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Strongly lensed supernovae: lessons learned

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Since a few years, we have finally entered the era of discoveries of multiply-imaged gravitationally lensed supernovae. To date, all cluster lensed supernovae have been found from space, while those deflected by individual galaxies were identified with wide-field ground-based surveys through the magnification of "standard candles" method, i.e., without the need of spatially resolving the individual images. We review the challenges in identifying these extremely rare events, as well as the unique opportunities they offer for time-delay cosmography and the study of the properties of the deflecting bodies acting as lenses.

1. Introduction

Following the early days of supernova cosmology, where CCD cameras exceeding a few arcminutes scale became available to search for high-redshift supernovae, targeted observations of massive lensing clusters used as "gravitational telescopes" were proposed to search for the most distant supernovae [1–3]. The gain factor in exposure length is μ^2, where μ is the flux amplification provided by the lens. However, this is partially balanced as the solid angle at the source planes shrinks by a factor μ behind the lens. Hence, earlier attempts using ground-based optical and infrared instruments to do monthly cadenced observations of lensing clusters did not uncover any multiply-imaged supernova [4,5]. It was only through Hubble Space Telescope (HST) observations that the first cluster lensed supernova, a core-collapse supernova at $z = 1.49$ lensed by the MACS J1149.6+2223 cluster was found [6]. The supernova was named "SN Refsdal", honouring the memory of Sjur Refsdal who first proposed to use time delays between multiple images of strongly lensed supernova (gLSNe) to measure the Hubble constant [7]. Continued HST monitoring of massive clusters, and more recently also with JWST, has led to the discovery of several other multiply imaged supernovae behind clusters [8–11], including three Type Ia supernovae (SNe Ia): SN H0pe and two "siblings", i.e., SNe hosted by the same galaxy, SN Requiem and SN Encore. While cluster lensed SNe have so far only been discovered from space, the three galaxy lensed SNe found to date were found in very wide-field surveys with ground-based telescopes. PS1-10afx was first reported as an unusual superluminous SN in the PanSTARRS transient survey [12]. Three years after the SN discovery (and too late for high-spatial resolution follow-up), it was shown in [13] that it was a highly magnified SN Ia at redshift $z = 1.388$, and eventually also the lens at $z = 1.117$ was identified [14]. Since then, two multiply-imaged SNe Ia have been found at Palomar Observatory. Starting with iPTF16geu, a SNIa at redshift $z_s = 0.409$, deflected by a galaxy at $z_l = 0.2163$, detected by the intermediate Palomar Transient Factory [15] and followed by another SNIa, SN Zwicky ($z_s = 0.354$; $z_l = 0.226$) [16] by the ongoing Zwicky Transient Facility (ZTF). Figure 1 shows space imaging for three multiply-imaged SNe Ia, highlighting the different angular scales for cluster and galaxy lens systems found to date. For a recent review of the status of lensing of supernovae, see [17]. The current manuscript focuses on lessons learned on gLSNe findings from ground-based transient surveys, iPTF16geu and SN Zwicky in particular.

