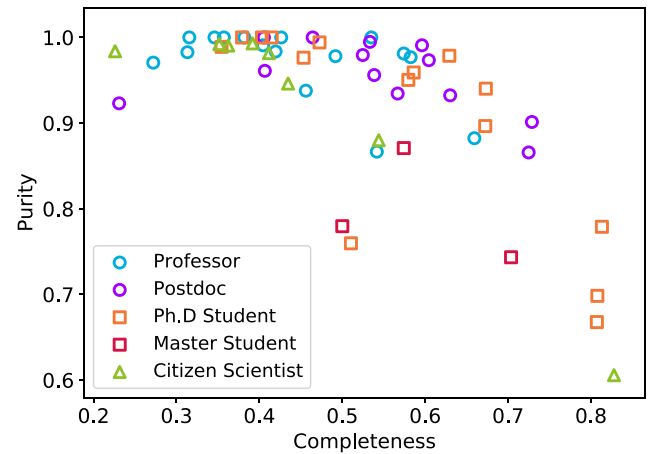


Figure 13. Completeness and purity percentages of each user when classifying our labelled data.

individual users, but time in the field, academic position or reported confidence are not predictive of a user’s classification skill.

4.2 How reliable are individual classifications?

To test the reliability of human classifications, we duplicated 105 objects in the sample. We randomly selected 15 objects from each of the following data sets: CNN-best, LRGs, CNN_s = 0, Random, Default simulations, ‘Bright’ simulations, and Non-lens simulations. The duplicate cut-outs were shown at random points in the experiment.⁷

⁷Because of the way Zooniverse serves images, some users finished the classification task but continued to classify a small number of randomly drawn images. We also took these into account in assessing the reliability of classifications.

