Predicting the Event Rates of Strongly Lensed Supernovae

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Motivation

Objects are **gravitationally strongly lensed** when they are located behind a massive object which causes the light they emit to be distorted, possibly through magnification or multiple observed images (Fig. 1). Supernovae, relatively uncommon events, are very rarely observed to be strongly lensed. Observations of strongly lensed Type Ia supernovae can constrain the **Hubble Constant, H_0**, through measurable time delays and lensing magnification constraints. For this reason, we aim to predict the event rates of strongly lensed Type Ia supernovae in the upcoming LSST survey through development of the LSST strong lensing simulation pipeline[1] (**SLSim**), a Python package which simulates and images strong lensing events involving source, host, and deflector populations. Within the package, we implement a realistic Type Ia supernovae population to predict the event rates of strongly lensed Type Ia supernovae within a specified sky area and time. In the future, we aim to utilize OpSim time series imaging with detection criteria to predict the rates of strongly lensed Type Ia supernovae events observed by LSST.

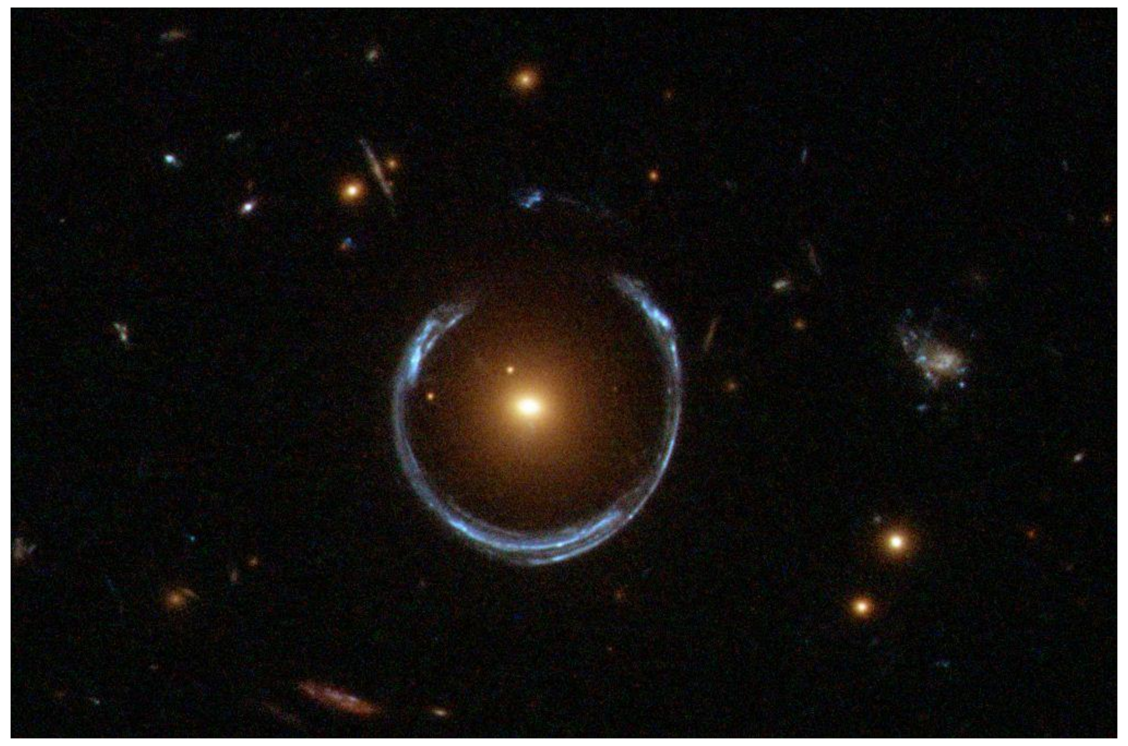

Figure 1 • A distant, blue galaxy is strongly lensed into an Einstein ring by the massive red galaxy it lies behind. This is an example of a magnified lens image[2].

Time Series Imaging

SLSim's time series imaging is used to image strongly lensed Type Ia supernovae events, with host galaxy matching and realistic offset generation applied.