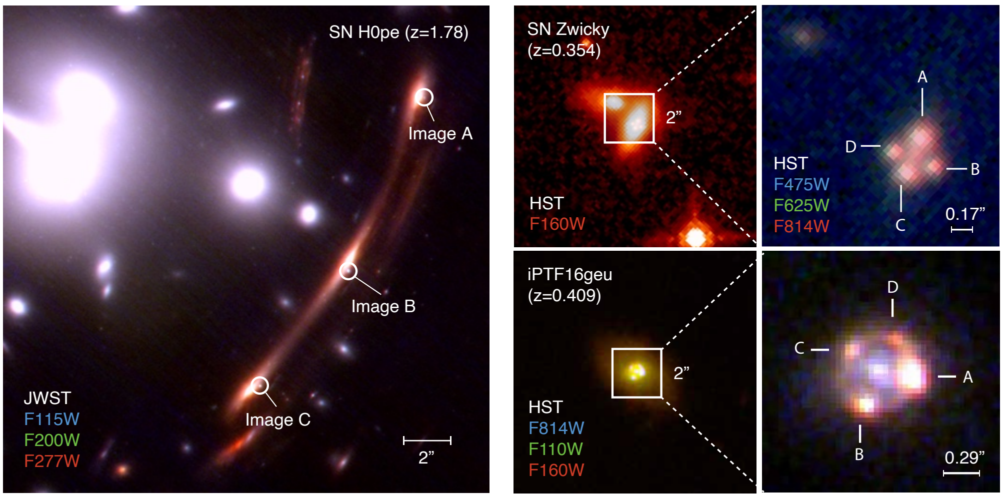

Figure 1. Gravitationally lensed Type Ia supernovae with multiple images, SN H0pe [10] lensed by a cluster of galaxies and iPTF16geu [15] and SN Zwicky [16,18] by individual galaxies. For the latter, the image flux ratios suggest that additional micro- or millilensing from stellar objects or substructures is taking place in the deflecting galaxy [19,20]. For iPTF16geu, a significant part of the intensity differences are due to extinction in the lensing galaxy [21].

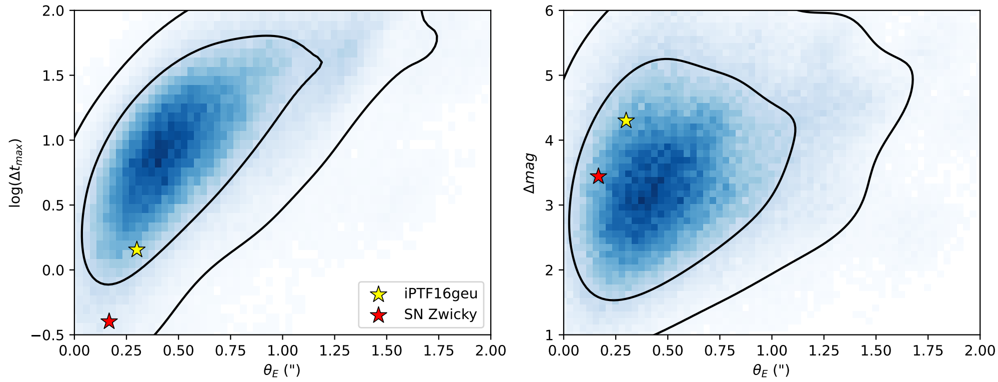

Figure 2. *Left:* Probability distribution of the time delays (in days) between multiple SN images vs the Einstein radius (arcseconds) for gLSN systems expected in ZTF. *Right*: Magnification (in magnitudes) vs Einstein radius. The two stars show the location in the parameter space of iPTF16geu and SN Zwicky. The black contours indicate the 68% and 95% confidence regions.

2. Spatially unresolved strongly lensed SNe

Wide-field imaging transient surveys like Palomar's PTF (2009-2012), iPTF (2013-2017) and ZTF (operating since 2018) have the ability to cover the entire visible sky from the Northern hemisphere in a single night. The extremely large search area of ZTF, facilitated by its 47.sq. deg field-of-view camera, makes it especially suitable to detect rare transient phenomena. The limiting factors are the small collecting area of the 1.2m telescope and the very coarse spatial resolution. With 1" pixel plate-scale and typically 2" seeing at Palomar, detecting spatially resolved gLSNe would be extremely rare. Simulations of the ZTF survey [22] indicate that only about 2% of the gLSNe within discovery range from ZTF would have image separations exceeding 3", at which point they could be detected as two individual point sources. The time delay between images is typically shorter than the typical time scale of the lightcurves, hence making also quite challenging to identify gLSNe from the vast pool of regular SN lightcurves through multiple detections separated in time. Figure 2 shows the distribution of time delays between SN images and the characteristic angular scale of strong lensing, the Einstein radius θ_E expected from simulations of the ZTF survey [23]. The extremely compact multi-image systems iPTF16geu $\theta_E = 0.3$" and SN Zwicky $\theta_E = 0.16$" (shown in Figure 1) could be identified through the magnification method. As indicated with stars in Figure 2, these two SNe where highly magnified $\Delta m = 2.5\log_{10}(\mu) > 3$mag, split into four images. Thanks to the "standard candle" nature of Type Ia supernovae, typically showing some ~ 0.15 mag of scatter after applying corrections for lightcurve stretch and colour, can be easily identified as outliers in brightness, *provided a spectrum is available with the spectral classification and the redshift of the SN.* We will return to this issue in Section 4.

