Identifying Gravitationally Lensed Supernova Type Ia in the Rubin LSST Data

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1. Lensed supernova type Ia and the LSST

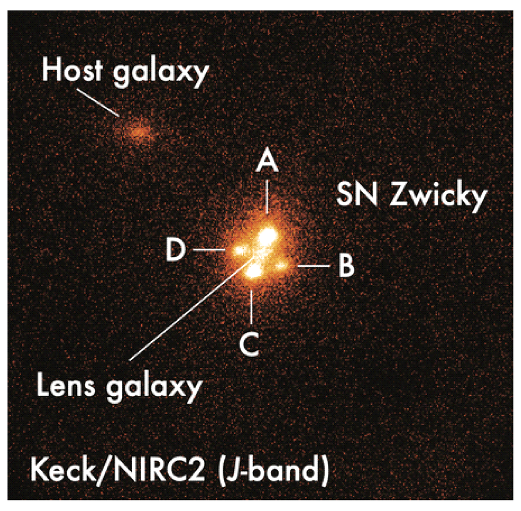

Figure 1. Quadruply-lensed SN Zwicky

- The time delay between two images of a lensed source is inversely proportional to the Hubble constant (H_0), providing an independent method to constrain H_0 if the information on the projected surface mass distribution and the redshift of the lens is available.
- Gravitationally lensed multiply-imaged supernova type Ia (SNIa) are uniquely suited for such measurements owing to their homogeneous and well-understood light curves and the transient and standard candle nature.
- Vera Rubin Observatory 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 of SNIa is predicted to reach percent-level precision in the LSST era.

Given these prospects, it becomes essential to devise effective methods to identify lensed SNIa systems from the LSST data.

2. Immediate goals

1. Construct and test a difference imaging analysis (DIA) pipeline to identify strongly lensed supernovae within the LSST Stack framework.
2. Devise early identification criteria for lensed SNIa by analyzing the color-magnitude diagram (CMD) of supernovae.

3. Implemented methods

1. Injected the simulated photometry of lensed SN1a into the real CCD images from the Subaru telescope. Performed difference imaging on the science images to study the recovery of the injected information.
2. Studied the simulated photometric data with the CMD for supernovae to determine the red limit for unlensed SNIa at a given magnitude (denoted by the bold black curve in Fig 2, 3). A CM study is also performed on the observed (un-)lensed SNIa data for comparison.