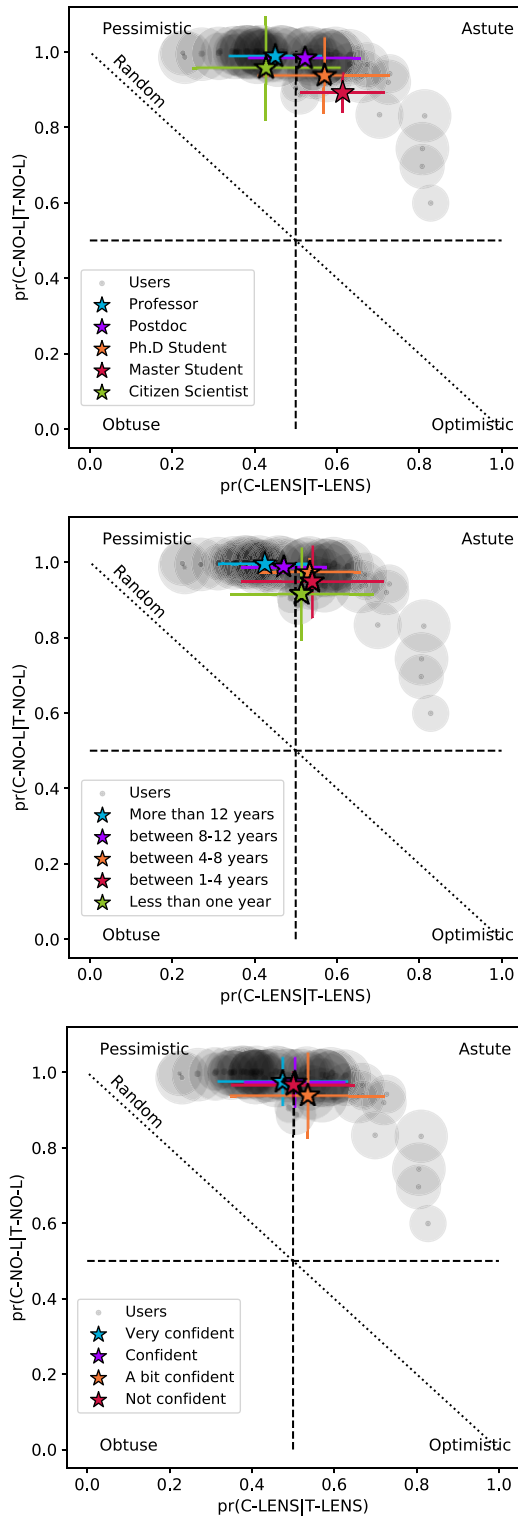


Figure 14. Probability that an object is classified as ‘Lens’ given that it is a lens (true positive rate) versus the probability that the object is classified as ‘Non-lens’ given that it is not a lens (true negative rate). The values for each of the users are displayed with a black circle, whose size represents the amount of classification made by that user. The coloured stars represent the joint result of the different groups of classifiers presented in this work, separated by academic position (top panel), years of experience (middle panel), and confidence in performing the classification task (bottom panel).

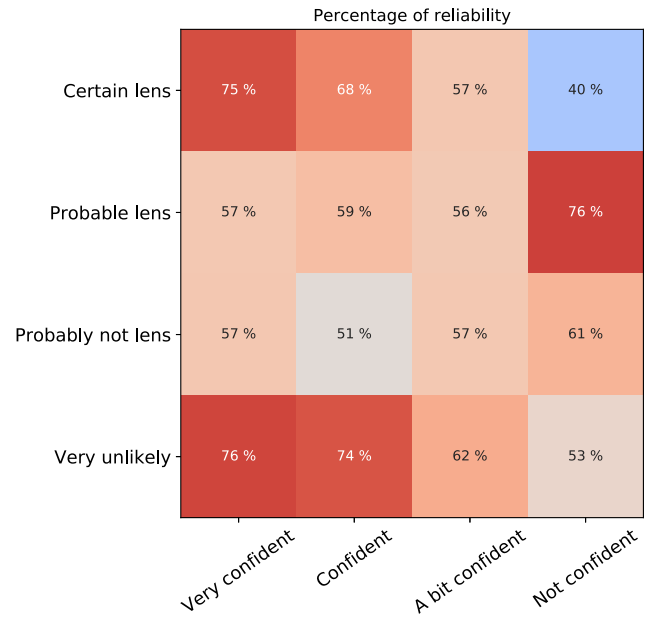


Figure 15. Reliability of repeat classifications by users, as a function of the classification and user reported confidence before starting the task. The percentages shown are the fraction of objects that have the same classification both times it was scored by a single user.

Overall, we had a total of 3797 duplicated classifications, with 73 per cent graded the same as before. On the other hand, 15 per cent (10 per cent) received an upgrade (downgrade) of one point in the classification, this means that if for example an object was originally classified as ‘Probable lens’ in the second time performing the classification the user classified the object as ‘Certain lens’ in the upgrade case and as ‘Probably not lens’ in the downgrade case. Only 1.3 per cent (0.6 per cent) of the classifications were upgraded (downgraded) by 2 points, and 0.13 per cent (0.03 per cent) by 3 points, which means changing completely the classification from ‘Certain lens’ to ‘Very unlikely’ or vice versa.

These very low percentages for extreme cases are a very good sign that the users are not obtuse classifiers and are somehow confident about their classifications. When we break these results down by self-reported confidence (Fig. 15), we see that ‘Very confident’ users perform relatively consistently, with a ~ 75 per cent of reliability in the two extreme classification options. On the other hand, the users that signed as ‘Not confident’ hesitate more at the time to use the ‘Certain lens’ option, reaching only 40 per cent of reliability in this class, but a 76 per cent of reliability in the option ‘Probable lens’ shows that they are more comfortable with this more ambiguous selection.

