Finding Strong Gravitational Lenses in the DESI DECam Legacy Survey

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ABSTRACT

We perform a semi-automated search for strong gravitational lensing systems in the 9,000 deg² Dark Energy Camera Legacy Survey (DECaLS), part of the DESI Legacy Imaging Surveys (Dey et al.). The combination of the depth and breadth of these surveys are unparalleled at this time, making them particularly suitable for discovering new strong gravitational lensing systems. We adopt the deep residual neural network architecture (He et al.) developed by Lanusse et al. for the purpose of finding strong lenses in photometric surveys. We compile a training set that consists of known lensing systems in the Legacy Surveys and DES as well as non-lenses in the footprint of DECaLS. In this paper we show the results of applying our trained neural network to the cutout images centered on galaxies typed as ellipticals (Lang et al.) in DECaLS. The images that receive the highest scores (probabilities) are visually inspected and ranked. Here we present 335 candidate strong lensing systems, identified for the first time.

Keywords: galaxies: high-redshift – gravitational lensing: strong

1. INTRODUCTION

Strong lensing systems (Walsh et al. 1979; Lynds & Petrosian 1986; Soucail et al. 1987, 1988; Paczynski 1987) have been used to study how dark matter is distributed in galaxies and clusters (e.g., Kochanek 1991; Koopmans & Treu 2002; Bolton et al. 2006; Koopmans et al. 2006; Vegetti & Koopmans 2009; Tessore et al. 2016). As a cosmological probe, time delays in multiply lensed quasars provide competitive constraints on the Hubble constant $H_0$ (e.g.,Refsdal 1964; Blandford &
Narayan 1992; Suyu et al. 2010, 2013; Treu & Marshall 2016; Bonvin et al. 2017) independent of the distance ladder approach.

In recent years, highly magnified, multiply imaged supernovae (SNe), both core-collapse (Kelly et al. 2015) and Type Ia (Quimby et al. 2014; Goobar et al. 2017), have been discovered. With their well-characterized brightness time evolution in optical and near-infrared wavelengths (the SN lightcurves), such strongly lensed SNe are ideally suited to measure time-delays and $H_0$ in future surveys (e.g., Goldstein & Nugent 2017; Goldstein et al. 2018a,b; Wojtak et al. 2019).

In this paper we show that hundreds of new strong lensing systems can be found in the three band imaging data ($grz$) from the Dark Energy Spectroscopic Instrument (DESI) Legacy Surveys\(^1\) (Dey et al. 2019). To find these lenses from a data set that covers one third of the sky, we adopt the residual neural network (He et al. 2015a,b, 2016) developed by Lanusse et al. (2018), the winning algorithm of the Strong Gravitational Lens Finding Challenge (Metcalf et al. 2018), to automate the process as much as possible. This paper is organized as follows. A brief description of the Legacy Surveys is given in § 2. In § 3, we describe our methodology and training sample. In § 4, we show the inference results and present our best strong lensing system candidates. We discuss our results in § 5, and conclude in § 6.

2. OBSERVATIONS

The details of the DESI Legacy Imaging Surveys are described in Dey et al. (2019, D19). Here we present a brief summary. The Legacy Surveys consist of three projects: the Dark Energy Camera Legacy Survey (DECaLS), observed by the Dark Energy Camera (Flaugher et al. 2015) on the 4-m Blanco telescope at the Cerro Tololo Inter-American Observatory; the Beijing-Arizona Sky Survey (BASS), by the 90Prime camera (Williams et al. 2004) on the Bok 2.3-m telescope owned and operated by the University of Arizona located on Kitt Peak; and the Mayall $z$-band Legacy Survey (MzLS), by the Mosaic3 camera (Dey et al. 2016) on the 4-meter Mayall telescope at Kitt Peak National Observatory. Together they will ultimately cover $\sim 14,000 \text{ deg}^2$ of the extragalactic sky visible from the northern hemisphere in $grz$ bands, with a $5\sigma$ $z$-band median limiting magnitude of 22.5 mag for galaxies with an exponential disk profile with $r_{i,\text{half}} = 0.45''$.

The combined survey footprint is split into two contiguous areas by the Galactic plane. DECaLS covers the $\sim 9000 \text{ deg}^2 \delta \lesssim +32^\circ$ sub-region of the Legacy Surveys. The image quality has a FWHM$\approx 1''$. The MzLS has imaged the $\delta \gtrsim +32^\circ$ (NGC) footprint of the Legacy Surveys in $z$-band that complemented the BASS $g$- and $r$-band observations in the same sub-region. While the delivered image quality of MzLS has a median seeing of $\approx 1.1''$, the median FWHM’s for BASS are 1.64'' and 1.86'' in the $g$- and $r$-bands, respectively. We choose here to focus on DECaLS due to its better $gr$ seeing than BASS. However, we intend in future work to apply the machine-learning framework we have developed for DECaLS to the northern BASS/MzLS area.

The Legacy Surveys used the Tractor package (Lang et al. 2016) as a forward-modeling approach to perform source extraction on pixel-level data. Tractor takes as input the individual images from multiple exposures in multiple bands, with different seeing in each. After source detection, the point source ("PSF") and spatially extended ("REX", round exponential galaxy) models are computed for every source and the better of these two is used when deciding whether to keep the source. The spatially extended sources (REX) are further classified if $\chi^2$ is improved by 9 by treating it as a

\(^1\) legacy surve y.org
deVaucouleurs (DEV), an exponential (EXP) profile, or a composite of deVaucouleurs + exponential (COMP). The same light profile (EXP, DEV, or COMP) is consistently fit to all images in order to determine the best-fit source shape parameters and photometry. The categories of DEV and COMP indicate the classification of elliptical galaxies. Given that the vast majority of lensing events are caused by early type galaxies, we decided to target only objects with DEV and COMP classifications in this paper.

3. THE TRAINING SAMPLE AND RESIDUAL NEURAL NETWORKS

3.1. Training Sample

Deep convolutional neural networks (CNNs) and their variations have been shown to be highly effective in image recognition. In recent years, this technique has been successfully applied to recognize instances of strong lenses in simulations (e.g., Metcalf et al. 2018, and references therein). In previous applications of CNNs to real observations, training samples are constructed from simulated lens images, combined with observed (Petrillo et al. 2017), simulated (Pourrahmani et al. 2018; Jacobs et al. 2017), or a mixture of observed and simulated non-lenses (Jacobs et al. 2019). This is because the number of known lenses, on the order of several hundred, is thought to be too small to effectively train CNN models. We note that the data set for Jacobs et al. (2017) is from the Canada-France-Hawaii Telescope Legacy Survey; Petrillo et al. (2017), the Kilo Degree Survey (de Jong et al. 2015); Pourrahmani et al. (2018), the Hubble Space Telescope ACS i-band observations of the Cosmological Evolution Survey (COSMOS; Capak et al. 2007) field; and Jacobs et al. (2019), the Dark Energy Survey (DES; The Dark Energy Survey Collaboration 2005). All of these searches were performed on completed surveys.

We decided to use only observed data for lenses and non-lenses in our training sample for partial deployment on DECaLS, which is near completion, and have obtained encouraging results. We identify the known lenses in the Legacy Surveys and DES DR1. A catalog of known lenses in the Legacy Surveys is also necessary in order to identify new lens candidates. Both DECaLS and DES used DECam (see D19). DES has griz observations with similar depths in the three bands common with Legacy Surveys. Due to the paucity of lenses, we have used known strong lenses in all of Legacy Surveys, while in this paper we will focus on finding new lenses only in the DECaLS footprint. The Master Lens Database\(^3\) (Moustakas et al. 2012), which contains hundreds of lensing events up to 2016, provided the initial list for the lens training sample. We have since added several hundred more lenses and lens candidates from more recent publications (Carrasco et al. 2017; Diehl et al. 2017; Pourrahmani et al. 2018; Sonnenfeld et al. 2018; Wong et al. 2018; Jacobs et al. 2017, 2019). In total we have identified \(\sim 700\) previously known lenses or lens candidates in the Legacy Surveys and DES. A number of these systems were discovered spectroscopically or through imaging with better seeing than the Legacy Surveys and DES. Some of them therefore have sub-arcsecond deflection angles. Through human inspection, we deem 617 as discernible lenses in the Legacy Surveys (199) and DES (418) footprints. For the lenses in the DES footprint, we only include griz bands. We also assemble 13,000 non-lens image cutouts from the Legacy Surveys, all with at least three passes in each of the griz bands. Of these, 5000 are galaxies categorized as DEV or COMP in D19 (see § 2), which are elliptical galaxies, and another 5000 of all types of galaxies. For both cases, we apply

\(^2\) http://legacysurvey.org/dr7/description/

\(^3\) http://admin.masterlens.org/index.php
a $z$-band magnitude cut of 22.5 mag. Given that on average we expect one strong lens in $\mathcal{O}(10^4)$ galaxies (e.g., Oguri & Marshall 2010), incidental inclusion of a lens or two in these galaxies is not a significant concern.

The reason for including non-elliptical galaxies is to provide more non-lens configurations for the neural net. Two of the co-authors have also selected another 3,000 non-lenses by eye so as to cover as many non-lens configurations as possible, especially cases that can potentially be confused by the neural net. These include unusual arrangements of galaxies or stars, bright elliptical galaxies, groups of elliptical galaxies, images having objects with different colors, cosmic rays appearing in different bands (some of which have curved trajectories), spiral galaxies of different sizes and spiral arm configurations, and finally certain data reduction artifacts. Simulated non-lenses typically do not cover these scenarios.