4. Results for the color-magnitude analysis

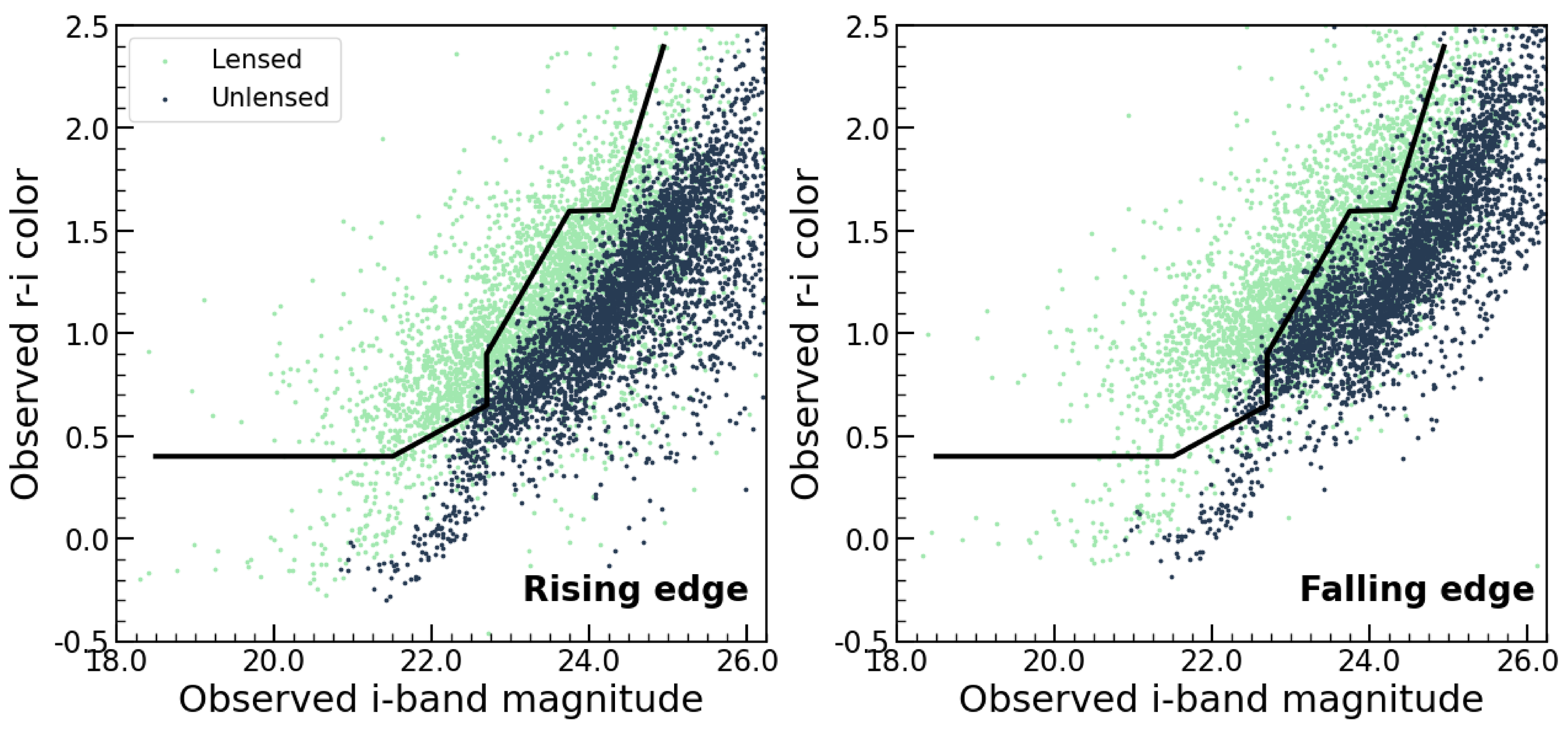

Figure 2. **CMD for simulated unlensed (dark blue) and lensed (green) SNIa.** We compare the photometric data recorded on rising (left pane) and falling (right panel) phase of the SNIa. *The proposed bold black curve, the "red" limit, allows us to demarcate the CM space between the lensed and the unlensed SNIa for SNIa both in the rising and falling phase.*

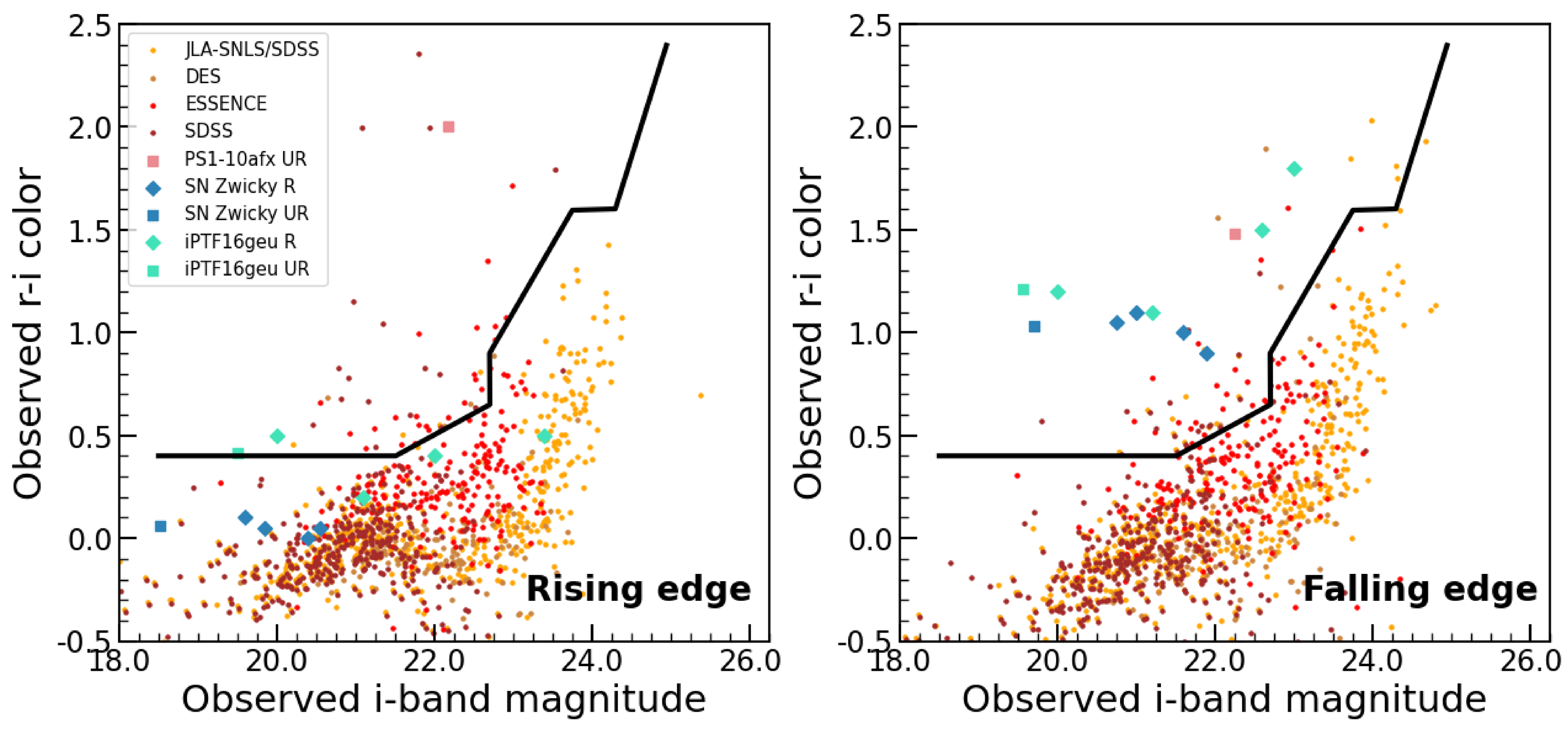

Figure 3. **CMD for observed unlensed and lensed SNIa.** Photometric data of the observed unlensed SNIa cataloged in various surveys (circles), observed resolved lensed SNIa (diamonds), and unresolved lensed SNIa (squares) in the CMD are shown. *The proposed bold black curve (same as in Figure 2) roughly succeeds in eliminating unlensed SNIa during both the rising and falling phases while enabling the selection of lensed SNIa, as outliers, mainly during the falling phase.*