3. A different population of lens systems

As can be appreciated from Figures 1 and 2, the systems found to date form the ground are extremely compact. Such small angular separation lensing systems are rarely found by other means given the extreme spatial resolution needed. Hence, it was shown in [16] that the gLSNe uncover a yet unexplored population of low stellar mass lensing galaxies. In particular, the compact systems provide interesting insights into the inner ~1 kpc region of lensing galaxies. The downside, discussed further in the Section 5, is that they are not suitable for cosmographic time-delay measurements.

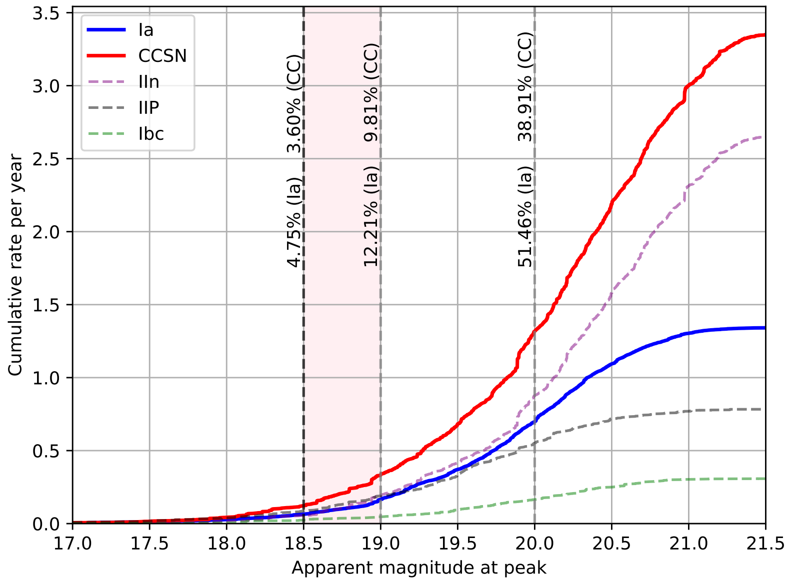

Figure 3. Expected yearly discovery rate as a function of the apparent magnitude threshold for SNe Ia (blue) and CCSNe (red) lensed supernovae. The dashed fainter curves are for subtypes of that are individual components of the red curve for CC: IIP, IIn, and Ibc, of which IIn is the dominant type wíth standard assumptions on their luminosity function and constant fraction of CC population, independent of redshift. The vertical dashed lines indicate the magnitude cuts of 18.5, 19, and 20 mag with the corresponding percentage of each SN type up to that cut. 18.5 mag corresponds to the BTS magnitude completeness cut, under which most supernovae are spectroscopically classified. We also include a region up to 19 mag as BTS extends to such magnitudes when the schedule allows is. Adapted from [23].

4. The discovery bottleneck: spectroscopic follow-up

Because of limited spectroscopic resources, only a small fraction of the transient discoveries in iPTF and ZTF were followed-up with the necessary spectroscopic screening needed to identify a lensed SN. While the photometric detection threshold in ZTF is around 20.5-21 mag [24], the spectroscopic classification, as a part of the Bright Transient Survey (BTS) is only complete to 18.5 mag [25]. Simulations of the ZTF survey [23] (see also [26]) show that the bright threshold of the BTS spectroscopic classification has been the bottleneck for identifying the gLSNe with the magnification method. In a recent work [27], an archival study of ZTF data was used to search for possible missed "live" candidates due to the magnitude limitation from BTS. The search efficiency was enhanced by having access to galaxy redshifts from the Dark Energy Spectroscopic Instrument (DESI), spatially associated with longlived, red candidates. The search has produced a handful of intriguing candidates. While superluminous supernovae (SLSNe) cannot be fully rejected as a possible explanation, two archival ZTF events, are significantly different from typical SLSNe and their lightcurves can be modelled as two-image lensed SNIa systems. From this two-image modelling, time delays of 22 ± 3 and 34 ± 1 days were estimated, respectively. If confirmed, it suggests that we may have found the first events with longer time delays with ground-based resources! The findings are in good agreement with the rate expectations from survey simulations in [23], shown in Figure 3.