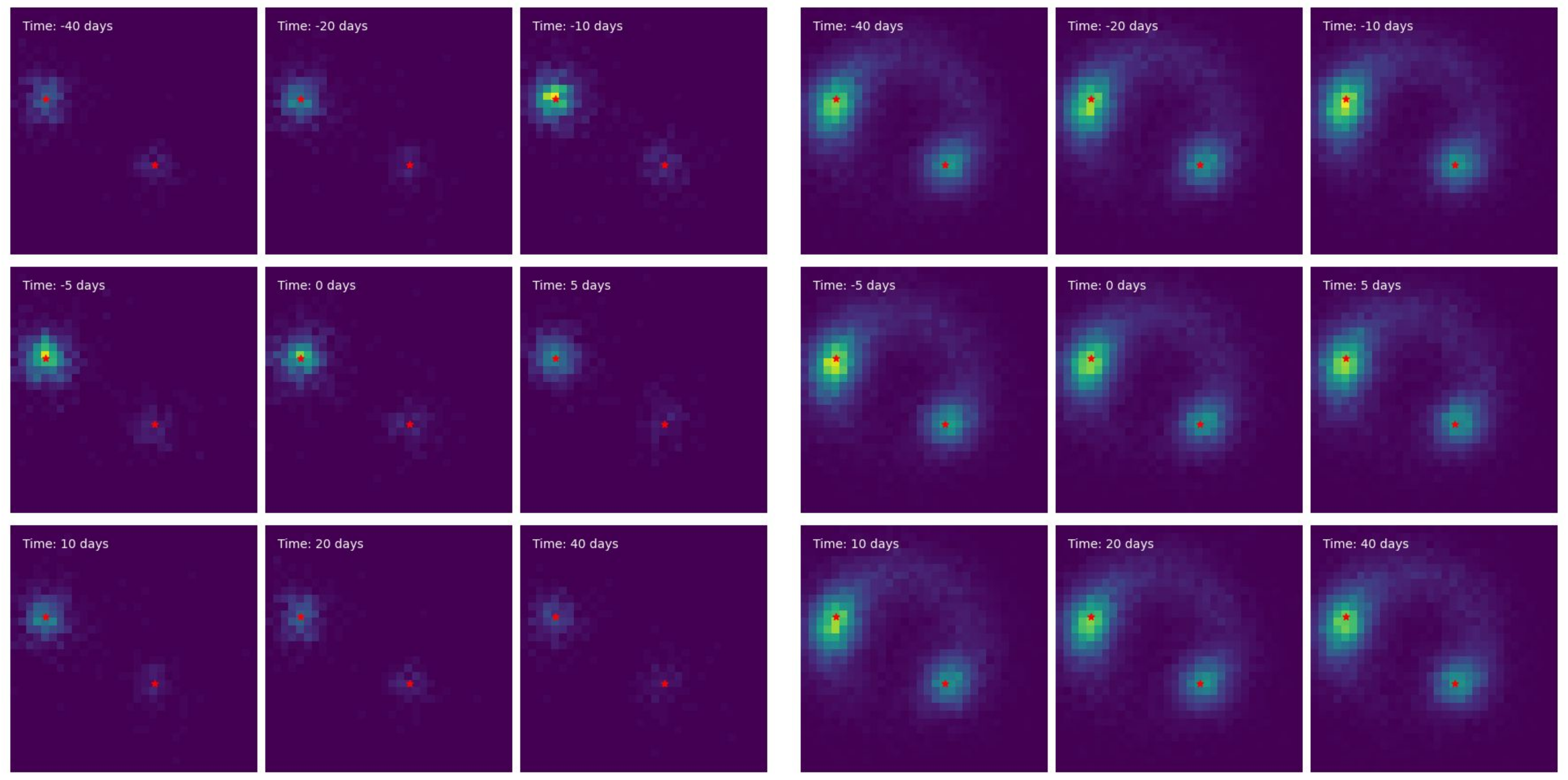

Figure 5 • Time series imaging of a Type Ia supernova event strongly lensed by an elliptical galaxy, with red stars marking the two centers of the supernova in the doubly imaged lens. The left series shows the Type Ia supernova event without the host galaxy included, while the right series includes the host galaxy. Neither series includes the deflector galaxy.

Procedure for Type Ia Supernovae Population Implementation in SLSim

1. Implemented **comoving number density** of Type Ia supernovae (Fig. 2) as a function of redshift, canonical efficiency, time delay distribution, and star formation rate[3].

