Strategies to identify strongly lensed type Ia supernovae in the Rubin LSST

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Background

- The Hubble constant (H_0) gives the rate of expansion of the Universe. The scale and the age of the Universe depend on the value of H_0, making it a fundamental number in cosmology. The value of H_0 calculated using two independent methods has been found to be inconsistent with each other.
- Gravitational lensing is the deflection in the path of light in the presence of high gravitational potential. This can lead to the source getting multiply imaged.

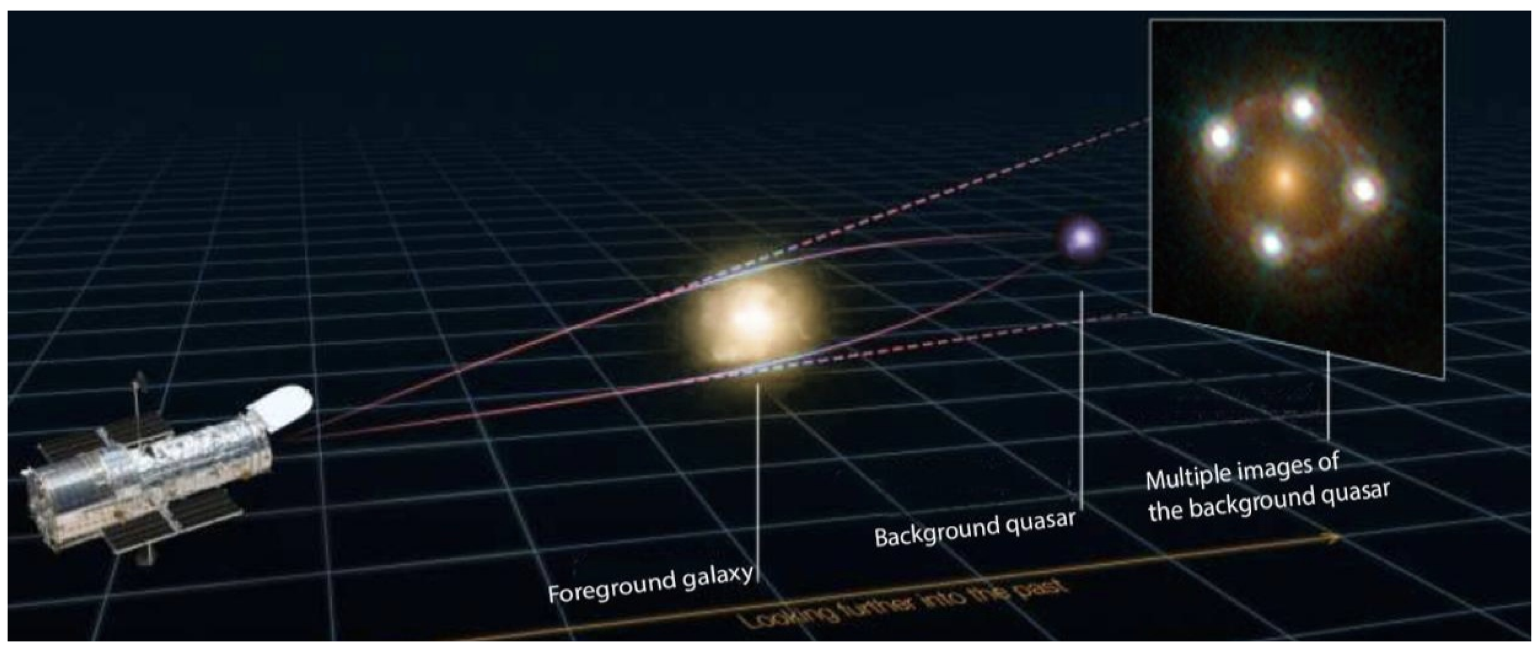

Figure 1. Gravitational lensing of a distance quasar by a foreground galaxy showing multiple images of the source along the different paths light takes.

