Chapter 4

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Strong Gravitational Lensing in the Era of Big Data
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The present & future of lensed supernovae: from ZTF to LSST

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Abstract. Gravitationally lensed supernovae (SNe) are rare and valuable probes of astrophysics and cosmology. While only seven lensed SNe have currently been discovered, these numbers are predicted to increase by orders of magnitudes with future transient surveys such as the Legacy Survey of Space and Time (LSST). These proceedings describe the ongoing live search with the Zwicky Transient Facility (ZTF), including the discovery of SN 'Zwicky': a lensed SN found in a remarkably low-mass lens galaxy. Finally, we look ahead at predictions for detecting lensed SNe with LSST.

Keywords. Strong gravitational lensing, supernovae, cosmology

1. Introduction

Strongly lensed supernovae (SNe) can give valuable insights into the expansion rate of the Universe, substructures in lens galaxies, and high-redshift supernova physics. When the time delay between the appearance of the multiple SN images is combined with a model of the gravitational potential of the lens galaxy, a measurement of the Hubble constant (H_0) can be obtained which is independent of the distance ladder and Cosmic Microwave Background (CMB) radiation. Currently, five strongly lensed SNe have been discovered in galaxy clusters: SN Refsdal (Kelly *et al.* 2015), SN Requiem (Rodney *et al.* 2021), 2022riv (Kelly *et al.* 2022), C22 (Chen *et al.* 2022), and SN H0pe (Frye *et al.* 2023). Additionally, two type Ia SNe have been found that were lensed by single elliptical galaxies: iPTF16geu (Goobar *et al.* 2017) and SN Zwicky (Goobar *et al.* 2023). For the cluster-scale lensed SNe, the limiting factor for precision cosmology is the galaxy cluster's complicated mass model. The two galaxy-scale lensed SNe, on the other hand, have a relatively simple mass model but extremely short time delays. In these conference proceedings, we describe the ongoing lensed SN search with the Zwicky Transient Facility (ZTF) and look ahead at forecasts for the upcoming Legacy Survey of Space and Time (LSST) to be conducted at the Vera Rubin Observatory.

2. Discovery of lensed SN 'Zwicky'

The ZTF, located in Palomar, California, has been observing the northern sky every 2 to 3 days for the past four years. Besides discovering SNe and other transients routinely, it has the potential to observe a handful of lensed SNe in its lifetime. On August 1st 2022, it detected a supernova (SN 2022qm, also known as 'SN Zwicky') that was bright enough to pass the threshold of automatic spectroscopic follow-up. The resulting spectrum, taken by SED Machine, revealed a type Ia supernova (SNIa) at a redshift of $z = 0.35$ that was ~ 25 times as bright as standard type Ia SNe. When the supernova redshift was confirmed by a spectrum from the Nordic Optical Telescope (NOT), our team

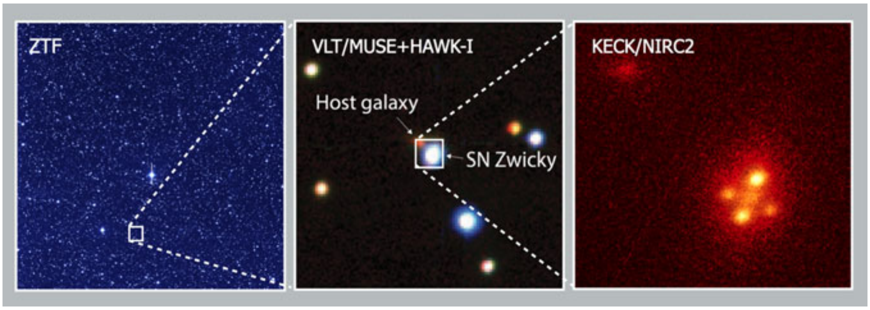

Figure 1. Zooming into lensed SN Zwicky: from ZTF to VLT to Keck observations. Adaptive Optics with Keck finally managed to resolve the four images of SN Zwicky. The host galaxy of the SN is located in the upper left corner.

knew that the supernova had to be gravitationally magnified to explain its exceptional brightness. We conducted follow-up observations with the Very Large Telescope (VLT) in Chile, which provided us with high-resolution spectra to improve the redshift estimates. However, VLT observations were unable to resolve the multiple images. The four images of SN Zwicky only became visible with observations from the Keck telescope in Hawaii using adaptive optics, as displayed in Figure 1. The Keck data allowed us to construct a lens model from the image positions and infer an Einstein radius of only $\theta_E = 0.167''$, one of the most compact lens systems ever discovered in the optical. A few days later, SN Zwicky was also observed with the Hubble Space Telescope (HST), which was also able to resolve the lens system (Pierel *et al.* 2023). SN Zwicky and the previously discovered galaxy-scale lensed SNIa, iPTF16geu, form a new population of low-mass and small image separation lens systems, as illustrated in Figure 2 (Goobar *et al.* 2023). Standard candles such as SNIa are a unique tool to discover and characterize the properties of these light, compact galaxy-scale gravitational lenses. However, this new population of lens galaxies are highly magnified, symmetric systems which often have very short time delays. The best-fit maximum time delay of SN Zwicky, obtained from the unresolved light curve and Keck flux ratios, is less than a day. Although such short time delays make these low-mass lens systems inconvenient for time-delay cosmography, they can reveal a lot about lens galaxy substructures and high-redshift supernova physics. The observed flux ratios of SN Zwicky are discrepant with the results from our best-fit lens model, hinting at additional magnification from substructures or microlensing of stars in the lens galaxy.