5. Preliminary results for difference imaging analysis

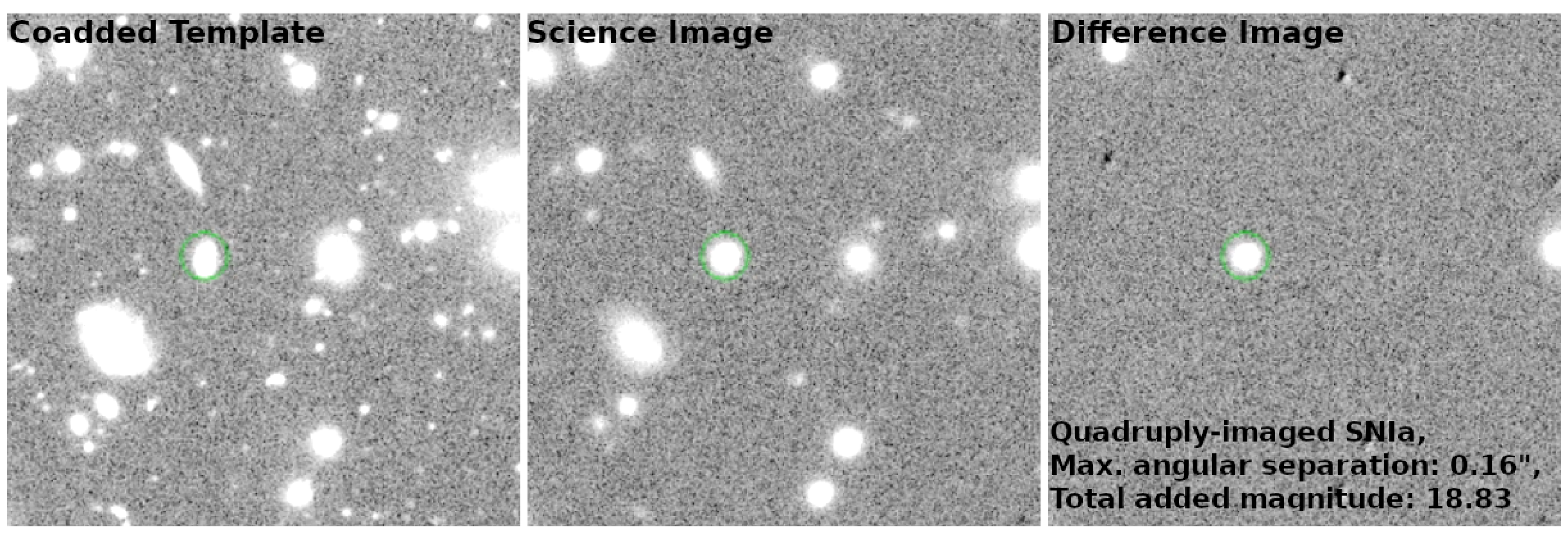

Figure 4. **Detection results of our pipeline for an injected *lensed* SNIa event**. The coadded template (left) prior to the SNIa going off shows the foreground lensing galaxy, science exposure (middle) shows the injected quadruply lensed SNIa where the multiple images are unresolved. *Difference image (right) shows successfully recovered lensed SNIa (green circle radius of 2") by the DI pipeline.* The images have a maximum angular separation of 0.16" and a combined magnitude of 18.83.

6. Conclusions

1. The difference imaging pipeline can recover and measure the injected sources, many of which are detected as unresolved sources in the difference images.
2. We propose the red limit on the r-i color of unlensed SNIa shown by the bold black curve separating the CM space between the lensed and unlensed SNIa both in the rising and falling phase. This curve roughly succeeds in eliminating the observed unlensed systems during the rising and falling phases. It selects the observed systems of lensed SNIa as outliers, particularly in the falling phase.

7. Ongoing work

- CM analysis: ompare the CMD of lensed SNIa with that of (un-)lensed core-collapse supernovae and study the contamination.
- DIA: Study distribution of sources recovered in DIA to check the efficacy of the DI pipeline. Study properties of these sources to devise a way to distinguish artifacts from lensed supernovae.
- Apply the proposed CMD diagnostics to the photometry of the sources recovered in DIA to identify lensed SNIa.

8. References

[1] Quimby R. M., et al., "Detection of the Gravitational Lens Magnifying a Type Ia Supernova," Science, vol. 344, pp. 396–399, Apr. 2014.
[2] More A., More S., "Improved statistic to identify strongly lensed gravitational wave events," Monthly Notices of the Royal Astronomical Society, vol. 515, pp. 1044–1051, 06 2022.