### 3.2. Residual Neural Networks

We have adopted the Residual Neural Network (ResNet) model of Lanusse et al. (2018, L18)

\[ \text{ResNet} \]

which used Theano\(^5\) and Lasagne\(^6\) libraries. We re-implemented their model in TensorFlow\(^7\), in part because major development for Theano ceased after the 1.0 release on November 15, 2017. We test the translated ResNet model using the simulated training set from the Strong Gravitational Lens Finding Challenge (Metcalf et al. 2018) and have reproduced the results in L18, which was the winning entry for the Lens Challenge. The architecture of the model is described in detail in L18.

L18 has provided much guidance to our approach. At this stage we have left their architecture and hyperparameters unchanged, including the batch size (128), total number of training epochs (120), pre-processing of the images, and data augmentation (random rotation, mirroring, and zooming within a range of $[0.9, 1.0]$; for details, see Section 3.3 of L18). The lens and non-lens images in the training sample are cutouts with a dimension of $101 \times 101$ pixels, following the specification in the Lens Challenge.

We split the training sample into training, validation, and testing sets, with ratios of 70:20:10. The sizes of our training and validation sets are then, respectively, 9876 (423) and 2818 (118), where the values in parentheses are the number of lenses. We set aside a testing set because we want to leave open the possibility of varying the architecture and hyperparameters to optimize the neural net’s performance. We then train the ResNet on the supercomputer Cori\(^8\) at the National Energy Research Scientific Computing Center (NERSC)\(^9\), using three Haswell computing nodes\(^10\), one worker each. The 120 epochs of training took 17 hours. The distributed training was accomplished by using Horovod\(^11\). Performing distributed training with deep (46 layers in this case; L18) neural networks can be non-trivial. We experimented with different numbers of decay epochs and found that with three workers, a decay epoch of 40 (i.e., the learning rate of the ResNet is decreased by a factor 10 every 40 epochs of training) works the best.

The ResNet attempts to minimize the cross entropy loss function:

\[ \text{Loss} = -\frac{1}{N} \sum_{i=1}^{N} (y_i \log \hat{y}_i + (1 - y_i) \log (1 - \hat{y}_i)) \]

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4. https://github.com/McWilliamsCenter/CMUDeepLens
5. http://deeplearning.net/software/theano/
6. https://github.com/Lasagne/Lasagne
7. https://www.tensorflow.org/
8. https://www.nersc.gov/users/computational-systems/cori/
9. https://www.nersc.gov/
10. https://www.nersc.gov/users/computational-systems/cori/configuration/cori-phase-i/
11. https://github.com/horovod/
\[- \sum_{i=1}^{N} y_i \log \hat{y}_i + (1 - y_i) \log(1 - \hat{y}_i) \]  

where $y_i$ is the label for the $i$th image (1 for lens and 0 for non-lens), and $\hat{y}_i \in [0, 1]$ is the model predicted probability.

While the loss function is monitored during the training process to determine the point of termination, the overall performance of the trained model is typically assessed by the Receiver Operating Characteristic (ROC) curve. The ROC curve shows the True Positive Rate (TPR) vs. the False Positive Rate (FPR) for the validation set, where P(ositive) indicates a lens and N(egative), a non-lens. With the definitions TP = correctly identified as a lens, False Positive = incorrectly identified as a lens, True Negative = correctly rejected, and False Negative = incorrectly rejected,

$$TPR = \frac{TP}{P} = \frac{TP}{TP + FN}$$

and

$$FPR = \frac{FP}{N} = \frac{FP}{FP + TN}$$

The curve is generated by gradually increasing the threshold probability for a positive identification from 0 to 1. Random classifications will result in a diagonal line in this space with an area under the ROC curve (or AUC) equal 0.5. For a perfect classifier, AUC = 1.

The decision of using three nodes was based on our experience with a smaller training set. We can significantly shorten the training time by employing six or more nodes. Since the training set has a total of 9876 images, with a batch size of 128 images and 3 workers, it takes 26 steps to complete one full training epoch.

In Figure 1, Panel A, we show how the cross entropy loss functions vary as training progresses. For the validation set, we show the value at every epoch. For the training set, the cross entropy was reported for every step, which we have boxcar smoothed with a window size of 26. As L18 also noted, the loss function (Equation 1) and the AUC for the validation set both plateau well within 120 epochs of training. Since the model has performed well, we have left the architecture and hyperparameters in L18 unchanged and moved directly to deployment. Thus so far we have not used the validation set, or the testing set, for training.
Figure 1. Panel A: The cross entropy loss functions for the training and validation sets over 120 epochs.
Panel B: The receiver operative characteristic (ROC) curve for the validation set with the area under the curve (AUC) = 0.98.

We achieve an AUC of 0.98 for the validation set (Figure 1, Panel B). Even though our training and validation sets contain far fewer lenses, our AUC matches the performance on simulated data in L18.

4. RESULTS

4.1. Inference and Lens Candidates

We apply our trained ResNet model to 5.7 million DEV and COMP type galaxies in DECaLS with at least three passes in each of the three bands (grz) and z-band magnitude ≤ 20.0. This magnitude cut was chosen because it includes 92% of the known lenses in the Legacy Surveys and results in a manageable number of images for human inspection. Five of the co-authors have inspected the cutout images that receive a probability ≥ 0.9. The criteria for human inspection are to look for small blue galaxy/galaxies (red galaxies are rare but certainly acceptable) next to the red galaxy/galaxies at the center that

- are typically 1 - 5″ away
- have low surface brightness
- curve toward the red galaxy/galaxies
- have counter/multiple images with similar colors (especially in Einstein-cross like configuration)
- are elongated (including semi- or nearly full circles)

Typically, most candidates do not have all these characteristics. In general, the greater the number of characteristics listed above an image has, the higher they are ranked by humans.

We have examined ~ 50,000 images. We rank our lens candidates in three grades A, B, and C:

- Grade A: We have a high level of confidence of these candidates. Many of them have one or more prominent arcs, usually blue. The rest have one or more clear arclets, sometimes arranged
in counter-image configurations with similar colors (again, typically blue). However, there are clear cases with red arcs.

- Grade B: They have similar characteristics as the Grade A’s. For the cutout images where there appear to be giant arcs they tend to be fainter than those for the Grade A’s. Likewise, the putative arclets tend to be smaller and/or fainter, or isolated (without counter images).

- Grade C: They generally have features that are even fainter and/or smaller than what is typical for the Grade B candidates, but that are nevertheless suggestive of lensed arclets. They are usually without counter images, except for a few cases. In almost all cases, if these are indeed lensing systems, the deflection angles are comparable to or only slightly larger than the seeing.