4.3 How many classifiers are needed for a reliable score?

The classification of an object into any of the options is a personal and subjective opinion. Even with clear guidelines and examples, there will be disagreement among users, as the visual inspection works in Rojas et al. (2022) and Savary et al. (2022) showed. Typical strong lens searches have had a handful of expert classifiers (e.g. 3 for Jacobs et al. 2019b). Given the individual expert variation seen in Section 4.1 and the lack of reliability seen in Section 4.2, it is to be expected that using a small number of experts can significantly bias final scores. To assess how significant this bias can be, we divide our classifications into random ‘teams’ of n users. We computed new

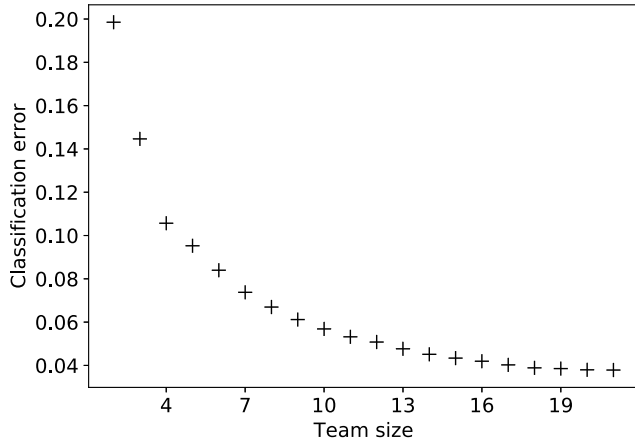


Figure 16. Comparison of the standard deviation of scores obtained from a subset (team) of users relative to the ‘truth’ from all classifiers. This figure shows that small teams are prone to inaccurate classifications.

scores using only the classification of the team members. We did this for team sizes ranging from 1 to 20 participants randomly drawn from our users.

We compare the team scores with the final score from the entirety of our classifiers. We created 200 teams of n random users to recalculate the score for objects labelled as lenses. Fig. 16 shows how the team size affects the scoring of images. The standard deviation error is substantial for very small teams but decreases quickly up to a team size of ~ 8 , which has a classification error of 0.07 per object. Above 8 users the classification error decreases much more slowly. Given that most objects are unambiguously classified as very unlikely (i.e. score of 0), these represent big differences in scores for the other objects: small teams are not very good at assessing the quality of a strong lens candidate.

The results in this section go some way to explaining why the scores of Rojas et al. (2022) vary from those of our classifiers. There are not enough systems with overlapping data to draw firm conclusions (nine images), but the standard deviation is 0.08, as is expected for a team of six classifiers.

Since teams will be most concerned about discovering marginal lenses, it is salient to focus on team accuracy when classifying lenses with marginal scores. Focusing on images with true scores between 0.3 and 0.8 the classification error grows substantially: it is 0.17 for a team of two classifiers, 0.12 for a team of four, and 0.07 for a team of eight. A team of six classifiers is required to achieve an expected accuracy better than 0.1, 15 are needed for an accuracy better than 0.05.

5 CONCLUSIONS

This work has investigated how strong lensing experts visually inspect images of galaxy-scale strong lens candidates. We showed them a sample of 1489 mock and real images of the Dark Energy Survey and asked them to grade each image as either Certain lens, Probable lens, Probably not a lens, or Very unlikely to be a lens. With the resulting 66 835 classifications, we can now answer our initial questions.

(i) What are the properties of lensing systems that human experts identify reliably as lenses, and what do they miss?

Most gravitational lenses are reliably identified with an Einstein Radius greater than 1.2 arcsec and an arc g -band magnitude less than 23. This corresponds to roughly 1.2 times the seeing of the Dark Energy Survey and a g -band signal-to-noise of 25. Some lenses are discovered with fainter or smaller radius arcs. The Einstein radius cut-off is sharp with only a handful of very bright arcs discovered with Einstein radius of less than 1.2 arcsec. The flux cut-off is smoother: roughly 20 per cent of lenses are recovered even with an arc signal to noise of between 4 and 10.

(i) Do human experts confuse non-lenses for lenses?