5. Time delays and the quest for the Hubble constant

One of the main motivations behind searching for gLSNe is to use their lightcurves to measure the time delays between the multiple images, from which the Hubble constant (H_0) can be inferred, as first suggested by Refsdal in 1964 [7]. In recent years, the interest in this type of measurement has gained a lot of interest due to the emergence of the so called "Hubble tension", suggesting that the value of H_0 obtained from the early universe CMB anisotropy data, extrapolated to the present universe using the ΛCDM model (67.4 ± 0.5 km s^{-1}Mpc^{-1}), is in conflict with the local distance ladder measurement from the SH0ES team (73.0 ± 1.0 km s^{-1}Mpc^{-1}), see [28] for a recent review. Time-delay cosmography offers an interesting independent way to measure the Hubble constant and could provide further support or reject the notion that physics beyond the ΛCDM model is required. For many years, time-delay cosmography has been carried out exclusively with multiply-imaged quasars, but the results are as of yet inconclusive (see e.g. [29] for a status update). The smooth lightcurves of supernovae coupled with their favourable time scales make them potentially superior to QSOs for time-delay cosmography. Furthermore, unlike QSOs, supernovae fade in roughly a year time-scale, allowing for detailed studies of the lens without contamination from the lensed images. Hence, the possibility to complement the time-delay cosmography from QSOs with gLSNe has generated a lot of interest.

Furthermore, thanks to the standard-candle nature of SNe Ia (after corrections for colour and lightcurve shape), their magnification can be inferred up to an uncertainty related to their intrinsic luminosity scatter, about 0.15 mag. This is potentially a key feature, since it can be used to break the so called mass-sheet degeneracy. In brief, the presence of a constant sheet of surface mass density leaves the predicted images unchanged, but alters the time delay between the images [30]. Breaking the mass-sheet degeneracy, e.g., through the model independent measurement of the SNIa magnification, is therefore a very important element for constraining H_0 [31].

In the following sections we will discuss some additional challenges to break the mass-sheet degeneracy posed by extinction by dust in the host and deflecting galaxy, as well as micro and millilensing.

(a) Cluster scale lenses

Through the monitoring of the multiple images of SN Refsdal [32] the time delays and magnification ratios among the images were measured, and the most accurate time delay between a pair of images was $376.0^{+5.6}_{-5.5}$ days [33]. This time-delay measurement with a relative uncertainty of 1.5% provided the first precise H_0 measurement from lensed SNe. Through lensing models of the cluster, [33] found $H_0 = 66.6^{+4.1}_{-3.3}$ km s^{-1}Mpc^{-1}. More recently, H_0 was measured for SN H0pe. A combination of a spectroscopic [34] (see Section (d)) and photometric [35] time-delay measurement were compared to the predictions of many cluster lens models to measure a value for the Hubble constant [36]. In combination with the magnification of this SNIa, yielded a value of $H_0 = 75.4^{+8.1}_{-5.5}$ km s^{-1}Mpc^{-1}.

(b) Galaxy scale lenses

While the H_0 measurements from SN Refsdal and SN H0pe are very encouraging and exciting, some caution needs to be exercised in interpreting these results. The lensing models are very challenging since the mass distributions of clusters are quite complex, implying that the multiple image region of clusters is expected to be rich in substructures. For that reason, galaxy lenses are much simpler to model and therefore preferable, as they involve smaller systematic uncertainties. However, the highly magnified compact systems within reach for shallow surveys like ZTF are expected to produce images which can be separated by just a few days, as shown in Figure 4, making it rather challenging for precision measurements of time delays. That was the case for both iPTF16geu [21] and SN Zwicky [16], as outlined in the next Section.

(c) The second maximum in the SN Ia near-IR lightcurves

Besides their "standard candle" nature, SNe Ia offer other benefits for time-delay cosmography. For the restframe lightcurves in bands beyond the *r* filter, a secondary maximum within about a month from the restframe *B*-band lightcurve peak can be used to measure photometric time delays. This is extremely useful, as it means that accurate arrival time differences between SN images can be measured accurately, even when the first maximum is missed or poorly sampled, as was the case for both iPTF16geu and SN H0pe, shown in Figure 5.

