Identifying Gravitationally Lensed Supernova Type Ia in the Rubin LSST Data

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Why lensed supernova type Ia?

Gravitationally lensed multiply-imaged supernova type Ia (SNIa) systems present a uniquely suited tool to test the disagreement between the measurements of the Hubble constant (H_0) from local-universe and early-universe probes. From the lensing theory, the time delay between two images of a lensed source is inversely proportional to H_0, providing an independent method to constrain the value of H_0 if the information on the projected surface mass distribution and the redshift of the lens is available. Time delay cosmography has so far been primarily attempted with strongly lensed quasars. However, accurate time-delay measurements for lensed quasars are difficult to obtain because of the stochastic and heterogeneous nature of quasar light curves. In contrast, SNIa light curves are remarkably homogeneous and relatively well-understood, allowing their time delays to be measured with far fewer observational constraints than those for quasars. The transient nature of SNIa also allows direct observations of both the lens and the host galaxy without contamination from the SNIa light, enabling the reconstruction of the lens mass distribution and host properties in a more straightforward way. As SNIa are standardizable candles, lensed SNIa systems also make it possible to directly determine the lensing magnification factors of individual images that help break the degeneracy between the lens potential and the H_0. So far, only very few lensed multiply-imaged SNIa have been detected. However, with the upcoming LSST, the prospects of detecting a sufficient number of lensed SNIa to achieve percent-level constraints on H_0 in the near future are good.

Vera Rubin Observatory's Large Synoptic Survey of Space and Time (LSST) and Transient Science

The upcoming Vera Rubin Observatory will survey the entire southern sky every night for ten years, imaging each region roughly 2000 times in six broad photometric bands. It is expected to detect an unprecedented number of faint transient objects owing to its deep-wide-fast observing strategy. It will detect about ten million supernovae in its lifetime, a few hundreds of thousands of which are expected to be SNIa. It is anticipated to improve the current sample of a few thousand detected SNIa and five detected multiply-imaged SNIa by an order of magnitude. With the improvements in the number of observations, the quality of data, and analysis techniques over the last couple of years, the value of H_0 measured with time-delay cosmography is predicted to reach the precision of as high as 1.5% in the LSST era with only three years of LSST observations. Given these prospects, it becomes essential to devise effective methods to identify lensed SNIa systems from the LSST data.

Research Objectives

1. To construct and test a difference imaging pipeline within the LSST Stack framework to identify strongly lensed supernovae.
2. Devise early identification criteria for lensed SNIa by studying the color magnitude space of supernovae.

Study Methodology

1. Lensing observables and lensed and unlensed SNIa light curves were simulated using a code adapted from More & More, 2022, and the SNCosmo package in Python, respectively. Raw images from the Subaru Hyper-Suprime Cam were processed in the LSST Stack. The simulated photometric data of SNIa was injected into these images to generate the science images. Difference imaging was performed on the science images to study the recovery of the injected information.
2. Studied the simulated photometric data in the color-magnitude space for supernovae to present the red limit for unlensed SNIa at a given magnitude. For comparison, a color-magnitude study was also performed on the observed unlensed and lensed SNIa data.