- The time delay between two images of a lensed source is inversely proportional to the H_0, providing an independent method to constrain its value.
- Gravitationally lensed multiply-imaged type Ia supernovae (SNe Ia) are uniquely suited for such measurements. However, they are extremely rare.
- Vera Rubin Observatory's Legacy Survey of Space and Time (LSST) can increase the current sample of lensed SNe Ia by order of magnitude, leading to percent-level constraints on H_0 in the LSST era.
Thus, it is essential to devise effective methods to identify lensed SNe Ia from the LSST data.

Results of difference imaging

Difference Imaging compares two images of the same sky area taken at different times and does pixel-by-pixel subtraction to identify sources that have varied in brightness. The template image to be subtracted from is constructed by stacking a subset of archival images with low sky noise, small PSF size, and high seeing.

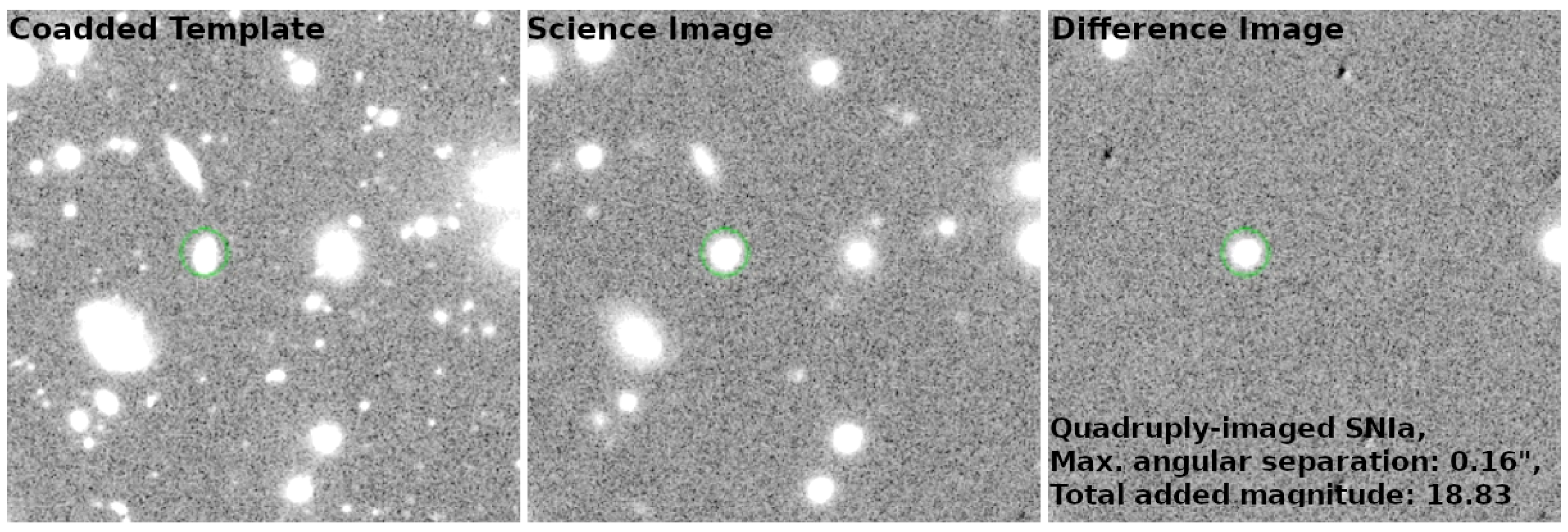

Figure 2. The coadded template (left) before the SN Ia goes off shows the foreground lensing galaxy, and the science exposure (middle) shows the injected quadruply lensed SN Ia where the multiple images are unresolved. **Difference image (right) shows successfully recovered lensed SN Ia (green circle radius of 2") by the DI pipeline.**

	Injected	Detected	% recovery
Total	74143	51520	**70**
Doubles	70050	48300	70
Quads	4093	3220	78

Table 1. Detection details of the injected information in difference imaging.