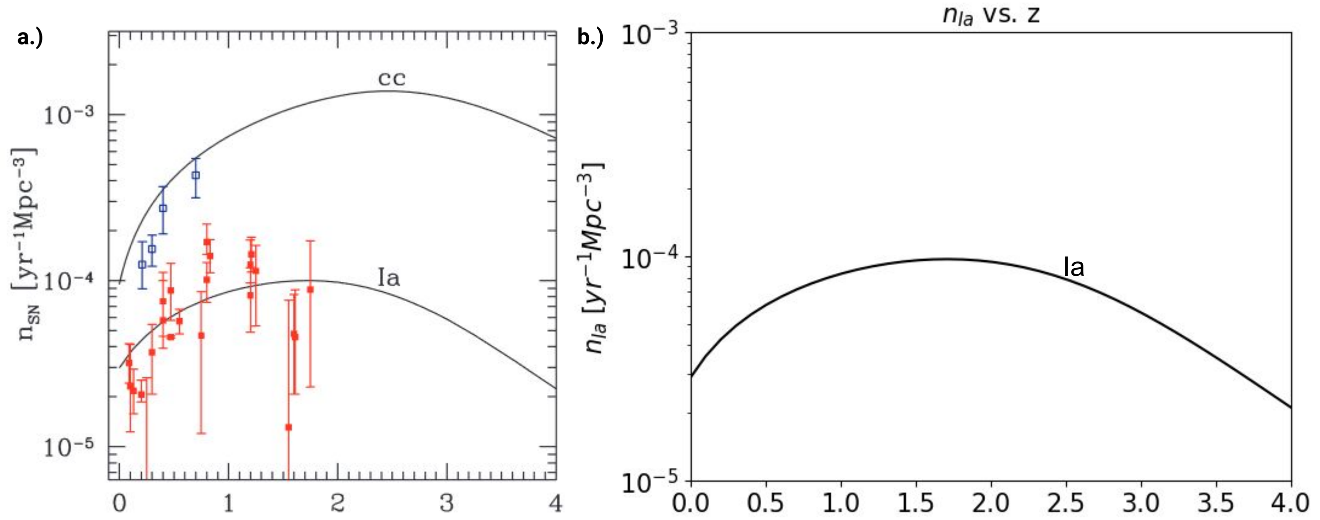

Figure 2 • (a) Fig. 2 of Oguri and Marshall 2010[2]: The bottom curve depicts Type Ia supernovae rate as a function of redshift fitted from empirical data. (b) This curve is replicated in SLSim as the base of the realistic population.

2. Integrated supernovae number density over a **light cone volume** to allow for Type Ia supernovae event rate prediction over a sky area and time (Fig. 3a) and treatment of the population as a source population within SLSim (Fig. 3b).