Results

Difference Imaging Pipeline

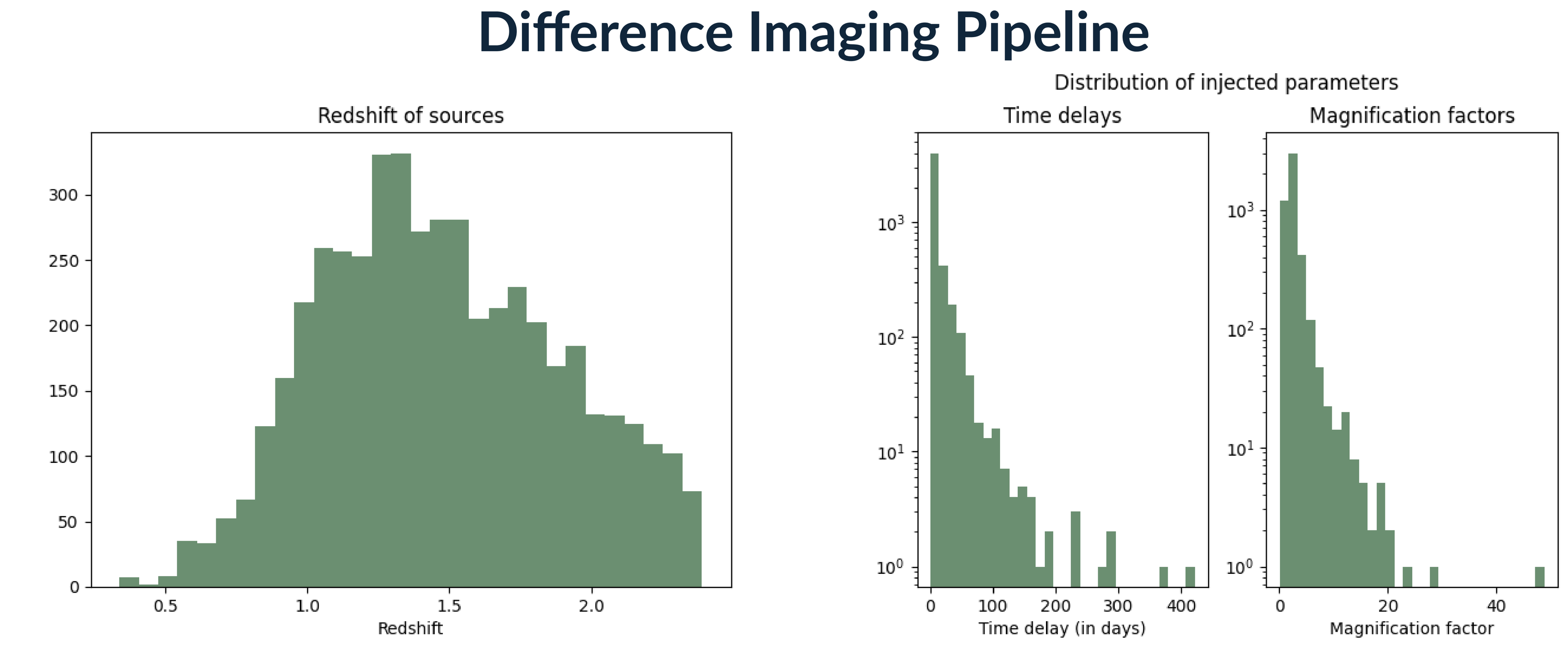

Figure 1. **Distribution of properties of a total of 1894 injected lensed SNIa systems (1791 systems with two images (doubles), 103 systems with four images (quads)).** Left panel: Redshift distributions of simulated lens galaxies and source SNIa. This redshift distribution follows from the volumetric rate of SNIa fitted to measurements of the observed SNIa rate as a function of redshift. Middle panel: Distribution of the time delay values between the two images in the doubles and the maximum time delay between any pairs of images in the quads. Right panel: Distribution of the magnification factors for the individual images of doubles and quads from the injected lensed SNIa sample.