For our labelled data, none of the non-lenses scored higher than 0.3. Our simulations do not include face-on spirals, or ring galaxies, but the experts had no problem rejecting chance alignments of blue sources close to LRGs. Our labelled sample had an almost equal split of lenses and non-lenses. Unless robotic candidate selection improves substantially, real lens searches will have far more non-lenses than lenses, even so, it seems that human experts are very good at discarding the kinds of non-lenses shown here. Follow-up campaigns should be confident that highly scored candidates are almost certainly lenses.

(i) How does expert classification depend on the experience and confidence of the experts?

We see substantial variation in the purity and completeness of individual classifiers, but there are no significant trends with experience, confidence, or academic position. None of these traits reliably predict the overpessimism or overoptimism of some users.

(i) How reliable are individual classifications?

Classifications are not reliable when repeated. Even classifiers who self-report as ‘very confident’ do not grade candidates consistently. When reclassifying the same images, certain and very unlikely lenses are scored the same roughly three-quarters of the time by confident and very confident classifiers, whereas probable and probably not lenses are only reproduced three-fifths of the time. Fewer than 2 per cent of reclassified targets changed by more than one classification step.

(i) When ranking lens candidates, what do the scores of teams of experts mean? How should lens searchers best build an expert team to classify their candidates?

Given the fact that classifications by a single expert are not reliable when repeated, it is not surprising that small teams make for poor classifiers. On a 0–1 scoring system, teams of six classifiers will produce results within 0.1 of the ensemble average of all users when classifying marginal systems. Senior classifiers are, on the whole, not better than junior classifiers so teams should classify independently and not defer to the opinions of senior faculty members.

We found no correlation between CNN and human scores suggesting that CNNs are not trained to recognize the same features as human experts. Bigger samples are needed to assess if this is a problem for lens finding in future surveys.

A traditional search would use a small number of classifiers to grade a large number of images. To understand the human classification process, we have done the opposite. In the real Universe, real lenses are much rarer than our sample, so it is possible that our results do not perfectly scale to a search of a billion objects. However, if we assume that our discovery thresholds map on to searches of entire surveys our results suggest that previous forecasts are likely to be somewhat optimistic. The discovery signal to noise of our experts is broadly consistent with the assumptions of Collett

(2015); however, our experts recovered few lenses with Einstein radius less than 1.2 arcsec, which represents ~ 40 percent of the forecasted DES population in Collett (2015). Collett (2015) had assumed that users would be shown lens-subtracted images, such as in Sonnenfeld et al. (2018) and future work should investigate if expert inspection can recover even more lenses with such an approach.

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DATA AVAILABILITY

The authors confirm that the data from which the findings of this study are derived are available in: <https://github.com/Krojas/Experts-visual-inspection-experiment>. If any additional information is required you can contact Dr. Karina Rojas email: karina.rojasolate@gmail.com.

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APPENDIX A: INVITATION

We send an invitation to members of the strong lensing community, including LSST, DES, and Euclid strong lensing working groups and we extended the invitation to Space Warp citizen scientists. They received the following invitation:

'We would like to invite you to participate in a lens classification experiment with the goal of understanding how people in the field of gravitational lensing are performing when they do a visual classification task. The task will take about an hour of your time. Participants will be invited to coauthor the resulting paper. The motivation of this experiment comes from the explosion of new lens systems discovered by the use of CNN and subsequent validation through visual inspection performed for each team. There seem to be lots of differences in the expert validation and we want to see if this can be understood and calibrated. We expect that with this social experiment we can get key conclusions about our performance, and hope that in the future

lens finders can benefit from this information. If you want to be part of this experiment please fill this quick google form first. The information requested here will help us to analyse the data, although your personal data (name, email, and galaxy zoo username) will remain private.

And now you are welcome to classify 1000 objects! If you follow this link⁸.