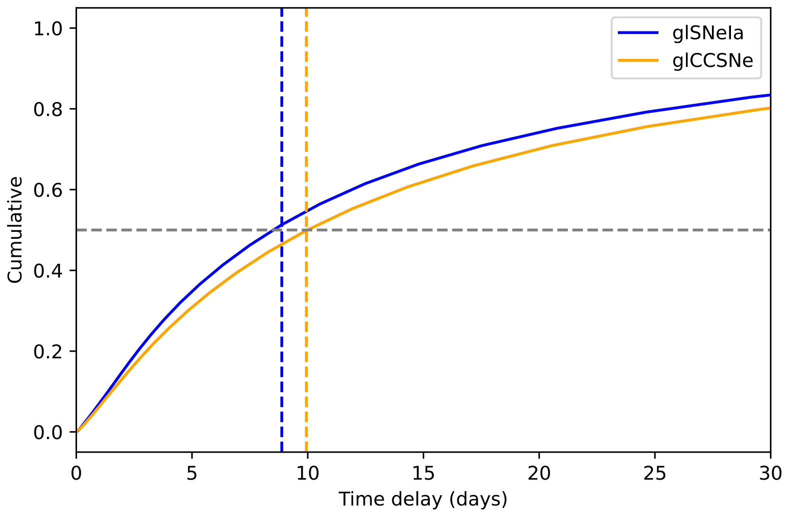

Figure 4. Expected cumulative distribution of time delays for gLSNe discovered by ZTF showing that the median time delay is close to 10 days for both core-collapse and Type Ia supernovae. Adapted from [23].

(d) Spectroscopic time delays

The two bottom panels of Figure 5 show another unique feature of the use of supernovae for time-delay cosmography. During the early phases of the supernova explosion, the atmosphere is thick and the supernova spectral energy distribution is formed by the outer layers with lower opacity, the photosphere. For a homologous expansion, $r = v \cdot t$, that corresponds to very high velocities. As the expansion thins out the atmosphere, the photosphere recedes, and the typical absorption features come from closer the centre, hence lower velocities. This change of velocities of the SN features can be used to extract the phase of the supernova at the time of observations. Spectroscopic time-delay measurements have been carried out successfully for iPTF16geu [38] and SN H0pe [34], as shown in Figure 5.

(e) Measuring time delays with (mostly) unresolved data

One of the important recent developments is the realisation that time-delays can be inferred from the unresolved lightcurves, provided there is at least one high-spatial resolution image of the system that gives the image multiplicity, their positions, and the relative image fluxes, as shown in Figure 6 from [16]. The publicly available, python-based software `sntd` [39] was used for for inferring the restframe B-peak magnitude, the lightcurve shape and colour SNIa SALT2 parameters [40] and the time-delays between the images. Unresolved photometry from the Palomar and Liverpool telescopes in g, r, i, z filters were included in the fit, along with a model including the flux contributions from the four sets of lightcurves accounting for extinction, each one with their own time of maximum The fit is constrained by imposing a prior on the image ratios at the date of the Keck/NIRC2 observations, shown in the right-hand side panel of Figure 6. The total lensing magnification was fitted, $\mu = 24.3 \pm 2.7$. Although negligible time delays were found in this case, the method is very promising for future systems.

6. The interstellar medium and differential extinction

As the light of gLSNe pierces through the inner regions of the deflecting galaxies, measurements of magnification crucially depend on the ability to accurately correct for losses due to scattering on dust grains, both in the host and lensing galaxy. For that purpose, multi-band imaging is used, since the magnitude increase (i.e., loss in flux in logarithmic units) to dust extinction is roughly inversely proportional with