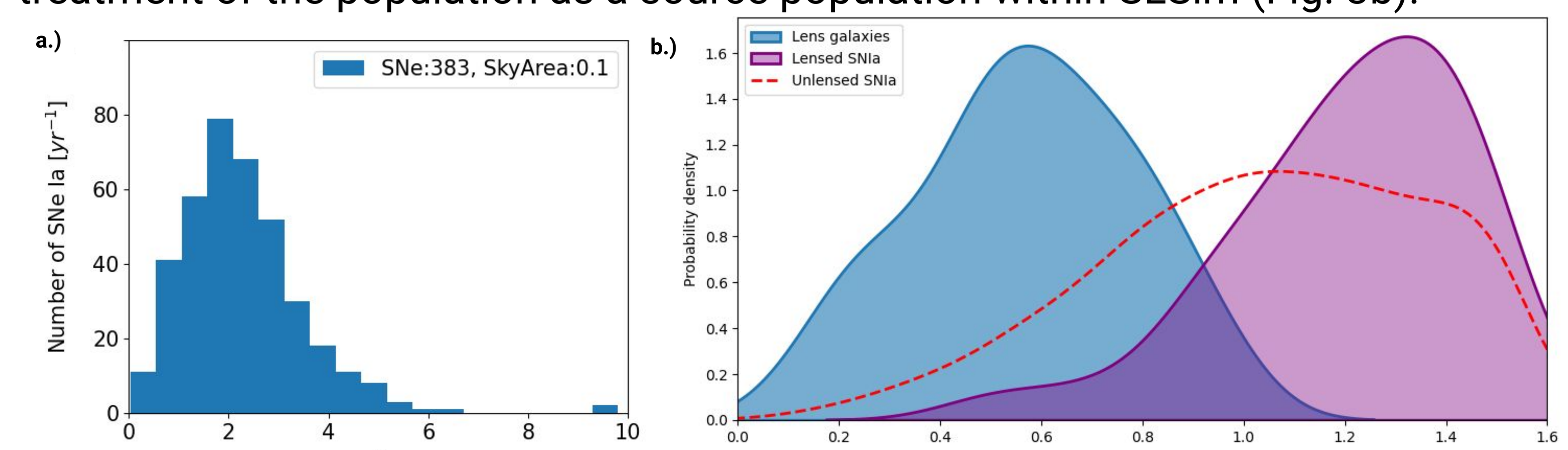

Figure 3 • (a) Histogram depicting predicted Type Ia supernovae events per year over sky area 0.1 deg^2, as a function of redshift. (b) Redshift distribution probability density of the lens galaxies (deflector population), lensed Type Ia supernovae (source population), and unlensed Type Ia supernovae population over a sky area of 50 deg^2.

3. Implemented **matching of host galaxies** to Type Ia supernovae (Fig. 4b) by weighting candidates according to an observed correlation between host galaxy stellar mass and Type Ia supernovae rate[4] (Fig. 4a).

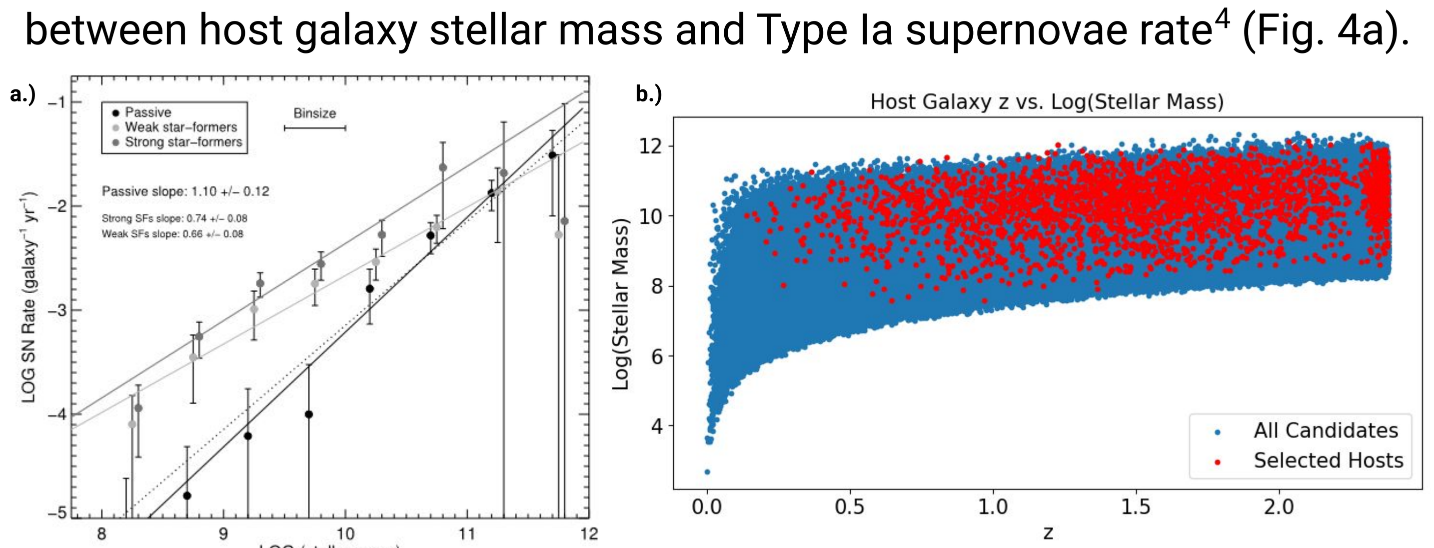

Figure 4 • (a) Empirical log-log relationship between host galaxy stellar mass and Type Ia supernovae event rate from Sullivan et al. 2008[4]. (b) Log stellar mass distribution of selected host candidates over all host candidates as a function of redshift for a population of lensed Type Ia supernovae within a sky area of 1 deg^2.

4. Applied realistic Type Ia supernovae **offsets from the host galaxy center** as a function of host galaxy angular size and ellipticity (Fig. 5b), using a lognormal distribution fitted to empirical Type Ia supernovae offset ratio data[5] (Fig. 5a).