You will see DES gri-colour composite images of each object, each stamp has a size of 50 x 50 pixels (13 arcmin x 13 arcmin). The same object is displayed in three different colour scales to help the recognition of features. The task is simple: you have to click on the option that better represents the object(s) in the image and go to the next.

You do not have the obligation to complete the classification all at once, this might take you a couple of hours. Your progress is recorded and you can come back anytime you want. For a successful analysis, we hope you can commit to completing the classification of the whole data set, or at least a big portion of it. Please share this among your group, postdocs, PhD students, masters students, etc., that work in the field of strong lensing. All are encouraged to participate as we want to test a broad variety of expertise, but please do not share it among people outside of the field.'

APPENDIX B: IMAGE SCALINGS

The 'default' and 'blue' composite images are scaled with an arcsinh stretch using (HumVI, Marshall et al. 2015). We tuned the *rgb*-scale parameters, the brightness (Q) and contrast (α) for default (blue) images as follows: r scale = 1.0 (0.51), g scale = 1.2 (0.68), b scale = 2.8 (3.12), Q = 1.0 (0.64), α = 0.03 (0.03). The third image is scaled using a square root image scaling. To ensure that the object of interest is not overshadowed by another brighter one we set minimum and maximum values for the pixels in the images. The minimum value is obtained using a square of 5×5 pixels in the corners of the *gri* images and we select the minimum value among them. On the other hand, the maximum value is obtained by placing a box of 10×10 pixels in the middle of the three images and obtaining the mean among them. We use these two values to scale the three *gri* images.

APPENDIX C: EXPERIENCE AND CONFIDENCE

In Fig. C1, we present the distribution of the levels of confidence compared to the academic status and years of experience in the field, according to the information provided by the classifiers when they subscribed to this experiment. From both plots, we can clearly see that at higher academic status or years of experience in the field, the classifiers feel more confident that they will perform a successful classification, while undergrad students and people with between 0 and 4 yr of experience feel 'not' or only a 'bit confident'.

⁸<https://www.zooniverse.org/projects/krojas26/experts-visual-inspection-experiment/classify>

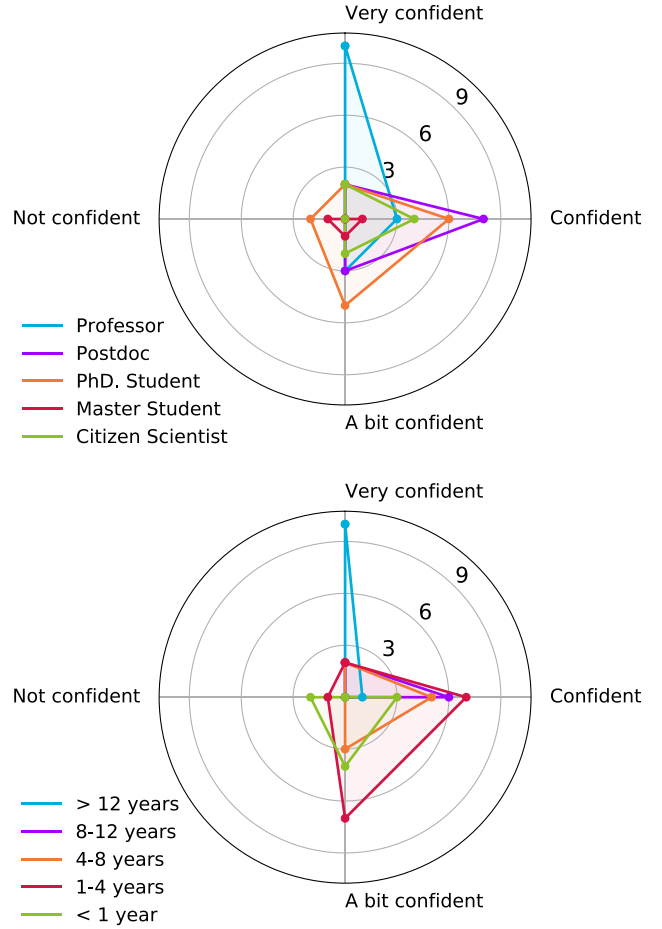


Figure C1. The radar charts show the level of confidence that users have to perform the classification task separately in academic status (top panel) and years of experience (bottom panel).