For Grade B and C candidates, we have included a few cases where it is difficult to judge whether it is a lensing event vs. a coincidental placement of galaxies, a spiral galaxy, or a ring galaxy. In total we have identified 341 candidates: 60 A’s, 105 B’s, and 176 C’s, listed in Tables 1, 2, and 3 and shown in Figures 2, 3, and 4.
Figure 2. The 60 Grade A lens candidates arranged in ascending RA. Each image is 101 pixels $\approx 26.2''$ on the side, with N up and E to the right. The exception is DESI-204.0002-03.5250, which is 151 pixel $\approx 40.3''$ on the side. The six image with a red rim are later found to be known lenses through an HST archive search. These were not in our training sample.
Figure 3. The 105 Grade B Lens Candidates. Each image is 101 pixels $\approx 26.2''$ on the side, with N up and E to the right. The exceptions are DESI-009.9772-12.2100, DESI-061.1134-17.2082, and DESI-167.8517+14.1473, which are 151 pixels $\approx 40.3''$ on the side.
Figure 4. The 176 Grade C Lens Candidates. Each image is 101 pixels $\approx 26.2''$ on the side, with N up and E to the right.
| Name         | Type | mag\_g | mag\_r | mag\_z | Probability | z   | Survey |
|--------------|------|--------|--------|--------|-------------|-----|--------|
| DESI-011.5084-01.9412 | DEV  | 20.94  | 19.19  | 17.97  | 0.936       | 0.5501 | BOSS   |
| DESI-015.8164+00.0823  | DEV  | 19.64  | 18.08  | 17.21  | 1.000       | 0.2662 | SDSS   |
| DESI-016.3319+01.7490  | DEV  | 19.95  | 18.17  | 17.27  | 0.987       | 0.3612 | BOSS   |
| DESI-016.5230+00.5463  | DEV  | 21.52  | 19.66  | 18.25  | 1.000       | 0.5941 | BOSS   |
| DESI-018.1074+02.3773  | DEV  | 21.27  | 19.35  | 18.12  | 0.948       | 0.5039 | BOSS   |
| DESI-019.4949-05.4550  | DEV  | 21.41  | 19.66  | 18.37  | 0.984       | 0.5797 | BOSS   |
| DESI-019.6618-05.4441  | DEV  | 22.30  | 20.38  | 18.99  | 0.969       |       |        |
| DESI-022.7106-16.0024  | COMP | 19.44  | 18.64  | 17.61  | 0.948       |       |        |
| DESI-024.1631+00.1384  | COMP | 18.83  | 17.18  | 16.29  | 0.998       | 0.3441 | SDSS   |
| DESI-025.2755-17.2232  | DEV  | 20.43  | 18.96  | 17.62  | 0.989       |       |        |
| DESI-026.1390-11.7026  | COMP | 20.09  | 18.39  | 17.00  | 0.961       |       |        |
| DESI-026.2679-04.9310  | COMP | 20.75  | 19.67  | 18.43  | 0.998       |       |        |
| DESI-026.4848+04.0413  | DEV  | 22.29  | 20.78  | 19.05  | 0.927       |       |        |
| DESI-027.3284-13.8180  | DEV  | 22.13  | 20.95  | 19.22  | 0.998       |       |        |
| DESI-027.9723-14.8069  | DEV  | 21.62  | 20.51  | 18.90  | 1.000       |       |        |
| DESI-029.6032-00.6665  | DEV  | 21.05  | 19.45  | 17.94  | 0.918       | 0.5970 | SDSS   |
| DESI-030.2832-15.8547  | DEV  | 21.12  | 19.26  | 18.16  | 0.997       |       |        |
| DESI-031.1712-15.0266  | DEV  | 20.08  | 18.35  | 17.40  | 0.996       |       |        |
| DESI-036.1436-00.0411  | DEV  | 21.67  | 20.33  | 18.78  | 0.962       | 0.7846 | eBOSS  |
| DESI-036.4422-07.6274  | DEV  | 20.98  | 19.08  | 17.89  | 0.990       | 0.5138 | BOSS   |
| DESI-037.0378-12.8812  | DEV  | 20.39  | 19.01  | 17.92  | 0.997       |       |        |
| DESI-038.2078-03.3006  | DEV  | 20.08  | 18.39  | 17.40  | 0.999       |       |        |
| DESI-040.3034-00.9646  | DEV  | 19.27  | 17.83  | 17.02  | 0.999       | 0.2418 | SDSS   |
| DESI-040.3168-06.5372  | DEV  | 20.63  | 18.94  | 17.96  | 0.997       |       |        |
| DESI-041.5205-06.1275  | DEV  | 23.97  | 21.99  | 19.92  | 0.999       |       |        |
| DESI-060.1043-16.3979  | DEV  | 19.05  | 17.88  | 17.16  | 0.987       |       |        |
| DESI-060.2420-13.9567  | DEV  | 21.07  | 19.54  | 18.11  | 0.931       |       |        |
| DESI-122.0852+10.5284  | DEV  | 19.94  | 18.14  | 17.10  | 0.997       | 0.4754 | SDSS   |
| DESI-133.5531-04.4026  | DEV  | 21.80  | 20.45  | 18.72  | 0.849       |       |        |
| DESI-133.6197+10.1374  | DEV  | 19.06  | 17.44  | 16.57  | 0.989       | 0.2978 | SDSS   |
| DESI-135.3125+09.9401  | COMP | 24.28  | 20.96  | 18.89  | 0.993       |       |        |
| DESI-137.8568+14.2991  | DEV  | 20.61  | 18.80  | 17.51  | 0.969       | 0.5464 | BOSS   |
| DESI-140.8110+18.4954  | DEV  | 20.20  | 19.60  | 18.65  | 0.875       | 0.8732 | BOSS   |
| DESI-141.0626+05.7690  | DEV  | 21.17  | 19.48  | 17.98  | 0.952       | 0.6128 | BOSS   |
| DESI-143.3887+09.3219  | DEV  | 22.16  | 20.41  | 18.71  | 0.999       | 0.7430 | BOSS   |
| DESI-145.9507+00.9906  | COMP | 20.53  | 18.97  | 17.90  | 1.000       |       |        |

*Table 1 continued on next page*
Table 1 (continued)

| Name           | Type | mag_g | mag_r | mag_z | Probability | z     | Survey |
|----------------|------|-------|-------|-------|-------------|-------|--------|
| DESI-152.0763+31.7005 | COMP | 21.23 | 19.45 | 18.18 | 0.991       | 0.5394 | SDSS   |
| DESI-154.6972-01.3590   | DEV  | 20.53 | 18.72 | 17.79 | 1.000       | 0.3883 | BOSS   |
| DESI-155.7366-05.0529   | DEV  | 20.64 | 19.00 | 17.54 | 0.987       |        |        |
| DESI-160.2351-01.0663   | DEV  | 17.80 | 16.33 | 15.51 | 0.942       | 0.2502 | SDSS   |
| DESI-162.4577+05.7749   | DEV  | 18.76 | 17.37 | 16.55 | 0.997       | 0.2640 | SDSS   |
| DESI-165.6876+12.1864   | DEV  | 23.23 | 21.46 | 19.36 | 0.983       |        |        |
| DESI-168.2943+23.9443   | DEV  | 17.44 | 15.82 | 14.95 | 0.968       | 0.3361 | SDSS   |
| DESI-186.3033-00.4390   | COMP | 19.49 | 18.17 | 17.44 | 0.987       |        |        |
| DESI-186.8292+17.4324   | COMP | 21.56 | 19.95 | 19.01 | 0.903       |        |        |
| DESI-189.5370+15.0309   | DEV  | 20.38 | 18.69 | 17.37 | 0.998       |        |        |
| DESI-194.5344+03.5358   | DEV  | 19.90 | 18.29 | 17.31 | 0.989       | 0.4279 | BOSS   |
| DESI-202.6690+04.6707   | DEV  | 18.84 | 17.21 | 16.33 | 0.987       | 0.3363 | SDSS   |
| DESI-204.0002-03.5250   | EXP  | 21.36 | 21.12 | 20.37 | 0.900       | 0.1764 | SDSS   |
| DESI-213.6664+19.4787   | DEV  | 19.05 | 17.34 | 16.09 | 0.993       | 0.5768 | BOSS   |
| DESI-214.6278+25.1814   | DEV  | 17.83 | 16.23 | 15.41 | 0.986       | 0.2909 | SDSS   |
| DESI-215.2654+00.3719   | DEV  | 21.32 | 20.05 | 18.73 | 0.974       |        |        |
| DESI-216.8280-06.7541   | DEV  | 18.64 | 17.14 | 16.34 | 0.972       |        |        |
| DESI-216.9538+08.1792   | DEV  | 20.83 | 19.16 | 17.99 | 0.960       | 0.5338 | BOSS   |
| DESI-219.7907+12.1404   | DEV  | 20.54 | 18.60 | 17.59 | 0.863       | 0.4273 | SDSS   |
| DESI-219.9855+32.8402   | DEV  | 19.65 | 17.84 | 16.87 | 0.812       | 0.4176 | SDSS   |
| DESI-318.0376-01.7568   | DEV  | 18.14 | 16.73 | 15.92 | 0.974       | 0.2241 | BOSS   |
| DESI-319.3483-00.9478   | DEV  | 20.05 | 18.20 | 17.17 | 0.935       | 0.4272 | SDSS   |
| DESI-349.5492-11.1012   | COMP | 19.51 | 17.78 | 16.12 | 0.980       |        |        |
| DESI-359.8897+02.1399   | DEV  | 18.94 | 17.04 | 16.05 | 0.993       | 0.4295 | BOSS   |