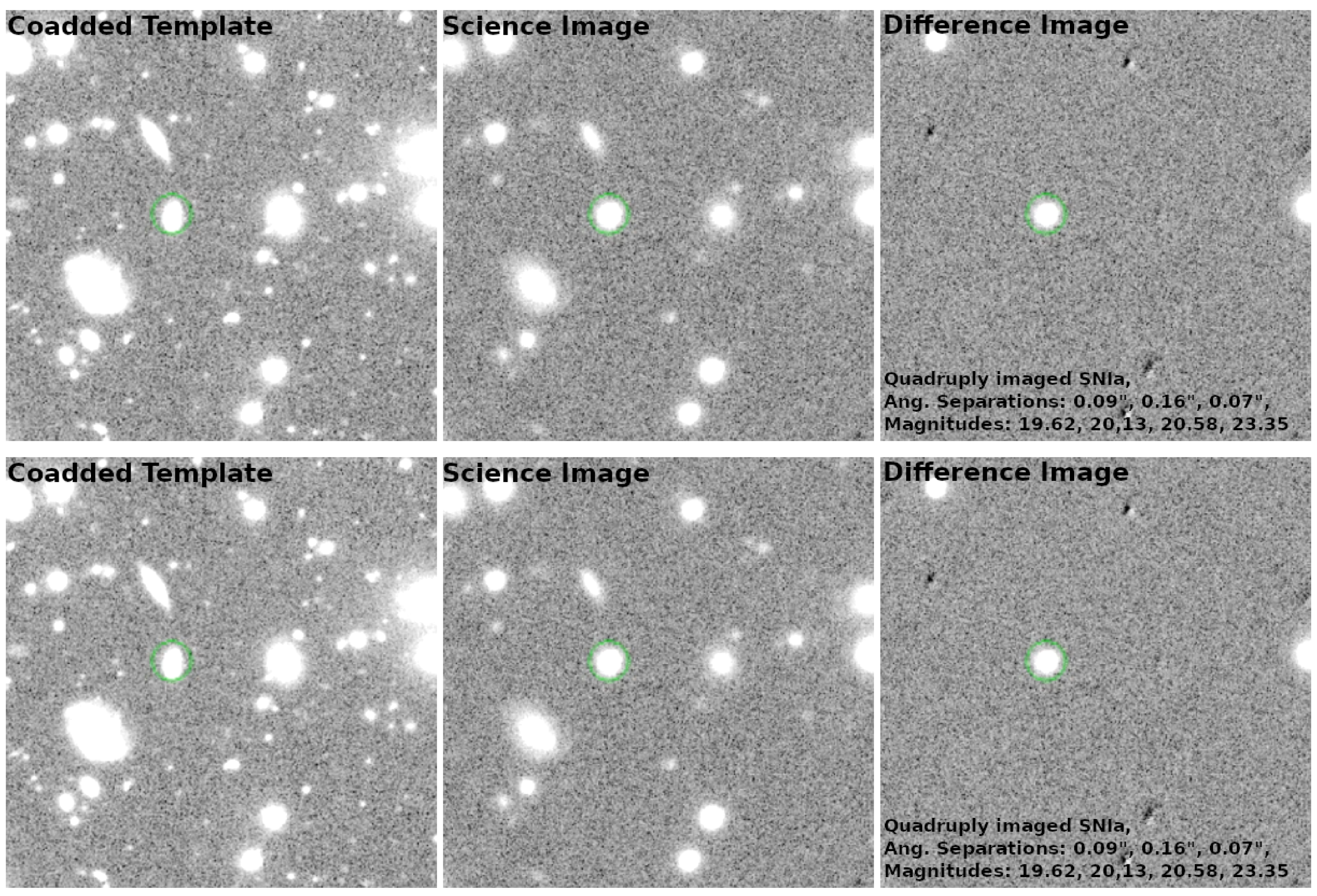

Figure 2. **Detection results of our pipeline for an injected SNIa.** Left panels: The mean coadded template image that does not include the injected SNIa information. Middle panels: A single band science exposure with injected photometric data. The green circle indicates the location of the SNIa event. Right panels: A single band difference image.