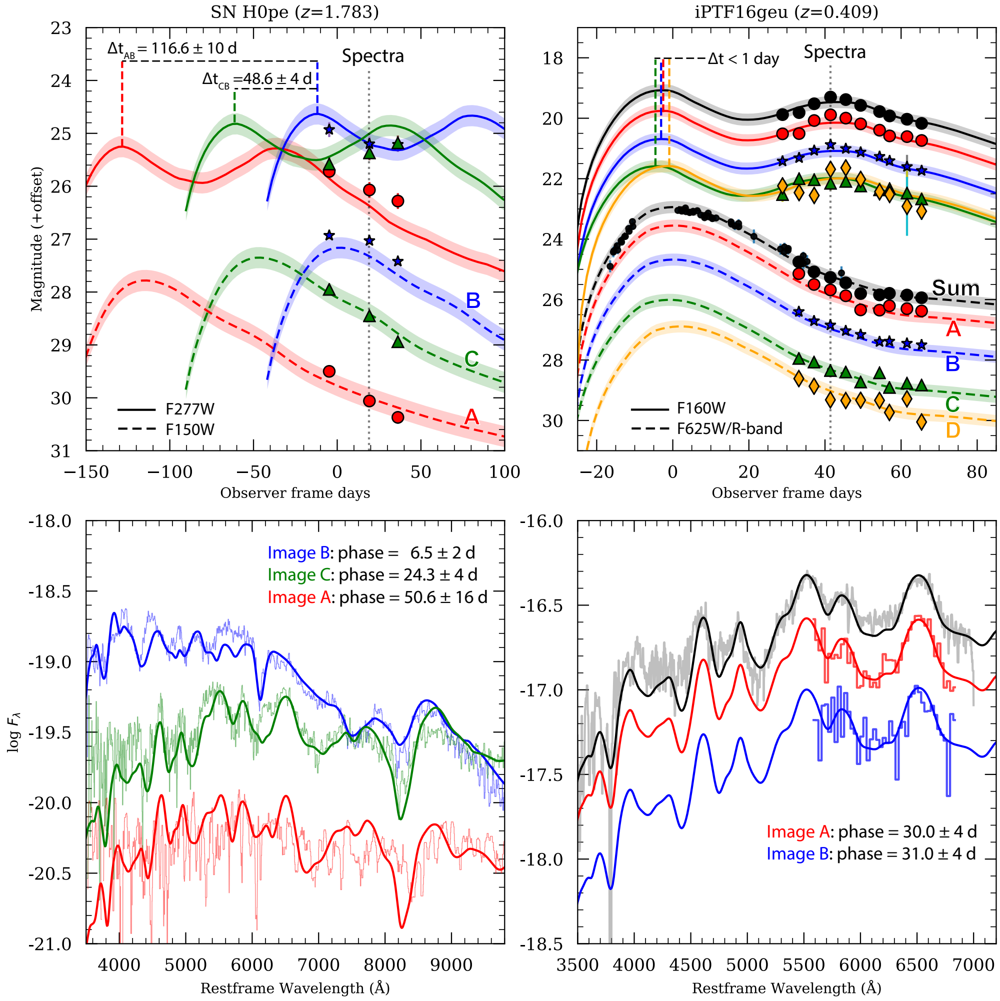

Figure 5. Top row: Photometric time-delay estimates from resolved images of SN H0pe (left) and iPTF16geu (right). In both cases, the "second IR maximum" was used to measure the difference in arrival times between the multiple SN images. Bottom row: spectroscopic time delays where the spectral features are dated using the SED template in [37]. Observations and further details can be found in [19,21,34,35].

wavelength, $A_\lambda \propto \lambda^{-1}$. To further complicate matters, observational evidence suggests that the composition and grain size distribution in the extragalactic interstellar medium could be very diverse [41], with total-to-selective extinction $R_V = A_V/E(B-V)$ potentially quite different from the Milky-Way value, hence the need to both fit the colour excess $E(B-V)$ and R_V, even from individual images. Since precise information of the range of properties for dimming by dust in other galaxies is so critical for accurate distance measurements in cosmology, it is very exciting to be able to carry out such measurements with resolved images of lensed SNe, as was the case for iPTF16geu [21], shown in Figure 7. Images C and D (see Figure 1) where particularly reddened, and thanks to having HST images in at least four filters useful constraints could be set on both the colour excess and R_V, providing unique a test of dust grain density and properties multiple lines of sight in an intermediate redshift galaxy.