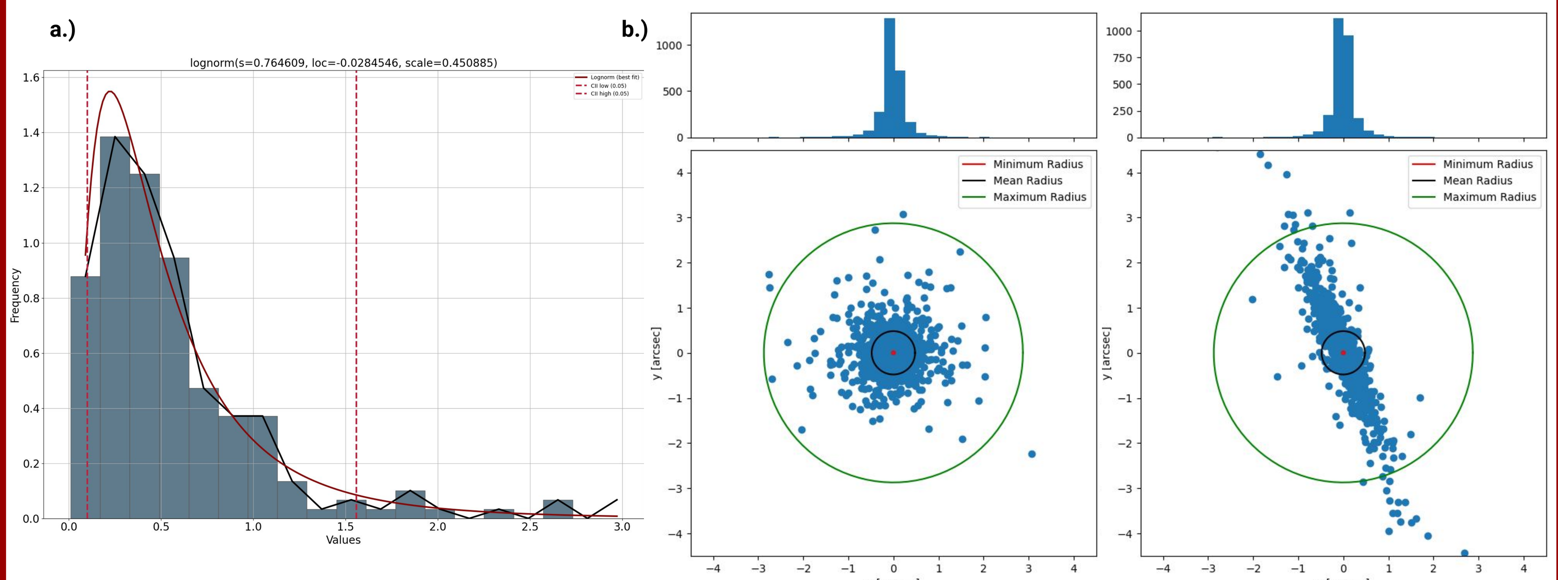

Figure 4 • (a) The fitting of a lognormal distribution to observed Type Ia supernovae offset ratio data from Wang et al. 2013[5]. (b) (Left) Type Ia supernovae offsets relative to their host galaxy centers for a sample population within 1 deg^2 sky area. (Right) Offsets of a single Type Ia supernovae relative to its host galaxy's center, where e_1, e_2= 0.5.

Results

With the implementation of a realistic strongly lensed Type Ia supernovae population, we observe the event rates of these objects within a specified sky area and calculate their relevant parameters. Within a sky area of 100 deg^2, (redshift z < 2.379) we observe 409 strongly lensed Type Ia supernovae events (Fig. 6). Future work will aim to constrain this sample according to detection criteria and LSST imaging cadence with the use of OpSim.