Note—Thirty three of the above 60 Grade A lens candidates have spectroscopic redshifts from SDSS (see text). All redshift uncertainties < 3.7 × 10^{-4}. 
| Name                  | Type | mag\_g | mag\_r | mag\_z | Probability | z   | Survey |
|-----------------------|------|--------|--------|--------|-------------|-----|--------|
| DESI-005.6187+01.8037 | DEV  | 20.93  | 20.09  | 18.59  | 0.889       |     |        |
| DESI-009.1701+00.7687 | DEV  | 21.91  | 20.44  | 18.82  | 0.964       |     |        |
| DESI-009.9772-12.2100 | DEV  | 21.93  | 20.06  | 18.91  | 0.900       |     |        |
| DESI-010.2401-09.0954 | COMP | 21.70  | 20.14  | 18.99  | 0.990       |     |        |
| DESI-010.2876-00.7303 | DEV  | 21.33  | 19.67  | 18.40  | 0.898 0.5633 | 0.5633 | SDSS  |
| DESI-010.3630-01.1298 | DEV  | 29.52  | 22.73  | 20.78  | 0.909       |     |        |
| DESI-011.0219-04.8058 | DEV  | 23.15  | 21.10  | 19.20  | 0.896 0.7715 | 0.7715 | eBOSS |
| DESI-011.9235-06.1032 | DEV  | 22.45  | 20.55  | 19.34  | 0.815       |     |        |
| DESI-012.5310-18.6438 | DEV  | 19.43  | 17.72  | 16.85  | 0.929       |     |        |
| DESI-014.0105+03.0152 | DEV  | 22.19  | 20.35  | 19.07  | 0.970 0.5367 | 0.5367 | BOSS  |
| DESI-014.0683-01.3924 | DEV  | 20.16  | 18.96  | 17.75  | 0.989       |     |        |
| DESI-014.0730-02.4262 | DEV  | 20.98  | 19.34  | 18.41  | 0.994       |     |        |
| DESI-014.4452-16.7457 | DEV  | 21.64  | 19.79  | 18.56  | 1.000       |     |        |
| DESI-014.6199-00.4627 | DEV  | 21.53  | 20.40  | 19.21  | 0.951       |     |        |
| DESI-015.0641-00.2718 | COMP | 21.00  | 19.31  | 18.33  | 1.000 0.4287 | 0.4287 | SDSS  |
| DESI-015.0721+00.0027 | DEV  | 20.04  | 18.53  | 17.75  | 0.958 0.2758 | 0.2758 | BOSS  |
| DESI-015.2668-17.5344 | COMP | 20.63  | 19.31  | 18.41  | 0.997       |     |        |
| DESI-015.2991+00.1673 | DEV  | 21.55  | 19.97  | 18.99  | 0.985       |     |        |
| DESI-015.3533-17.0192 | DEV  | 22.03  | 20.28  | 19.11  | 0.902       |     |        |
| DESI-015.3806+00.5700 | DEV  | 22.56  | 20.98  | 19.40  | 0.987       |     |        |
| DESI-015.4415+03.2399 | DEV  | 20.93  | 19.42  | 18.39  | 0.968 0.5518 | 0.5518 | BOSS  |
| DESI-015.5430-00.3184 | DEV  | 21.43  | 20.10  | 18.83  | 1.000 0.6376 | 0.6376 | BOSS  |
| DESI-015.6201-00.4207 | DEV  | 20.71  | 19.09  | 18.21  | 0.998       |     |        |
| DESI-015.6531-00.0963 | COMP | 20.75  | 19.11  | 18.21  | 1.000 0.3675 | 0.3675 | BOSS  |
| DESI-015.9831+00.3187 | DEV  | 21.19  | 19.79  | 18.50  | 1.000 0.6205 | 0.6205 | BOSS  |
| DESI-016.1439-00.5185 | COMP | 18.66  | 17.01  | 16.14  | 1.000 0.3453 | 0.3453 | SDSS  |
| DESI-016.2119+00.4207 | DEV  | 21.19  | 19.64  | 18.54  | 0.998 0.5293 | 0.5293 | BOSS  |
| DESI-016.2273+00.0668 | DEV  | 19.58  | 18.07  | 17.19  | 0.999 0.2757 | 0.2757 | SDSS  |
| DESI-016.2921-18.3895 | DEV  | 22.46  | 20.76  | 19.31  | 0.972       |     |        |
| DESI-016.3969+00.1169 | COMP | 18.93  | 17.53  | 16.76  | 0.990       |     |        |
| DESI-016.7876+01.2914 | DEV  | 20.25  | 18.39  | 17.41  | 0.999 0.4217 | 0.4217 | BOSS  |
| DESI-016.8597+03.2136 | COMP | 17.84  | 16.25  | 15.35  | 0.977 0.3245 | 0.3245 | BOSS  |
| DESI-016.9695-14.4480 | DEV  | 21.30  | 19.38  | 18.07  | 0.999       |     |        |
| DESI-017.0297-03.5796 | DEV  | 19.77  | 18.34  | 17.54  | 0.985       |     |        |
| DESI-017.4350-14.6600 | DEV  | 21.17  | 19.54  | 18.02  | 0.995       |     |        |
| DESI-017.5240-02.5417 | COMP | 19.31  | 17.49  | 16.53  | 0.933 0.4312 | 0.4312 | BOSS  |

*Table 2 continued on next page*
| Name            | Type | mag$_g$ | mag$_r$ | mag$_z$ | Probability | $z$ | Survey |
|-----------------|------|---------|---------|---------|-------------|-----|--------|
| DESI-018.0754-04.5830 | COMP | 21.38   | 19.78   | 18.64   | 0.993       | 0.5290 | BOSS   |
| DESI-018.1714-19.0457 | DEV  | 20.58   | 18.93   | 17.49   | 0.999       |       |        |
| DESI-018.2548-03.7210 | DEV  | 20.00   | 18.34   | 17.45   | 0.992       | 0.3156 | BOSS   |
| DESI-018.4039-18.9942 | DEV  | 21.48   | 19.86   | 18.80   | 0.963       |       |        |
| DESI-020.4712-17.9274 | COMP | 19.49   | 17.72   | 16.26   | 0.925       |       |        |
| DESI-020.7598-13.2227 | DEV  | 22.60   | 20.83   | 19.25   | 0.936       |       |        |
| DESI-022.3389+00.6547 | DEV  | 22.85   | 21.29   | 19.64   | 0.992       |       |        |
| DESI-023.6765+04.5639 | DEV  | 20.93   | 19.03   | 17.70   | 0.951       | 0.5508 | BOSS   |
| DESI-029.0400-10.4926 | COMP | 22.79   | 21.24   | 19.85   | 0.999       |       |        |
| DESI-034.9916-14.9460 | DEV  | 22.88   | 21.30   | 19.64   | 0.927       |       |        |
| DESI-035.0816-04.1971 | DEV  | 19.83   | 18.39   | 17.63   | 0.994       |       |        |
| DESI-035.7821-05.4661 | DEV  | 22.21   | 20.37   | 19.23   | 0.999       | 0.4963 | BOSS   |
| DESI-036.0677-16.3767 | DEV  | 21.45   | 19.75   | 18.36   | 0.987       |       |        |
| DESI-036.2542-05.6058 | DEV  | 21.13   | 19.29   | 18.34   | 0.978       | 0.4381 | BOSS   |
| DESI-036.3915-05.0365 | DEV  | 19.25   | 18.14   | 17.43   | 0.998       |       |        |
| DESI-036.4490-15.0922 | DEV  | 21.60   | 20.11   | 18.71   | 0.959       |       |        |
| DESI-037.0336-05.2927 | COMP | 20.58   | 19.48   | 18.77   | 0.999       |       |        |
| DESI-038.9951-06.0696 | DEV  | 22.83   | 20.96   | 19.60   | 0.988       |       |        |
| DESI-040.5720-16.4116 | DEV  | 21.02   | 19.15   | 17.76   | 0.939       |       |        |
| DESI-040.7053-00.5888 | DEV  | 22.08   | 20.22   | 19.24   | 1.000       | 0.4119 | BOSS   |
| DESI-040.8111-00.1499 | DEV  | 22.19   | 20.21   | 18.50   | 1.000       | 0.7167 | BOSS   |
| DESI-041.4742-00.7052 | DEV  | 21.23   | 20.09   | 19.39   | 1.000       |       |        |
| DESI-041.9391-00.5247 | DEV  | 21.25   | 19.38   | 18.06   | 1.000       | 0.5801 | SDSS   |
| DESI-046.4723-14.8812 | DEV  | 23.96   | 21.67   | 19.60   | 0.946       |       |        |
| DESI-047.7087-17.7748 | DEV  | 22.51   | 20.93   | 19.45   | 0.950       |       |        |
| DESI-047.7647-13.2341 | DEV  | 19.33   | 18.58   | 17.59   | 0.957       |       |        |
| DESI-060.0471-15.8799 | DEV  | 22.22   | 21.54   | 19.85   | 0.971       |       |        |
| DESI-060.8033-15.1261 | COMP | 22.54   | 20.82   | 19.33   | 0.993       |       |        |
| DESI-060.8089-15.0458 | DEV  | 22.06   | 20.65   | 19.41   | 0.993       |       |        |
| DESI-061.1134-17.2082 | DEV  | 22.61   | 20.68   | 18.72   | 0.999       |       |        |
| DESI-061.1909-14.5760 | COMP | 18.53   | 16.70   | 15.76   | 0.921       |       |        |
| DESI-063.6323-04.5427 | DEV  | 20.36   | 18.74   | 17.87   | 0.990       |       |        |
| DESI-131.3607+00.0361 | DEV  | 24.15   | 21.79   | 19.70   | 0.800       |       |        |
| DESI-134.0057-07.2488 | DEV  | 19.55   | 17.84   | 16.87   | 0.990       |       |        |
| DESI-135.9714+07.1954 | DEV  | 25.90   | 23.38   | 20.87   | 0.900       |       |        |
| DESI-140.8863+20.3278 | DEV  | 20.77   | 19.04   | 18.06   | 0.873       |       |        |
| DESI-143.0565-05.6041 | DEV  | 21.45   | 19.61   | 18.51   | 0.866       |       |        |
| DESI-144.1511+08.8633 | COMP | 20.53   | 18.79   | 17.25   | 0.987       |       |        |

