Strong Lensing Model and Implementation for ELAsTiCC

Richard Kessler and Justin Pierel (July 14, 2022)

The final test set for the "Extended LSST Astronomical Time Series Classification Challenge" (ELAsTiCC[1]) includes ∼5 million events and ∼50 million alerts spanning more than 30 transient models. This internal DESC[2] note briefly describes a strong lens (SL) model that was implemented as part of the final test set, but was NOT included in the training sample, nor the 10% development samples.

The strong lens model is from J.Pierel et al., 2021[3] (herafter P21) that was used to forecast cosmological constraints using strongly-lensed supernovae expected to be found by the Roman Space Telescope. While this model included achromatic micro-lensing effects, these micro-lensing effects are not included for ELAsTiCC since it requires more work (separate post-processing step after simulation) and because these subtle effects have little impact on the main goal of testing SL-finding capabilities in the LSST brokers.

The P21 model consists of a SL catalog (hereafter SLC) that is read by the SNANA simulation[4] to convert model SN lightcurves into magnified strongly-lenses SNe, and to simulate instrumental effects. For ELAsTiCC, the SLC was re-created without selection requirements and to a depth of ∼27th magnitude so that detection limits and selection effects are completely determined by the same SNANA simulation that was used to generate the ELAsTiCC data set. The SLC is described in the appendix. The term "lensed image" below refers to catalog information since no CCD images are used in the simulation.

The lensing magnification model in P21 was used in ELAsTiCC without alteration. However, the following simulation improvements were implemented regarding the treatment of the observed host galaxy and the ability to resolve nearby lensed sources:

- Using the lens galaxy redshift and stellar mass from SLC, a lens galaxy is selected from the HOSTLIB[5] to closely match the SLC lens properties. This lens galaxy is assigned to be the host galaxy in the data files and alerts.
- For each lensed image `DDLR = SNSEP/DLR` is computed, where `SNSEP` is the image-lens separation and `DLR` is the directional light radius. `DDLR < 4` is required to report a host-match.
- Resolving each lensed image is estimated following Oguri and Marshall 2010.[6] First, `MINSEP` is computed as the minimum separation to all other lensed images. A resolved source is assumed if `MINSEP` is greater than $\frac{2}{3}\theta_{\rm PSF}$, where $\theta_{\rm PSF}$ is the PSF-FWHM.
- The redshift-dependent SN rate model, $R(z)$, is modified to be $R(z) \to R(z) \times P_{\rm lens}(z)$ where $P_{\rm lens}(z)$ is the probability of strong lensing from Eq. 30 (Fig 5) in Oguri 2019.[7] This rate-model update enables an absolute prediction for the rate of observed SL events in ELAsTiCC.
- The simulation outputs a `[VERSION].SL` truth table with one-row-per-lens summary that includes a list of time delays, magnifications, and SNIDs.

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[1] https://indico.in2p3.fr/event/26887/contributions/111730/attachments/71748/102266/Narayan_ELAsTiCC_BDL_20220623.pdf

[2] DESC: Dark Energy Science Collaboration

[3] Pierel et al., 2020: https://ui.adsabs.harvard.edu/abs/2021ApJ...908..190P

[4] https://github.com/RickKessler/SNANA

[5] HOSTLIB is a host galaxy library used by SNANA simulation.

[6] Oguri and Marshall: https://ui.adsabs.harvard.edu/abs/2010MNRAS.405.2579O

[7] Oguri 2019: https://ui.adsabs.harvard.edu/abs/2019RPPh...82l6901O

TRIGGER

The simulated ELAsTiCC trigger requires a "difference-imaging analysis" (DIA) detection in any band for at least one observation. While the ELAsTiCC simulation does not use DIA directly, the simulated detection efficiency vs. SNR ($\epsilon_{\rm SNR}$) is determined from DIA and shown in Fig. 9 of Sanchez et al. 2022.[8] The $\epsilon_{\rm SNR}$ curve reaches 50% at SNR= 5.8, and this efficiency curve is used to evaluate a detection for every observation. For SL events, the trigger also requires a resolved source defined as more than $\frac{2}{3}\theta_{\rm PSF}$ separation from other lensed sources. For double systems, the two images are both resolved or both unresolved. For quad systems, it is possible that a subset is resolved. For observations that fail detection due to proximity closer than $\frac{2}{3}\theta_{\rm PSF}$, forced photometry is correctly reported because we do not model photometry errors due to blended sources.