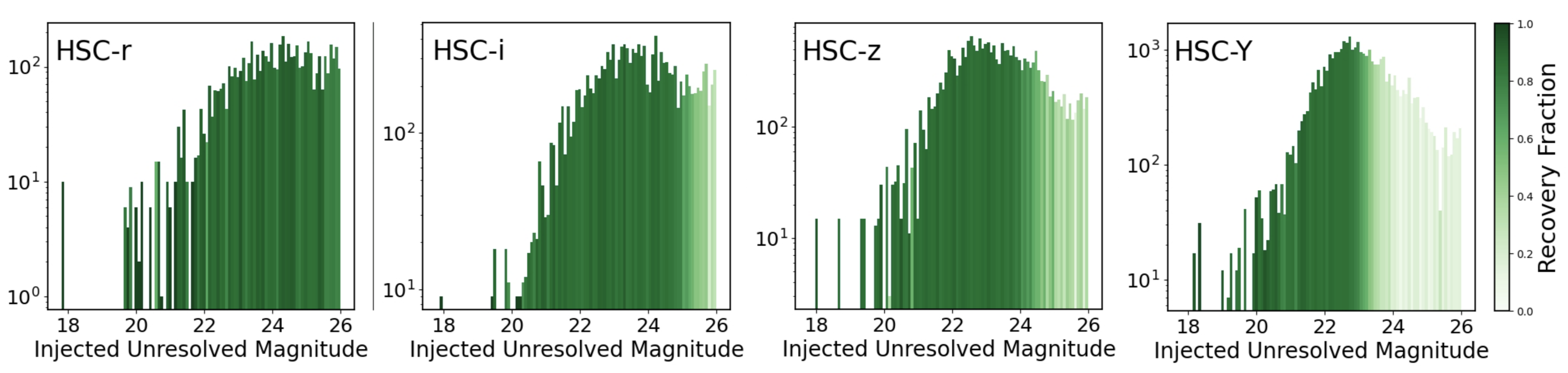

Figure 3. Variation of the recovery fraction of injected information with the brightness of the injections for HSC *rizy* bands. **The recovery fraction decreases gradually for the fainter injections. The magnitude limit at which the recovery fraction drops drastically decreases for higher wavelengths.**

Objectives

- **Objective 1:** Construct and test a difference imaging analysis (DIA) pipeline to identify strongly lensed supernovae within the LSST Stack framework.
- **Objective 2:** Devise early identification criteria for lensed SNe Ia by analyzing the colour-magnitude diagram[1] (CMD) of supernovae.

Study methodology

- Injected the simulated lensed SNe Ia into the real CCD images from the Subaru telescope. Performed difference imaging on the science images to study the recovery of the injected information.
- Studied the simulated photometric data in the CM space for supernovae to set the red limit for unlensed SNe and (un-)lensed CC SNe at a given magnitude.