Table 2 continued on next page
| Name                  | Type | mag$_g$ | mag$_r$ | mag$_z$ | Probability | z    | Survey  |
|----------------------|------|---------|---------|---------|-------------|------|---------|
| DESI-144.4242+31.4659 | COMP | 19.16   | 17.56   | 16.27   | 0.949       | 0.5969 | BOSS    |
| DESI-144.6321-04.2535 | COMP | 21.15   | 19.36   | 18.03   | 0.921       |       |         |
| DESI-145.0099+05.4279 | DEV  | 21.35   | 20.12   | 18.86   | 0.900       |       |         |
| DESI-150.0945+00.0047 | COMP | 18.92   | 18.64   | 18.18   | 1.000       |       |         |
| DESI-150.8860-02.9493 | DEV  | 20.89   | 18.95   | 17.36   | 0.992       | 0.6817 | BOSS    |
| DESI-154.5307-00.1368 | DEV  | 20.38   | 18.59   | 17.68   | 0.943       | 0.3718 | SDSS    |
| DESI-154.7654+17.0697 | COMP | 18.73   | 17.16   | 16.32   | 0.939       | 0.3013 | BOSS    |
| DESI-155.4865+11.2037 | DEV  | 19.83   | 18.62   | 17.82   | 0.995       |       |         |
| DESI-157.9622+01.7544 | COMP | 20.34   | 18.78   | 17.77   | 0.989       |       |         |
| DESI-158.7893-02.3037 | COMP | 22.13   | 20.39   | 18.82   | 0.996       |       |         |
| DESI-167.8517+14.1473 | DEV  | 17.82   | 16.44   | 15.65   | 0.904       | 0.2211 | SDSS    |
| DESI-170.6983+25.2669 | DEV  | 20.00   | 18.11   | 17.12   | 0.983       | 0.4310 | SDSS    |
| DESI-176.8122-06.5158 | COMP | 17.68   | 16.12   | 15.26   | 0.983       |       |         |
| DESI-194.5900+15.6322 | DEV  | 22.41   | 20.50   | 18.86   | 0.977       | 0.6847 | BOSS    |
| DESI-194.8376+11.6490 | COMP | 19.62   | 18.33   | 17.51   | 0.935       |       |         |
| DESI-201.7783+02.2129 | DEV  | 20.33   | 18.81   | 17.98   | 0.636       |       |         |
| DESI-201.7841-02.2996 | COMP | 21.79   | 19.97   | 18.25   | 0.931       | 0.7441 | BOSS    |
| DESI-202.3729+31.3290 | DEV  | 21.30   | 19.64   | 18.67   | 0.989       |       |         |
| DESI-204.1663-05.7814 | DEV  | 20.06   | 18.31   | 17.37   | 0.991       |       |         |
| DESI-204.6057+28.3294 | DEV  | 20.92   | 19.32   | 18.02   | 1.000       | 0.5841 | BOSS    |
| DESI-211.0927+02.7242 | DEV  | 21.47   | 19.83   | 18.92   | 0.951       |       |         |
| DESI-216.1003+25.2423 | DEV  | 20.53   | 19.06   | 18.27   | 0.989       | 0.2325 | BOSS    |
| DESI-217.1429-07.0963 | DEV  | 20.02   | 18.48   | 17.62   | 0.938       |       |         |
| DESI-217.4784+12.0433 | DEV  | 21.54   | 19.98   | 18.74   | 0.942       | 0.5531 | BOSS    |
| DESI-219.0374-01.3295 | DEV  | 20.10   | 18.66   | 17.60   | 0.847       |       |         |
| DESI-219.9228+00.5073 | DEV  | 18.67   | 17.67   | 17.00   | 0.837       | 0.1377 | SDSS    |
| DESI-241.0592+06.4200 | DEV  | 20.93   | 19.70   | 18.93   | 0.999       |       |         |
| DESI-241.5432+14.1008 | COMP | 19.99   | 18.38   | 17.43   | 0.989       |       |         |
| DESI-317.3884+05.1456 | COMP | 21.71   | 19.56   | 18.10   | 0.976       | 0.5642 | BOSS    |
| DESI-328.5453+00.6329 | COMP | 18.81   | 17.62   | 16.92   | 0.998       |       |         |
| DESI-351.4891-00.8741 | DEV  | 23.36   | 21.27   | 19.52   | 0.982       |       |         |

Note—Thirty six of the above 105 Grade B lens candidates have spectroscopic redshifts from SDSS (see text). All redshift uncertainties < $3.6 \times 10^{-4}$. 
Table 3. Grade C Candidates

| Name            | Type | mag_g | mag_r | mag_z | Probability | z  | Survey |
|-----------------|------|-------|-------|-------|-------------|----|--------|
| DESI-005.7434+00.1667 | DEV  | 21.28 | 20.92 | 20.37 | 0.835       |    |        |
| DESI-009.9958+00.5677 | DEV  | 21.03 | 19.43 | 18.25 | 0.989       | 0.5255 | SDSS   |
| DESI-010.2439-02.0572 | DEV  | 20.22 | 19.19 | 18.57 | 0.917       |    |        |
| DESI-013.5957-05.7105 | DEV  | 21.44 | 19.59 | 18.44 | 0.961       | 0.5036 | BOSS   |
| DESI-013.9264-01.0692 | DEV  | 20.54 | 19.17 | 18.29 | 0.982       |    |        |
| DESI-013.9873-00.6495 | DEV  | 21.16 | 19.61 | 18.38 | 0.973       | 0.5659 | SDSS   |
| DESI-014.6980+00.2355 | DEV  | 21.83 | 20.16 | 19.24 | 0.996       |    |        |
| DESI-014.7160-00.3509 | COMP | 18.77 | 17.67 | 16.99 | 0.997       | 0.2399 | SDSS   |
| DESI-015.0586+01.8480 | DEV  | 20.54 | 18.81 | 17.88 | 0.934       | 0.4046 | BOSS   |
| DESI-015.1785-18.8779 | DEV  | 21.37 | 19.92 | 19.14 | 0.908       |    |        |
| DESI-015.1912+03.7221 | COMP | 20.21 | 18.37 | 17.43 | 0.970       | 0.3979 | BOSS   |
| DESI-015.2403-16.9542 | COMP | 19.98 | 18.72 | 17.92 | 0.922       |    |        |
| DESI-015.2570-17.7561 | DEV  | 21.28 | 19.40 | 18.18 | 0.991       |    |        |
| DESI-015.3628-00.9079 | COMP | 21.16 | 19.28 | 18.18 | 0.901       | 0.4635 | SDSS   |
| DESI-015.3792-03.3438 | COMP | 19.82 | 18.69 | 17.99 | 0.962       |    |        |
| DESI-015.8070-17.7531 | DEV  | 20.75 | 18.99 | 18.07 | 0.931       |    |        |
| DESI-015.9669-18.0271 | DEV  | 21.10 | 19.46 | 18.53 | 0.987       |    |        |
| DESI-016.1507-00.5780 | DEV  | 21.26 | 19.72 | 18.79 | 0.990       |    |        |
| DESI-016.1763-02.4491 | COMP | 22.77 | 20.87 | 18.88 | 0.936       |    |        |
| DESI-016.1889-00.5809 | DEV  | 21.79 | 20.10 | 19.26 | 0.990       |    |        |
| DESI-016.2032-00.6226 | DEV  | 21.65 | 19.85 | 18.86 | 0.973       |    |        |
| DESI-016.2995-00.0690 | DEV  | 21.93 | 20.32 | 19.27 | 0.994       |    |        |
| DESI-016.3200+00.9163 | DEV  | 21.36 | 19.78 | 18.85 | 0.923       |    |        |
| DESI-016.4625+02.8614 | DEV  | 21.49 | 19.84 | 18.87 | 0.913       |    |        |
| DESI-016.4883-00.1774 | COMP | 22.85 | 21.02 | 19.35 | 0.992       |    |        |
| DESI-016.5355-00.2139 | DEV  | 18.28 | 17.16 | 16.42 | 0.922       | 0.1971 | SDSS   |
| DESI-016.8009-16.8580 | DEV  | 20.94 | 19.41 | 18.53 | 0.901       |    |        |
| DESI-016.8554-00.7320 | COMP | 20.47 | 19.00 | 17.61 | 0.976       |    |        |
| DESI-016.9199-05.3919 | DEV  | 21.30 | 19.64 | 18.44 | 0.970       | 0.5214 | BOSS   |
| DESI-016.9228-03.8680 | COMP | 21.06 | 19.46 | 18.18 | 0.979       |    |        |
| DESI-016.9682+00.3567 | COMP | 19.59 | 17.97 | 17.09 | 1.000       | 0.3133 | SDSS   |
| DESI-017.2362-17.9241 | DEV  | 21.44 | 19.79 | 19.01 | 0.924       |    |        |
| DESI-018.0415+00.1861 | DEV  | 19.67 | 18.29 | 17.50 | 0.916       |    |        |
| DESI-018.4701+03.4968 | DEV  | 22.37 | 20.52 | 19.23 | 0.996       | 0.5517 | BOSS   |
| DESI-019.8976-12.8253 | DEV  | 21.96 | 20.12 | 18.95 | 0.945       |    |        |
| DESI-020.3517+00.1654 | DEV  | 21.01 | 19.92 | 18.75 | 0.971       | 0.7690 | BOSS   |