APPENDIX D: SCORING SYSTEM

In addition, we wanted to explore the impact of weighting the classification of the users according to their percentage of correct classifications in each of the four options given. To obtain this percentage, we computed a 2×4 confusion matrix similar to Fig. 11, but this time for each user. Then we take the four relevant percentages: Classified as 'Certain lens' or 'Probable lens' given that it is a lens and 'Probably not lens' or 'Very unlikely' given that it is not a lens. Using these percentages as weight we then calculated a weighted mean score, this means that we multiply each score by the corresponding weight, sum them and divide by the sum of the weights. After weighting all the classifications, we re-scale the mean score weighted between 0 and 1 as we did with the previous score.

We expected that weighting the mean score could provide a better score system because it will take into account the performance of the users, but most of the users performed in a pretty similar way. We can see in Fig. D1 that the mean score and the mean score weighted are highly correlated. For this reason, we are going to continue our analysis using only the mean score and we are not going to explore the mean score weighted implications in further analysis.

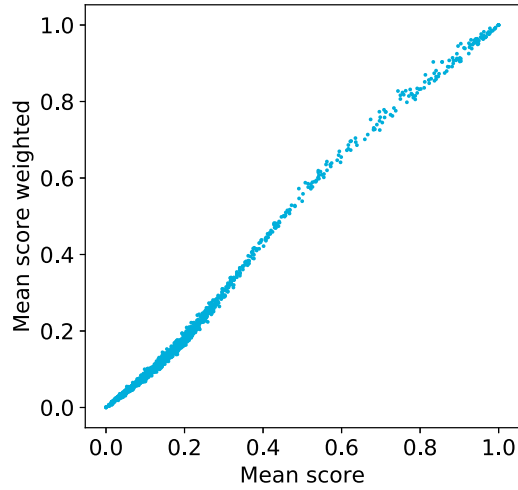


Figure D1. Scatter plot of the mean score compared with the mean score weighted by the corresponding percentage of successful classification in the options displayed.

APPENDIX E: STANDARD DEVIATION

We calculated the standard deviation of the scores given to each object in the experiment. With this information, we create a heat map (Fig. E1) to compare the standard error of the recovery fraction of the simulated lenses data sets in response to the signal-to-noise ratio in the g band, the magnitude of the arc in the g band and the Einstein radius of the lens. In contrast with the heat maps with the average scores (Fig. 5), we do not see any trend in the standard deviation.