3. Prospects for detecting lensed SNe with LSST

Although the current sample of lensed SN discoveries is small, these numbers are about to increase by a few orders of magnitude with the advance of the next generation of survey telescopes such as the Vera Rubin Observatory and the Nancy Grace Roman Space Telescope. In this section, we focus on predictions for lensed SNIa discoveries in LSST. This survey will take multi-colour *ugrizy* images and cover ∼20,000 square degrees of the sky in a ten-year period. 90% of observing time will be spent on the Wide-Fast-Deep (WFD) survey, consisting of an area of 18,000 square degrees. The WFD survey is expected to proceed using a rolling cadence, in which certain areas of the footprint will be assigned more frequent visits than others, in order to improve the light curve sampling of objects in the high-cadence regions.

In order to assess the impact of the observing strategy on lensed SNIa detections, we simulate a large data set of lensed SNIa light curves. We include microlensing effects and take cadence simulations from the OpSim database. We consider two strategies for

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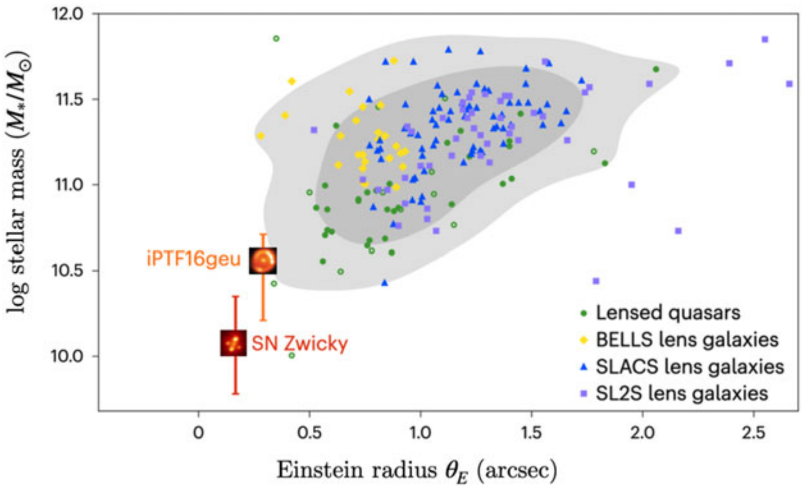

Figure 2. A comparison of SN Zwicky and iPTF16geu with other galaxy-scale lenses. Both in terms of stellar mass and Einstein radius, Zwicky and iPTF16geu are outliers. They point to a new population of low-mass and small-image-separation lensing systems.

detecting lensed SNe: the image multiplicity method, which looks for multiple resolved images, and the magnification method, which searches for objects that appear significantly brighter than a typical SNIa at the redshift of the lens galaxy (Wojtak *et al.* 2019). As a result, we predict to find ~ 44 lensed SNIa in the WFD survey per year, of which ~ 26 have time delays longer than 10 days (Arendse *et al.* in prep.). The effects of microlensing lower the predicted lensed SNIa detections by $\sim 8\%$. We also investigated how to separate the populations of lensed and unlensed SNIa. Since LSST will also discover unlensed SNIa at high redshifts (up to $z \sim 1$), looking for objects that appear 'redder' will not be sufficient anymore. Instead, we should combine colours with apparent peak magnitudes, since lensed SNIa are magnified and hence brighter than unlensed ones at the same redshifts (Arendse *et al.* in prep.).

4. Conclusion

We are entering an exciting era where the number of lensed SN discoveries will increase by several orders of magnitude with the advance of LSST and other upcoming surveys. Presently, we have found two galaxy-scale lensed SNIa, SN Zwicky and iPTF16geu. These are both symmetric, high-magnification lens systems with short time delays. They are part of a new population of very low-mass and compact lens galaxies, and are valuable for learning more about lens galaxy substructures and high-redshift supernova physics. With the upcoming Vera Rubin Observatory, we are expecting to discover around 40 lensed SNIa per year. However, many challenges remain that relate to the identification of these rare objects. We found that a decent separation between lensed and unlensed SNIa can be achieved when considering jointly their colours and apparent peak magnitudes.

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