Table 3 continued on next page
### Table 3 (continued)

| Name                  | Type | mag$_g$ | mag$_r$ | mag$_z$ | Probability | z     | Survey |
|-----------------------|------|---------|---------|---------|-------------|-------|--------|
| DESI-020.5273-04.8117 | DEV  | 21.20   | 19.36   | 18.40   | 0.985       | 0.3978| BOSS   |
| DESI-021.5439-00.5883 | DEV  | 21.33   | 19.79   | 18.95   | 0.985       |       |        |
| DESI-021.8518-05.7560 | DEV  | 21.75   | 20.15   | 19.11   | 0.944       |       |        |
| DESI-021.9637+00.0975 | DEV  | 21.43   | 20.15   | 19.39   | 0.967       |       |        |
| DESI-022.6104-15.3370 | DEV  | 21.47   | 19.70   | 18.37   | 0.980       |       |        |
| DESI-023.6659-06.9344 | COMP | 22.22   | 20.65   | 19.76   | 0.921       |       |        |
| DESI-023.7790+01.5306 | DEV  | 22.82   | 21.13   | 19.60   | 0.921       |       |        |
| DESI-024.7012-07.5349 | DEV  | 21.38   | 19.67   | 18.61   | 0.975       | 0.4924| BOSS   |
| DESI-025.8361-10.0680 | COMP | 19.79   | 18.67   | 17.97   | 0.980       | 0.2422| SDSS   |
| DESI-026.2451-01.5934 | DEV  | 22.38   | 20.80   | 19.62   | 0.905       |       |        |
| DESI-026.2771-00.7284 | COMP | 20.29   | 19.39   | 17.97   | 0.949       |       |        |
| DESI-027.5388-12.3284 | DEV  | 20.88   | 19.15   | 18.28   | 0.926       |       |        |
| DESI-027.8872-08.5764 | COMP | 21.94   | 20.07   | 18.71   | 0.945       | 0.5735| BOSS   |
| DESI-028.2710-09.8289 | DEV  | 22.48   | 20.66   | 19.27   | 0.972       | 0.5973| BOSS   |
| DESI-028.3093-00.4385 | DEV  | 22.39   | 21.07   | 19.39   | 0.958       |       |        |
| DESI-028.8348-13.9044 | COMP | 20.24   | 19.28   | 18.71   | 0.900       |       |        |
| DESI-029.1778-10.1834 | DEV  | 22.01   | 20.90   | 19.47   | 1.000       |       |        |
| DESI-030.8114-09.1587 | DEV  | 20.11   | 18.62   | 17.87   | 1.000       |       |        |
| DESI-031.8778-14.8046 | DEV  | 24.15   | 21.92   | 20.34   | 0.954       |       |        |
| DESI-033.9735-12.6841 | DEV  | 21.85   | 20.04   | 18.87   | 0.992       |       |        |
| DESI-034.0253-04.5771 | DEV  | 22.25   | 20.46   | 19.29   | 1.000       |       |        |
| DESI-034.3281-05.1331 | DEV  | 23.33   | 21.65   | 20.26   | 0.993       |       |        |
| DESI-035.7202-03.9575 | COMP | 22.69   | 21.50   | 19.82   | 1.000       | 0.8368| eBOSS  |
| DESI-035.8285-04.3979 | DEV  | 21.41   | 19.72   | 18.80   | 0.937       |       |        |
| DESI-035.8379-07.3794 | COMP | 19.89   | 17.97   | 16.63   | 0.995       |       |        |
| DESI-035.8438-06.3246 | COMP | 20.05   | 18.32   | 17.47   | 0.967       | 0.3560| BOSS   |
| DESI-035.8660-18.4836 | COMP | 18.51   | 16.97   | 16.16   | 0.954       |       |        |
| DESI-035.9027-06.8806 | COMP | 19.97   | 18.58   | 17.43   | 0.999       |       |        |
| DESI-035.9185-05.8453 | DEV  | 22.43   | 21.00   | 19.88   | 0.996       |       |        |
| DESI-035.9393-04.4005 | DEV  | 20.12   | 18.53   | 17.62   | 1.000       | 0.3037| BOSS   |
| DESI-036.0184-04.4084 | DEV  | 21.71   | 20.19   | 19.39   | 1.000       |       |        |
| DESI-036.0256-06.4796 | DEV  | 21.58   | 20.29   | 19.47   | 0.986       |       |        |
| DESI-036.0536-06.1645 | DEV  | 20.81   | 19.19   | 18.34   | 0.979       |       |        |
| DESI-036.0653-05.8029 | DEV  | 22.90   | 21.55   | 19.62   | 0.998       |       |        |
| DESI-036.0879+00.0726 | COMP | 19.59   | 18.29   | 17.52   | 0.959       |       |        |
| DESI-036.1151-05.2254 | DEV  | 22.06   | 21.00   | 19.61   | 0.998       | 0.9028| eBOSS  |
| DESI-036.1457-05.4990 | DEV  | 21.98   | 20.87   | 19.50   | 0.991       |       |        |
| DESI-036.2194-04.3486 | DEV  | 22.68   | 21.65   | 19.95   | 1.000       |       |        |

*Table 3 continued on next page*
Table 3 (continued)

| Name              | Type | mag_g | mag_r | mag_z | Probability | z   | Survey |
|-------------------|------|-------|-------|-------|-------------|-----|--------|
| DESI-036.2244-06.3029 | DEV  | 22.39 | 20.74 | 19.54 | 0.956       |     |        |
| DESI-036.2714-06.8192 | DEV  | 19.62 | 18.92 | 18.38 | 0.983       |     |        |
| DESI-036.3530-04.6792 | DEV  | 19.01 | 17.48 | 16.67 | 1.000       | 0.2643 | BOSS   |
| DESI-036.3795-04.2093 | DEV  | 22.97 | 21.32 | 19.65 | 1.000       | 0.7726 | eBOSS  |
| DESI-036.4031-04.2550 | DEV  | 22.08 | 20.32 | 19.05 | 1.000       | 0.5557 | BOSS   |
| DESI-036.4081-05.2473 | DEV  | 20.63 | 19.04 | 18.17 | 0.999       |     |        |
| DESI-036.4268-05.1548 | DEV  | 19.80 | 18.63 | 17.94 | 1.000       |     |        |
| DESI-036.4827-16.8621 | DEV  | 19.41 | 17.99 | 17.14 | 0.984       |     |        |
| DESI-036.6282-04.6316 | DEV  | 22.26 | 20.51 | 19.22 | 1.000       | 0.5906 | BOSS   |
| DESI-036.6556-03.7101 | DEV  | 22.13 | 20.56 | 19.43 | 0.999       |     |        |
| DESI-036.6760-03.6801 | DEV  | 20.33 | 19.05 | 18.21 | 1.000       |     |        |
| DESI-036.6777-03.6555 | COMP | 21.80 | 20.40 | 19.82 | 1.000       |     |        |
| DESI-036.6819-03.6905 | DEV  | 21.02 | 19.39 | 18.53 | 1.000       | 0.3284 | eBOSS  |
| DESI-036.7198+00.2833 | DEV  | 19.91 | 18.32 | 17.33 | 0.996       | 0.3022 | SDSS  |
| DESI-036.7325-05.1276 | DEV  | 21.73 | 19.87 | 18.76 | 1.000       | 0.4361 | BOSS   |
| DESI-036.8076-05.0255 | DEV  | 22.14 | 20.88 | 19.90 | 0.999       |     |        |
| DESI-036.8133-03.9033 | COMP | 19.64 | 18.88 | 18.15 | 0.999       |     |        |
| DESI-036.9560-06.1539 | DEV  | 21.46 | 19.67 | 18.69 | 0.932       | 0.4324 | BOSS   |
| DESI-037.0345-04.5015 | DEV  | 22.20 | 20.50 | 19.45 | 1.000       |     |        |
| DESI-037.1686-04.0027 | DEV  | 20.09 | 18.75 | 18.01 | 1.000       |     |        |
| DESI-037.2011-04.1161 | DEV  | 20.17 | 19.28 | 18.67 | 0.993       | 0.1406 | BOSS   |
| DESI-037.2064-01.2158 | DEV  | 21.05 | 19.64 | 18.34 | 0.984       | 0.6895 | BOSS   |
| DESI-037.2945+03.7522 | DEV  | 24.56 | 22.05 | 19.98 | 0.945       |     |        |
| DESI-037.4766+03.1089 | DEV  | 22.26 | 20.84 | 19.46 | 0.985       |     |        |
| DESI-038.2709-10.4498 | DEV  | 22.03 | 20.38 | 19.19 | 0.957       |     |        |
| DESI-038.8461-10.5125 | DEV  | 20.76 | 19.29 | 18.51 | 0.964       |     |        |
| DESI-039.0463-06.3428 | DEV  | 22.71 | 21.00 | 19.42 | 0.973       |     |        |
| DESI-039.2003+03.3583 | DEV  | 20.93 | 19.31 | 18.25 | 0.984       | 0.4673 | BOSS   |
| DESI-039.9261-01.4632 | DEV  | 19.68 | 18.51 | 17.68 | 0.957       |     |        |
| DESI-040.6372-12.1891 | DEV  | 19.92 | 17.98 | 17.00 | 0.999       |     |        |
| DESI-040.6769-00.6487 | DEV  | 23.64 | 21.84 | 19.95 | 0.968       |     |        |
| DESI-040.7046+02.2423 | DEV  | 19.69 | 18.72 | 18.07 | 0.942       |     |        |
| DESI-040.8745-01.9373 | DEV  | 23.10 | 21.18 | 19.68 | 1.000       |     |        |
| DESI-041.3678-01.2016 | DEV  | 21.65 | 20.27 | 18.97 | 1.000       | 0.6669 | BOSS   |
| DESI-041.4318-08.6492 | COMP | 21.44 | 20.05 | 18.64 | 0.999       | 0.7261 | BOSS   |
| DESI-041.5548-00.7524 | COMP | 22.47 | 21.24 | 19.80 | 0.997       |     |        |
| DESI-041.7915-08.4225 | DEV  | 21.39 | 19.50 | 18.31 | 0.957       | 0.5221 | BOSS   |
| DESI-041.9910-00.7425 | DEV  | 21.70 | 20.45 | 19.68 | 0.999       |     |        |