Results of the colour-magnitude analysis

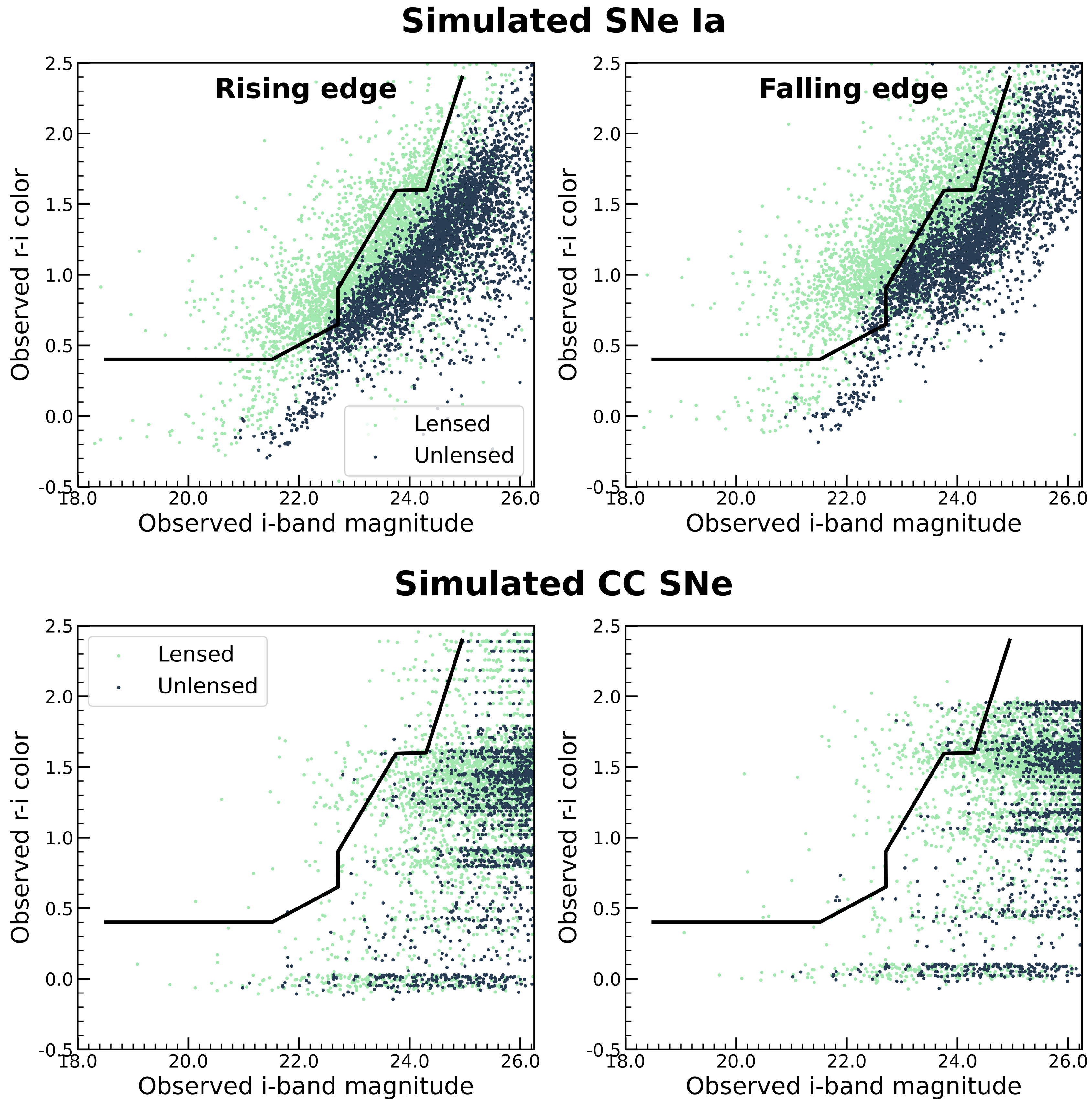

Figure 4. CMD for simulated unlensed (dark blue) and lensed (green) SNe Ia (upper panel) and core-collapse (CC) SNe (lower panel). **The proposed bold black curve, the "red" limit, allows demarcation of the CM space between the lensed and the unlensed SNe Ia and (un-)lensed CC SNe both in the rising (left panels) and falling (right panels) phases.**

Conclusions

- Employed difference imaging pipeline recovers $\sim 70\%$ of the injected data of lensed SNe Ia. The recovery fraction decreases for fainter injected systems. It is slightly higher for quads and decreases significantly for the HSC y-band.
- Colour-magnitude criteria hold well for simulated and observed (un-)lensed SNe Ia till redshift 2.4, both on rising and falling edge. Contamination from (un-)lensed CC SNe is low.

Further work

- Study if extendedness can be used as a marker for unresolved lensed systems.
- Incorporate LSST cadence in the entire analysis.
- Test the DI pipeline on LSST-like datasets simulated by the LSST Collaboration.

[1] Quimby R. M., et al., "Detection of the Gravitational Lens Magnifying a Type Ia Supernova," Science, vol. 344, pp. 396–399, Apr. 2014.