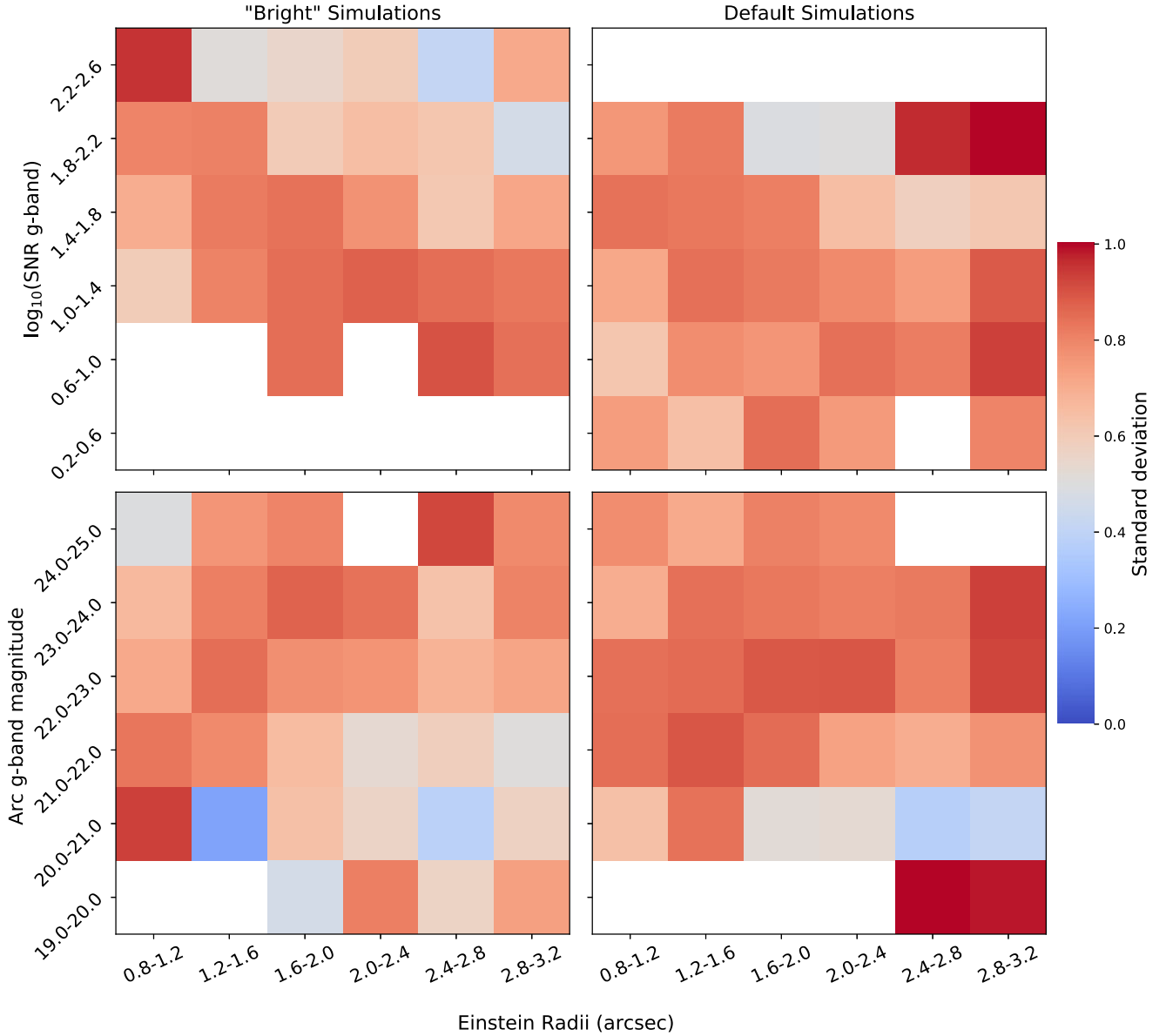


Figure E1. Heat maps with the average standard deviation of the mean score per bins for the objects in the simulated lenses data sets. The left-hand panels correspond to the ‘Bright’ simulations, while the right-hand panels to the ‘Default’ simulations. In the top panels, we display the logarithm of the SNR in g band, while in the bottom panels we present the magnitude of the arc in the g-band.

APPENDIX F: VISUAL INSPECTION VERSUS CNN SCORE

In Section 3.4, We compared the results of this experiment with the score given by the CNN trained by Rojas et al. (2022). In order to understand why the CNN is able to classify slightly more systems than human we displayed in Fig. F1 examples of those simulations

that the CNN graded as good candidates ($\text{CNN} > 0.9$) but human visual inspectors graded with a low score ($s < 0.5$), meaning they were classified as not good lens candidates. Additionally, we explored the opposite CNN range of classification score ($\text{CNN} < 0.1$), where CNN and humans agree given that all simulations obtain $s < 0.5$, as can be seen in Fig. 10.