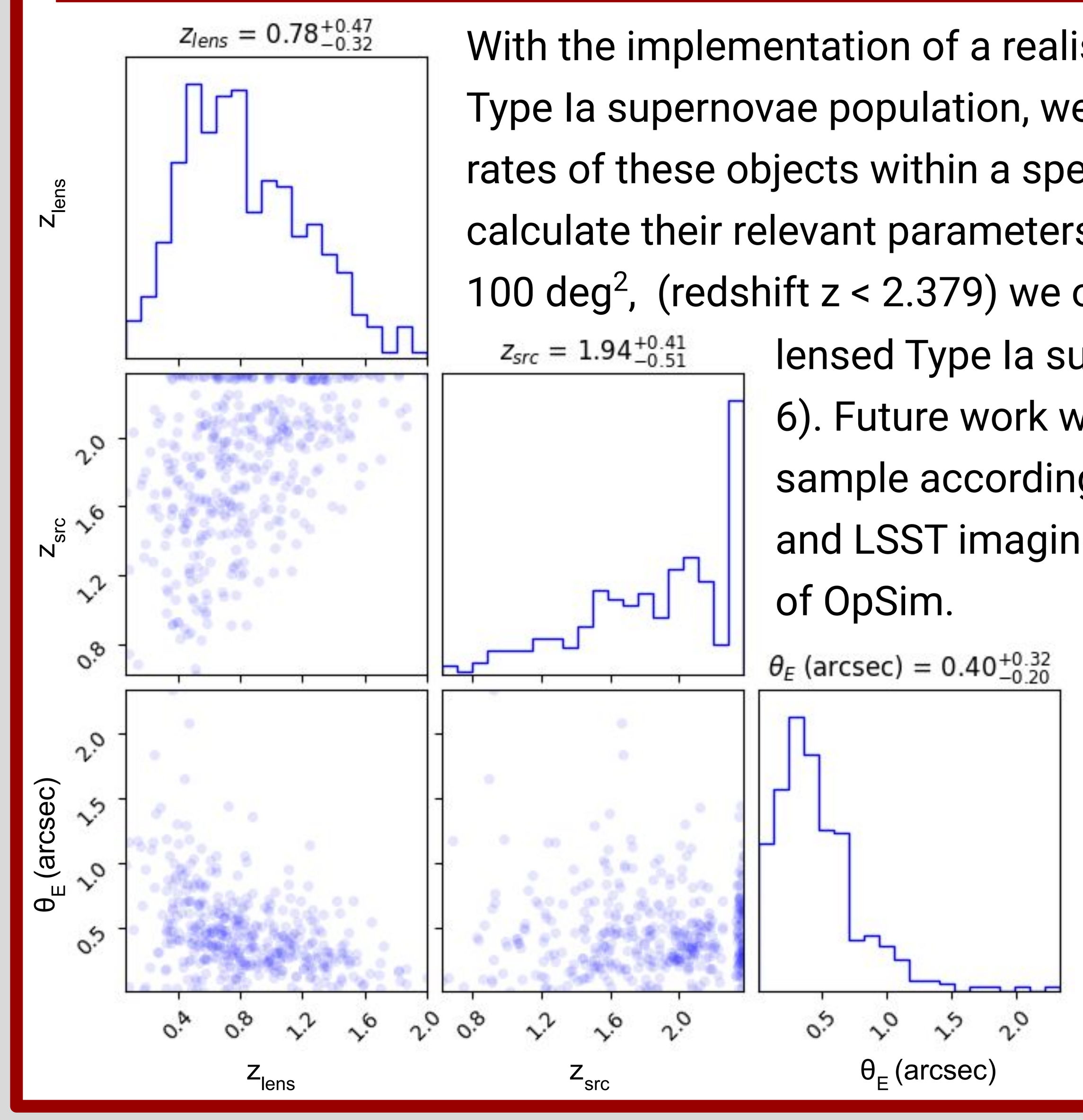

Figure 6 • Corner plot showing the source redshift, deflector redshift, and Einstein radius for the strongly lensed Type Ia supernovae population, generated by SLSim over a sky area of 100 deg^2 with all galaxy types as deflectors and z < 2.379.

References and Acknowledgments

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1. (2024). Strong lensing simulation pipeline [Software]. GitHub. https://github.com/LSST-strong-lensing/slsim
2. Lensshoe_hubble.jpg: ESA/Hubble & NASAderivative work: Bulwersator, Public domain, via Wikimedia Commons
3. Masamune Oguri, Philip J. Marshall, Gravitationally lensed quasars and supernovae in future wide-field optical imaging surveys, *Monthly Notices of the Royal Astronomical Society*, Volume 405, Issue 4, July 2010, Pages 2579–2593, https://doi.org/10.1111/j.1365-2966.2010.16639.x
4. Sullivan, M. et al (2008). Rates and Properties of Type Ia Supernovae as a Function of Mass and Star Formation in Their Host Galaxies. The Astrophysical Journal. 648. 868. 10.1086/506137.
5. Wang, Xiaofeng, et al. "Evidence for Two Distinct Populations of Type Ia Supernovae." Science, vol. 340, no. 6129, Apr. 2013, pp. 170-173. https://doi.org/10.1126/science.1231502.