Table 3 continued on next page
| Name                  | Type | mag\_g | mag\_r | mag\_z | Probability | z   | Survey  |
|-----------------------|------|--------|--------|--------|-------------|-----|---------|
| DESI-042.2156-00.5329| DEV  | 19.33  | 18.02  | 17.22  | 0.995       | 0.2547 | BOSS    |
| DESI-042.9152-00.5600| DEV  | 22.07  | 20.10  | 18.70  | 1.000       | 0.5846 | BOSS    |
| DESI-046.6993-15.0593| DEV  | 22.53  | 20.97  | 19.64  | 0.985       |       |         |
| DESI-047.3321-13.5368| DEV  | 22.19  | 20.49  | 19.21  | 0.998       |       |         |
| DESI-060.4389-14.7568| DEV  | 20.04  | 18.57  | 17.77  | 0.986       |       |         |
| DESI-060.6860-15.7303| COMP | 19.67  | 18.89  | 18.30  | 0.976       |       |         |
| DESI-061.0991-13.883 | COMP | 22.79  | 21.03  | 18.97  | 0.954       |       |         |
| DESI-064.4878-03.6133| DEV  | 19.04  | 17.83  | 17.07  | 0.997       |       |         |
| DESI-125.6392-00.4650| DEV  | 21.11  | 19.20  | 17.94  | 0.951       | 0.5253 | BOSS    |
| DESI-131.8556+14.2550| COMP | 19.98  | 18.67  | 17.89  | 0.841       |       |         |
| DESI-138.6664-00.0821| DEV  | 22.79  | 21.03  | 19.69  | 0.953       |       |         |
| DESI-149.1942+00.7137| DEV  | 21.93  | 20.48  | 19.35  | 0.998       |       |         |
| DESI-150.2022+01.6538| DEV  | 18.52  | 17.20  | 16.45  | 0.998       |       |         |
| DESI-150.4045+02.5544| DEV  | 19.56  | 18.11  | 17.32  | 0.991       | 0.2477 | BOSS    |
| DESI-151.2006-03.7158| DEV  | 20.00  | 18.64  | 17.92  | 0.911       |       |         |
| DESI-151.7664+02.1430| DEV  | 20.51  | 18.84  | 17.95  | 0.972       |       |         |
| DESI-151.9855+02.4052| DEV  | 21.90  | 20.17  | 18.97  | 0.943       | 0.5307 | BOSS    |
| DESI-152.5264-01.9658| DEV  | 22.31  | 20.50  | 19.43  | 0.993       |       |         |
| DESI-152.8042-02.0432| DEV  | 17.72  | 16.39  | 15.62  | 0.965       |       |         |
| DESI-153.0462-00.8142| COMP | 20.91  | 20.00  | 18.72  | 0.983       |       |         |
| DESI-154.3116+02.4885| DEV  | 19.42  | 17.68  | 16.73  | 0.999       | 0.3576 | SDSS    |
| DESI-155.4226+00.6966| DEV  | 22.48  | 20.58  | 19.12  | 0.919       | 0.6186 | BOSS    |
| DESI-158.0944+15.8846| DEV  | 21.57  | 20.03  | 18.45  | 0.949       |       |         |
| DESI-158.8311-00.5674| DEV  | 19.48  | 17.85  | 16.94  | 0.992       | 0.3157 | SDSS    |
| DESI-170.8533+15.1850| DEV  | 19.04  | 17.36  | 16.46  | 0.987       | 0.3406 | BOSS    |
| DESI-176.2181+08.9457| DEV  | 21.36  | 19.55  | 18.44  | 0.943       | 0.4971 | BOSS    |
| DESI-180.0490-00.4182| COMP | 23.41  | 21.54  | 19.96  | 0.971       |       |         |
| DESI-181.9442+27.6152| COMP | 18.56  | 17.04  | 16.20  | 0.995       | 0.3282 | SDSS    |
| DESI-184.3703+15.6730| DEV  | 21.69  | 20.21  | 19.05  | 0.942       |       |         |
| DESI-193.6112-08.7744| DEV  | 20.42  | 18.85  | 17.94  | 0.991       |       |         |
| DESI-201.4063+04.1883| DEV  | 20.87  | 19.50  | 18.65  | 0.455       |       |         |
| DESI-203.3751-02.1804| DEV  | 21.52  | 20.00  | 18.90  | 0.947       |       |         |
| DESI-204.7174-08.3381| DEV  | 20.36  | 18.83  | 18.03  | 0.743       |       |         |
| DESI-205.7370+22.6135| DEV  | 21.04  | 19.69  | 18.63  | 0.813       | 0.5198 | BOSS    |
| DESI-210.3880+13.3370| DEV  | 20.12  | 18.83  | 18.05  | 0.856       |       |         |
| DESI-212.6868-07.1025| DEV  | 20.45  | 19.12  | 18.34  | 0.942       |       |         |
| DESI-240.0759+05.6966| DEV  | 21.18  | 19.44  | 18.52  | 0.995       |       |         |
| DESI-240.3397+05.0773| DEV  | 21.87  | 20.91  | 19.89  | 0.981       |       |         |

*Table 3 continued on next page*
Table 3 (continued)

| Name                | Type | mag.g | mag.r | mag.z | Probability | z   | Survey     |
|---------------------|------|-------|-------|-------|-------------|-----|------------|
| DESI-240.4006+05.5796 | DEV  | 20.43 | 18.97 | 18.21 | 0.993       |     |            |
| DESI-240.5350+06.0657 | DEV  | 22.56 | 20.99 | 19.66 | 1.000       |     |            |
| DESI-240.7203+06.5371 | COMP | 21.62 | 19.97 | 18.67 | 0.997       |     |            |
| DESI-241.2494+06.8555 | DEV  | 21.68 | 20.27 | 19.36 | 0.999       |     |            |
| DESI-241.3833+15.8226 | DEV  | 19.76 | 18.27 | 17.22 | 0.969       | 0.5119 | BOSS      |
| DESI-241.7841+07.0210 | COMP | 20.76 | 20.04 | 19.41 | 0.969       |     |            |
| DESI-241.8463+07.1753 | COMP | 21.47 | 19.49 | 18.04 | 1.000       | 0.5903 | BOSS      |
| DESI-242.0285+03.8786 | DEV  | 22.07 | 21.07 | 19.44 | 0.909       |     |            |
| DESI-242.4262+06.1599 | DEV  | 22.07 | 20.20 | 18.97 | 0.996       | 0.5453 | BOSS      |
| DESI-249.9825+19.0354 | COMP | 20.72 | 18.84 | 17.40 | 0.921       | 0.6064 | BOSS      |
| DESI-251.0765+01.6752 | DEV  | 21.32 | 19.46 | 18.41 | 0.921       |     |            |
| DESI-251.1722+04.9724 | DEV  | 20.45 | 18.90 | 17.99 | 0.901       |     |            |
| DESI-317.2431+03.9841 | COMP | 19.70 | 18.96 | 18.34 | 0.957       |     |            |
| DESI-319.7989+00.0575 | DEV  | 20.16 | 18.79 | 18.00 | 0.958       |     |            |
| DESI-338.0990+01.5111 | DEV  | 22.37 | 20.79 | 19.51 | 0.992       |     |            |
| DESI-351.1264-11.6503 | DEV  | 21.83 | 19.94 | 18.55 | 1.000       |     |            |
| DESI-351.1287-11.2566 | COMP | 21.80 | 20.75 | 19.72 | 0.998       |     |            |
| DESI-351.1413-12.4955 | DEV  | 20.75 | 18.92 | 17.98 | 1.000       |     |            |
| DESI-351.2285-11.6281 | DEV  | 21.89 | 20.09 | 19.11 | 0.999       |     |            |
| DESI-351.2576-12.7728 | DEV  | 24.17 | 22.08 | 19.89 | 0.997       |     |            |
| DESI-351.3096-12.5492 | COMP | 20.71 | 19.13 | 18.29 | 1.000       |     |            |
| DESI-351.3891-12.0013 | DEV  | 20.74 | 19.38 | 18.59 | 0.998       |     |            |
| DESI-351.4008-11.9943 | DEV  | 21.19 | 19.36 | 18.44 | 0.998       |     |            |
| DESI-351.4290-12.2431 | DEV  | 20.59 | 18.78 | 17.88 | 1.000       |     |            |
| DESI-351.4915-11.6013 | DEV  | 20.47 | 19.17 | 18.41 | 0.998       |     |            |
| DESI-351.5372-11.3464 | DEV  | 21.76 | 20.16 | 19.38 | 0.999       |     |            |

Note—Fifty one of the above 176 Grade C lens candidates have spectroscopic redshifts from SDSS (see text). All redshift uncertainties < 3.9 × 10^{-4}.

We have checked our candidates against the HST Source Catalog (HScv3)\(^{12}\), and found six known lenses among the Grade A candidates: DESI-016.3319+01.7490 and DESI-026.2679-04.9310 (Stark et al. 2013), DESI-036.1436-00.0411 (Gladders et al. 2003), DESI-168.2943+23.9443 (Kubo et al. 2009), DESI-204.0002-03.5250 and DESI-219.7907+12.1404 (SDSS DR12 BCG; Sharon et al. 2019). These are not in our training sample, and shown with a red rim in Figure 2. This leaves the number of new Grade A candidates as 54, and the total number of new lens candidates, 335.