Color-magnitude Analysis

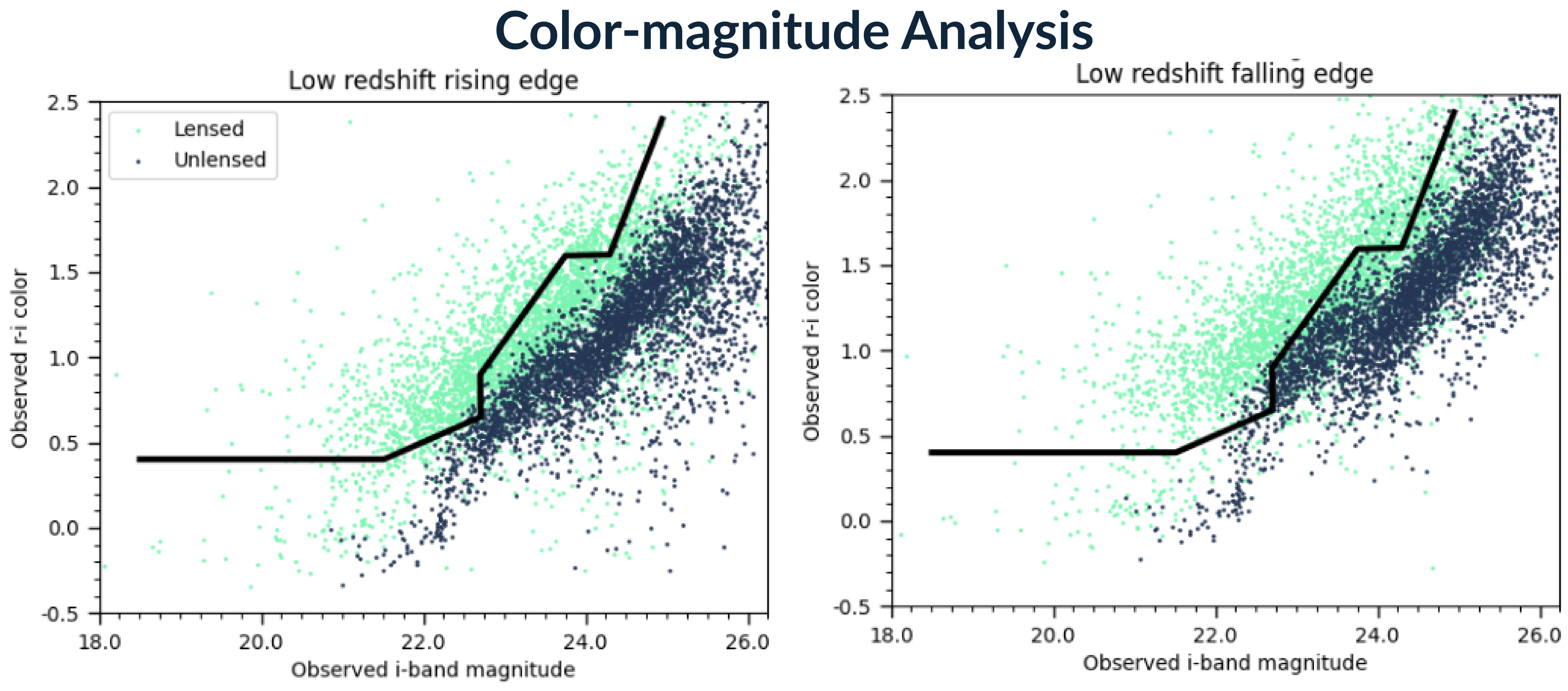

Figure 3. **Color-magnitude diagram for simulated unlensed and lensed SNIa.** The dark yellow scatter points show the expected color-magnitude distribution for unlensed SNIa, and the brown scatter points correspond to the distribution for lensed SNIa. The r − i colors for low redshift unlensed SNIa are relatively blue, but the color becomes redder for high redshift SNIa as the peak of the rest-frame spectral energy distribution passes through the observer-frame bands. Considering that the high redshift SNIa are more likely to get lensed, the thick black line denotes the proposed red limit for unlensed SNIa at a given i-band magnitude. The left and right panels compare how well the criteria hold for the photometric data recorded on the rising (peak minus three days) and the falling (peak plus seven days) edge of the SNIa light curve, respectively.