SUPERNOVA MODELS

The SL simulation for ELAsTiCC was applied to four SN models:

1. SNIa (SALT2-extended), $N_{\rm GEN} = 4532$
2. SNII (V19_SNII+HostXT) , $N_{\rm GEN} = 18645$
3. SNIb (V19_SNIb+HostXT) , $N_{\rm GEN} = 2390$
4. SNIc (V19_SNIc+HostXT) , $N_{\rm GEN} = 2390$

where the V19 SED-template models are from Vincenzi et al., 2019.[9] The number of generated events ($N_{\rm GEN}$) per model was computed by the simulation using the rate model, 3-year ELAsTiCC time window, redshift range, and WFD solid angle of 5.7 steridians.

[8] Sanchez et al., 2022: https://ui.adsabs.harvard.edu/abs/2021arXiv211106858S

[9] Vincenzi et al., 2019: https://ui.adsabs.harvard.edu/abs/2019MNRAS.489.5802V

RESULTS

These preliminary results are based on generating only the SL events. When the SL events are generated together with the other `ELAsTiCC` models, a different random seed will result in statistical fluctuations compared to what is shown below. The main results are shown in Table 1. The number of generated lens systems per model (2nd column) is almost 5,000 for SNIa, and more than 20,000 for the three SNCC models. An accepted lens (3rd column) is counted if one or more of the lensed light curves is detected; the total number is ∼100 summed over all models. The last column shows the number of lenses for which LSST data alone are potentially useful for measuring time delays and the Hubble constant; these are defined as having 2 or more detected light curves. The total number of useful lenses is ∼25, and includes two triplets and two quads. Beware that a real analysis will apply selection requirements on SNR and sampling, and thus the useful lens sample will be smaller than shown in Table 1.

Fig. 1 shows the lens redshift vs. source redshift for lensed SNIa and SNCC events passing `ELAsTiCC` detection. To illustrate the impact of the $\frac{2}{3}\theta_{\rm PSF}$ separation requirement, Fig. 2 shows the accepted lensed SN distribution $N_{\rm ACC}$ distribution on the left without a separation requirement, and on the right with the nominal requirement. The separation cut reduces the sample by about a factor of 2.

Table 1: Summary of lens-simulation statistics for 3-year `ELAsTiCC` sample

model	Generated $N_{\rm LENS}$	Accepted $N_{\rm LENS}$	$N_{\rm LENS}$ with $N_{\rm ACC}=$ 2	3	4	suffix in sim-folder name
SNIa	4532	71	14	1	1	`CACHE-1`
SNII	18645	47	5	1	0	`CACHE-2`
SNIb	2390	12	3	0	0	`CACHE-3`
SNIc	2390	16	0	0	1	`CACHE-4`