We have found at least 13 new cluster/group scale strong lenses: DESI-019.6618-05.4441, DESI-060.2420-13.9567, DESI-167.8517+14.1473 DESI-219.9855+32.8402, and DESI-359.8897+02.1399 (with a giant red arc) among Grade A, and DESI-009.9772-12.2100, DESI-018.1714-19.0457,

\(^{12}\) https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html
Among the hundreds of galaxy scale candidates, there are many notable lensing events. We especially would like to highlight: **DESI-135.3125+09.940**, a system having a lens with $g - r = 3.3$, likely indicating a high redshift (e.g., Jacobs et al. 2019); **DESI-041.5205-06.1275**, a nearly perfect Einstein Cross; and **DESI-038.2078-03.3906**, a nearly complete Einstein ring, which resembles the well-known “Cosmic Horseshoe” lens (Belokurov et al. 2007; Schuldt et al. 2019), but with a smaller Einstein radius ($\approx 4.1\arcsec$).

Finally we checked our candidate list against the spectroscopic database from SDSS I and II (York et al. 2000), SDSS III/BOSS (Eisenstein et al. 2011), and SDSS IV/eBOSS (Blanton et al. 2017) and found 120 matches, which is slightly greater than one third of all candidates. The available redshifts are included in Tables 1, 2, and 3.

### 4.2. Probability Bins Lower than 0.9

It is notable that there are typically many more candidates with probability greater than 0.9 than with probabilities between 0.8 and 0.9. In a small testing inference run that covers $\approx 4\%$ of the DECaLS footprint, we have examined and found lens candidates with probability $< 0.9$. The yield typically rapidly diminishes with lower probabilities. As stated earlier, for the deployment on galaxies typed DEV and COMP, we impose a magnitude cut at $z \leq 20.0$ mag. For our small test inference run, we included all objects with $z \leq 22.5$ mag. From that run, we have found one Grade B lens (DESI-135.9714+07.1954) with a $z$-band magnitude of 20.87. Given that a strong majority of the best lens candidates are from the probability $> 0.9$ bin for the categories of DEV and COMP, in this paper we focus on this subset for human inspection.

The completeness is difficult to estimate at this point, even just for elliptical galaxies because 1) the data reduction for the Legacy Surveys has not completed (recall for this deployment, we have only included images with at least 3 passes in each band) and 2) we have not run inference on the REX category, which contains an unknown number of elliptical galaxies.

A rough estimate of completeness can be performed by checking how many lensing systems from the training sample would be “re-discovered.” This depends on the threshold. For images in the training set, 47% have probability $> 0.9$, and the validation set, 40%. If the threshold is lowered to probability $> 0.8$, 57% and 44% of the training and validation sets, respectively, would be recovered. The percentages for the testing set are similar to those for the validation set. The implication seems to be that there are hundreds more lenses to be discovered in lower probability bins. We can already confirm there are good lens candidates with probability below 0.9 based on visual inspection for a small subset of the data. However, we caution against a simple forecast based on these percentages. The images in the training sample that receive low probability often are less obvious lenses for the human inspector. In fact for the next round of training, we would remove some of them from the training sample. They were included in the current training sample as we tried to balance the aims for purity and completeness. With the experience of this deployment, we have a better sense of which ones to include next time.

### 4.3. Lenses in Other Tractor Galaxy Types

Most galaxies in the Legacy Surveys catalog are classified as the morphological type REX, i.e., the best-fit source model has a round exponential profile. The REX category contains an order
of magnitude more objects than the DEV and COMP types combined, since most faint, extended galaxies are preferentially modeled by the REX profile. It likely includes many elliptical galaxies, though the percentage is unknown. Even so, given the total number of objects in this category is much larger than those in DEV and COMP categories, there will likely be a large number of lensing systems to be discovered. Among the 199 known lenses from the Legacy Surveys in the training sample, 18 are typed as REX. Out of these, 12 have $z < 20.0$ mag and one with $z = 20.2$ mag. We will run inference on this category (and the much smaller category of EXP, in order to be thorough) after the next round of training and report the results in a follow-up publication.

4.4. Purity of the ResNet Results

Below we briefly discuss the purity of the ResNet results thus far. In total we have examined $\sim 50,000$ objects. On average one in 150 objects is a lens candidate. The Legacy Surveys data is catalogued by Tractor and organized in folders, with each folder corresponding to one degree of RA on the sky. The efficiency of our trained ResNet is highly uneven. The number of ResNet-recommended objects per folder in the probability $> 0.9$ bin vary from under 200 to over 3,000. We have examined folders with both small and large numbers of objects. In general the folders with lower numbers of objects have higher purity. We have approximately covered 3/4 of the sky for the DEV and COMP objects in this probability bin. For the remaining 1/4 of the folders, the number of objects are all high ($\gtrsim 1000$/folder). We have stopped human inspection for now. One possible reason for nonuniform efficiency is the difference in coverage. While for all images we require a minimum of three passes in each band, the depth of coverage can be very different from one part of the sky to the next. The situation will vastly improve after the data reduction for the survey has been completed, which will be soon. However, there can be other reasons, e.g., a relatively small number of lenses and non-lenses in the training sample and the inclusion of 21 known lenses in the training sample from the northern MzLS/BASS area, which have very different seeings in $gr$ bands. Based on our experience so far, we believe we can build a better, i.e., larger and more representative training sample, and retrain. With the new training sample (see § 5 for a list of how our training sample can be improved), we believe we can significantly increase the efficiency. It is also important to retrain because we want to search for lenses in the REX category as well, which as pointed out in the previous section, has an order of magnitude more objects.

5. DISCUSSION

Our results so far are encouraging. Here we will identify where we can improve. In our current training sample we have only used 423 lenses. This is generally considered too small a number for a deep neural net. Nevertheless, we have succeeded in finding hundreds of new lens candidates over a large area of the sky for cutout images centered on elliptical galaxies. For the parts of the sky where our trained neural net is not effective, it is likely that we need a larger non-lens sample (there are 13,000 in the current training sample) to cover a much greater variety of image configurations and possibly subtle sky background condition variations. In our experience, having a large number of non-lenses is very helpful in terms of giving the neural net a better chance to reject a diverse variety of non-lenses. This experience comports with what has been reported by other authors. Metcalf et al. (2018) used 20,000 simulated non-lenses in the Lens Competition, which do not include the many complications arising in real observations. Jacobs et al. (2019) used 130,000 non-lenses in their training sample for an ensemble of CNN models to find high redshift lenses in DES. In addition, we
will make sure to include the following (many of these have been given greater than 0.9 probability of being a lens by the current trained ResNet model): star clusters; instances of interacting galaxies, ring galaxies, and more varieties of spiral galaxies than in the current training sample; and more cosmic ray examples, especially those with curved and/or thick tracks.

As stated in § 3, so far we have not used the validation and testing sets in our training. We have ∼ 600 lenses in the entire current training sample. We can add ∼ 160 lens candidates with high confidence, including all Grade A and Grade B candidates in this paper. Thus we will have ∼ 760 lenses in our next training sample, ∼ 80% more lenses than used for the current trained model.

We believe by using more workers/nodes on Cori at NERSC or possibly GPU’s, the ResNet can train on this larger sample within a reasonable amount of time. Though at this stage we have left the architecture and hyperparameters of the ResNet from L18 unchanged, we may vary both to optimize performance.

Finally, we would like to emphasize the importance of the Grade B and C candidates. The “re-discovered lenses” outside the training sample are in the A category (6 out of 60). This is not a surprise: typically having brighter arcs with larger deflection angles, these systems are comparatively easy to find. Higher redshift lensing systems from ground-based surveys are likely not in the Grade A category but in B or C. The current known lensing sample mostly consists of luminous elliptical galaxies at redshifts from approximately 0.4 to 0.8 (e.g., Brownstein et al. 2012; Wong et al. 2018). Our lens candidates are fainter, and mostly have optical and infrared colors consistent with \( z > 0.8 \) (e.g., Jacobs et al. 2019). Higher lens redshifts significantly increase the power relative to lower redshift samples for constraining the mass function of low-mass CDM halos, due to the greater optical depth for perturbations by low-mass halos associated with a longer path length along the line of sight (Despali et al. 2018; Ritondale et al. 2019). In addition, the lensed sources will tend to have higher redshifts than in known lensing systems as well.

6. CONCLUSIONS

We have carried out a proof of concept end-to-end implementation of applying a deep residual neural network developed by Lanusse et al. (2018), trained on observed lenses and non-lenses, to a subset of the Legacy Surveys data — 5.7 million elliptical galaxies from DECaLS with a \( z \)-band magnitude cut of 20.0 mag. We use only real observations for training. In total, we have found 60 Grade A candidates (of these, 54 are new), 105 Grade B and 176 Grade C candidates (all new). The results are promising. Despite using a relative small training set with 423 lens and 9451 non-lenses with non-uniform coverage (given the survey has not yet been completed), in this paper we report the discovery of the first batch of 335 new strong lens candidates from the Legacy Surveys. We will improve our training sample and model for the next round of training for full deployment on the entire 14,000 deg\(^2\) footprint and all galaxy types in the Legacy Surveys.

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