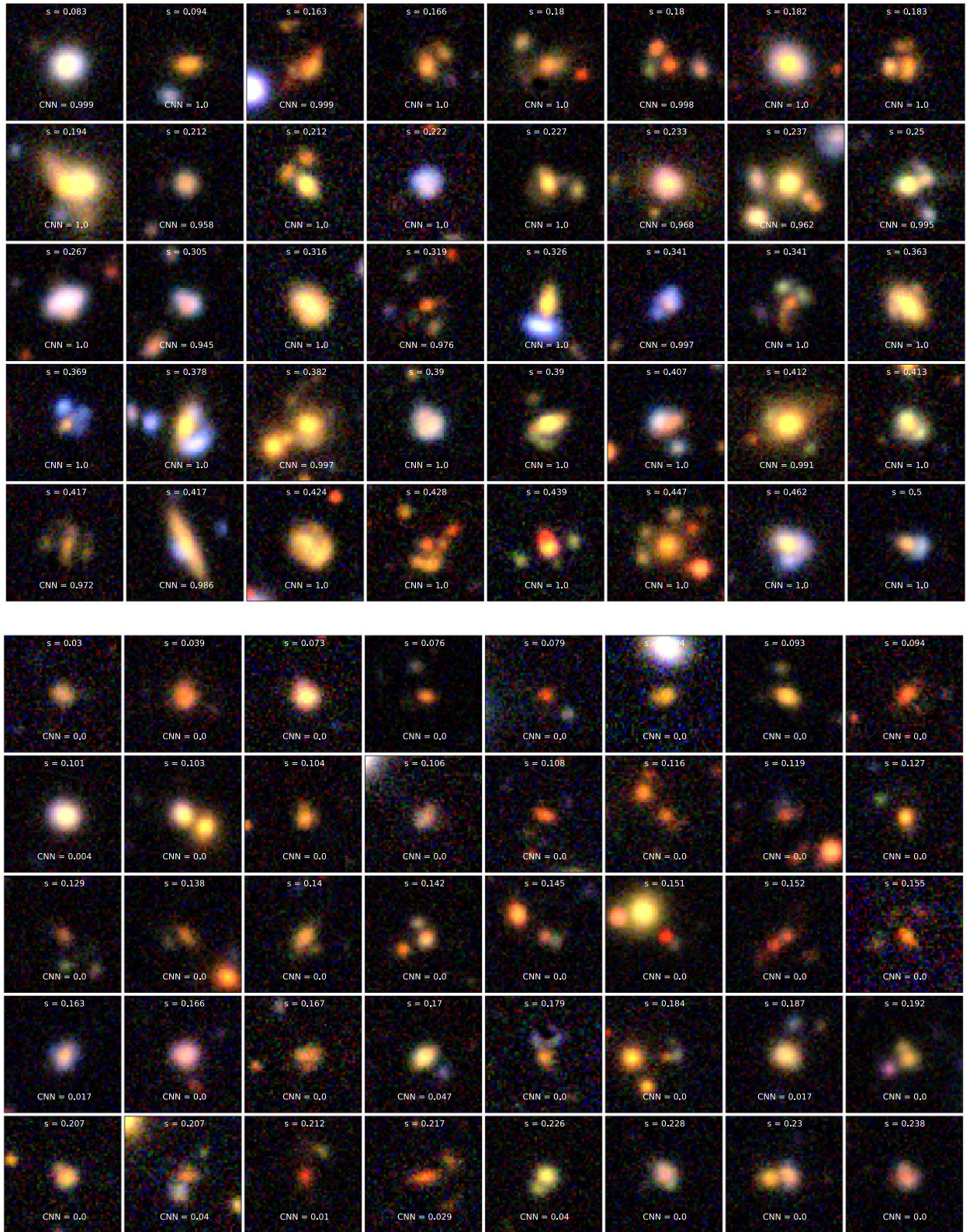


Figure F1. Mosaic with 80 examples of simulations that human visual inspectors graded with a score below 0.5. The first 40 are images where the humans and CNN disagree (CNN with a score above 0.9) and the other 40 show broad agreement between human and CNN (CNN score < 0.1 0).

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