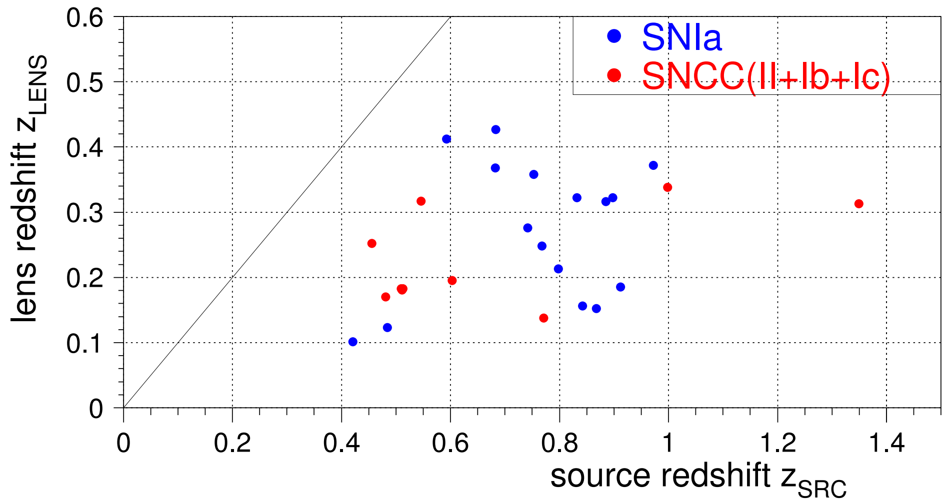

Figure 1: Lens-galaxy redshift vs. source redshift for SNIa (blue) and SNCC (red). Diagonal lines shows where `ZLENS = ZSRC`. Sample is for 3-year `ELAsTiCC`, and satisfies single-detection trigger with $\frac{2}{3}\theta_{\rm PSF}$ separation from other lensed light curves.

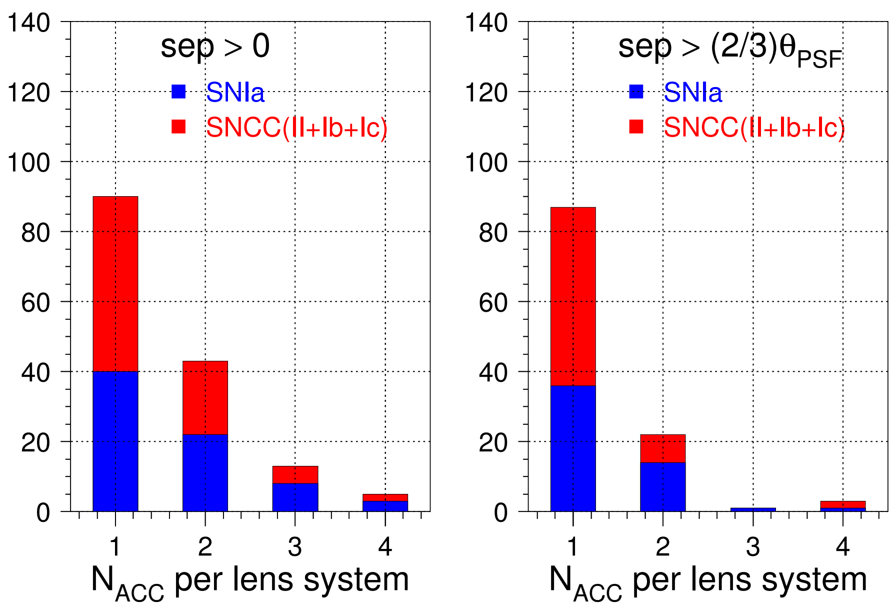

Figure 2: Number of trigger-accepted light curves per lens without separation requirement (left) and with $\frac{2}{3}\theta_{\rm PSF}$ separation requirement (right).

APPENDIX

A Strong Lens Catalog (SLC)

The SLC is based on P21 and Oguri and Marshall 2010;[10] it is available in the SNANA environment at
`$SNDATA_ROOT/models/lensing/STRONGLENS_P21.DAT`

Each lens in the SLC contains the following information:

- LENSID: unique identification number
- NIMG: number of lensed images
- LOGMASS_LENS: log of lens-galaxy stellar mass assuming the empirical Auger+2010 relationship between simulated velocity dispersion and host galaxy mass
- LOGMASS_ERR_LENS: uncertainty on above
- ZSRC: source redshift
- ZLENS: lens-galaxy redshift
- XGAL_SRC: source shift w.r.t. lens galaxy center along X=RA-axis, arcsec
- YGAL_SRC: source shift w.r.t. lens galaxy center along Y=DEC-axis, arcsec
- XIMG_SRC: comma-sep list of NIMG image shifts w.r.t. lens galaxy center along X=RA-axis, arcsec
- YIMG_SRC: comma-sep list of NIMG image shifts w.r.t. lens galaxy center along Y=DEC-axis, arcsec
- MAGNIF: comma-sep list of NIMG image magnfications
- DELAY: comma-sep list of NIMG image delays (one of the delays is always zero)

[10] See footnote [6]