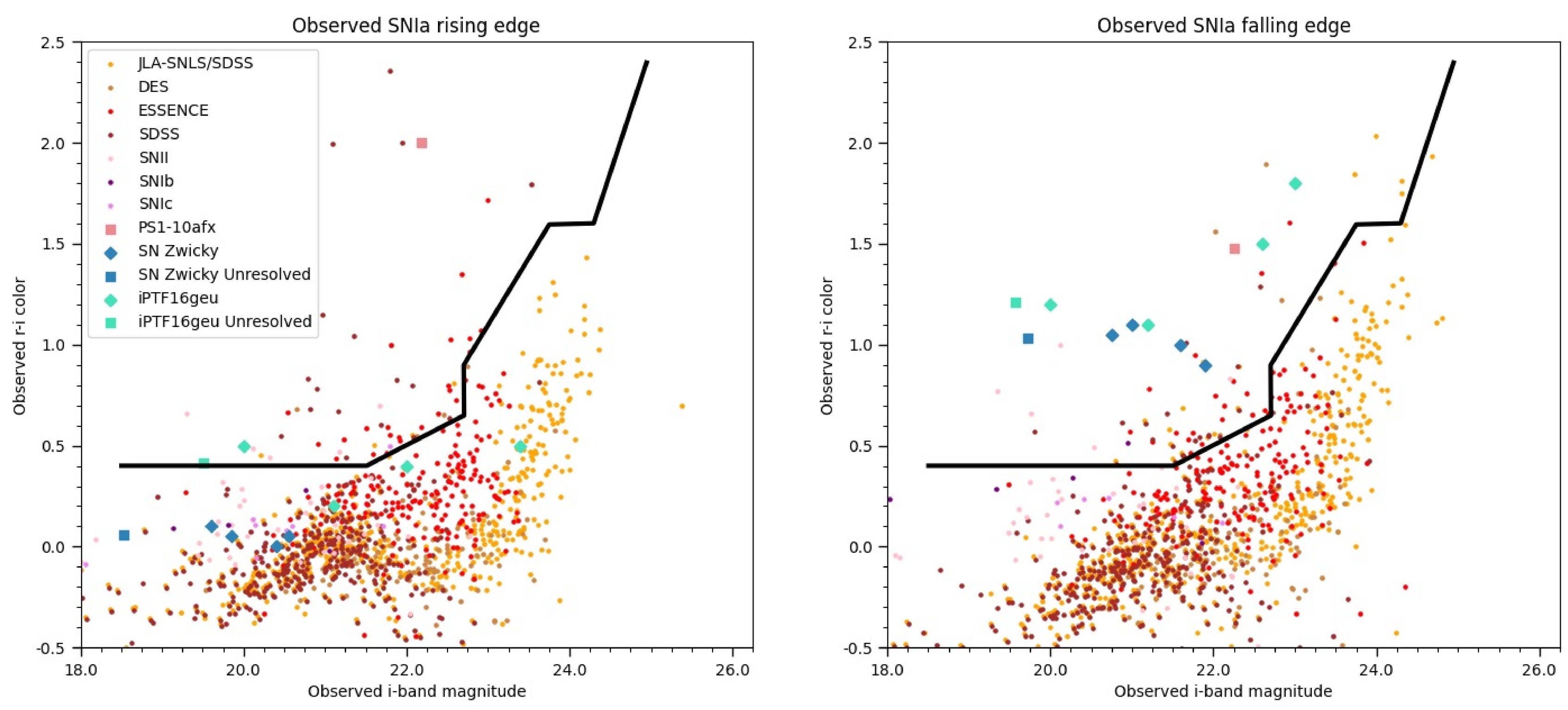

Figure 4. **Color-magnitude diagram for observed unlensed and lensed SNIa.** The circular scatter points show the color-magnitude distribution for detected unlensed SNIa cataloged in various surveys. The diamond-shaped scatter points show the color-magnitude distribution of resolved images of detected lensed SNIa, whereas the square-shaped scatter points correspond to the unresolved photometric data of detected SNIa. The left and the right panel have the same meaning as in Figure 3. The proposed red limit for unlensed SNIa is shown by the same line as in Figure 3. (JLA: Joint Light-Curve Analysis; DES: Dark Energy Survey; ESSENCE: the Equation of State: Supernovae trace Cosmic Expansion; SDSS: Sloan Digital Sky Survey)

Future work

1. Study source properties to distinguish lensed SNIa from artifacts recovered in difference images.
2. Study the contamination in the color-magnitude space of lensed SNIa by unlensed SNIa and core-collapse supernovae.
2. Use the color-magnitude analysis criterion on the photometry of recovered sources.

References

[1] R. M. Quimby, M. Oguri, A. More, S. More, T. J. Moriya, M. C. Werner, M. Tanaka, G. Folatelli, M. C. Bersten, K. Maeda, and K. Nomoto, "Detection of the Gravitational Lens Magnifying a Type Ia Supernova," *Science*, vol. 344, pp. 396–399, Apr. 2014.