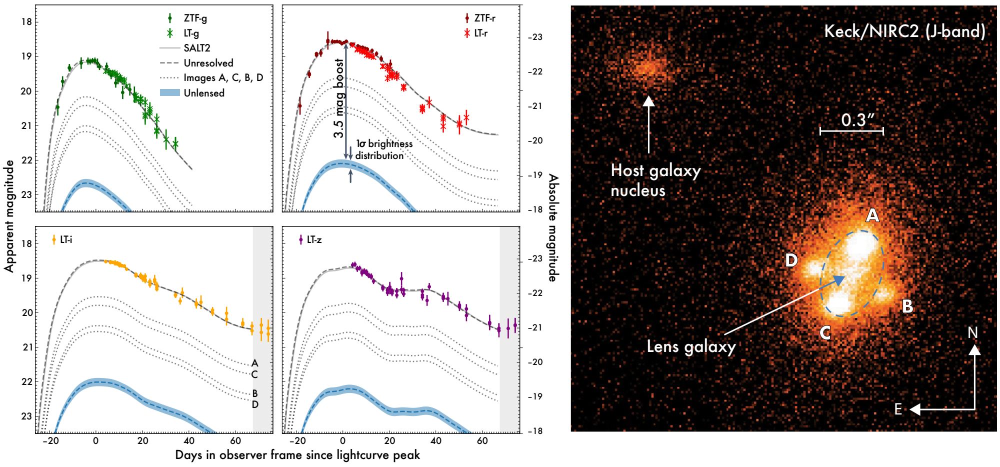

Figure 6. Ground-based (unresolved) lightcurves for SN Zwicky and resolved Keck/AO images from [16]. Using the prior from the Keck/AO image showing the quad configuartion and the fluxes at one epoch, time delays could be measured accurately with the unresolved multi-band data.

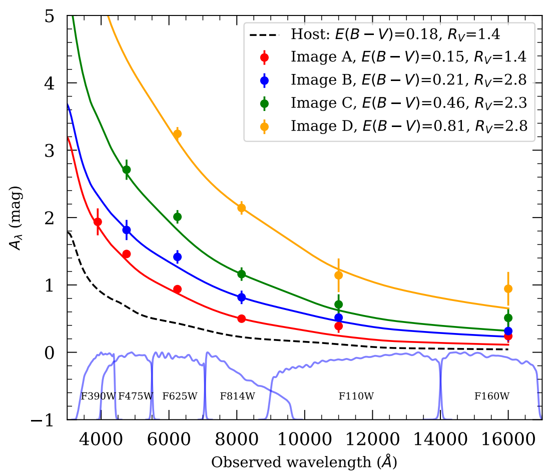

Figure 7. Inferred wavelength dependent extinction, A_λ, for the four resolved images of iPTF16geu measured with HST. The absorption from the host galaxy dust is plotted with dotted black line. For Image A we can see that the host galaxy is the dominant source of extinction, and for Images B, C, D there is a progressively larger contribution from the dust in the lens galaxy (see [21] for data and analysis information).

7. Macro vs milli/microlensing

Using multi-band follow-up observations of iPTF16geu with HST, an accurate (model independent) measurement of the total magnification was made, $\mu = 67.8^{+2.6}_{-2.9}$ [21], after correction for non-negligible extinction by dust in both the host and lens galaxies, as discussed in Section 6. The time delays between the SN images for this system were very small, about a day or less [21,42]. However, the flux ratios between the supernova images (see Fig. 1) were not consistent with expectations from (macro) lensing of a smooth extended deflector, even accounting for differential extinction, hinting at additional lensing contributions from galactic sub halos (millilensing) or stellar objects (microlensing) [19]. In either case, the sub-spliting of the SN images is too small to be resolved as it is of order milli-arcseconds or less, whereas e.g., the HST angular resolution is at least a few tens of milli-arcseconds. The situation was very similar for SN Zwicky ($\mu = 23.7 \pm 3.2$), except that there was no ambiguity between dimming by dust and microlensing (de-)magnification [16,18]. While extinction by dust can be identified and corrected through its wavelength dependence, microlensing by stellar objects is a more severe challenge [43]. The intrinsic size of a SN is comparable to the Einstein radius of an individual star in the deflecting galaxy. Hence, the observed magnification is sensitive to the unknown positions of stars and substructures in the lensing galaxy. A thorough discussion on microlensing of SNe can be found in [17] and potential means to mitigate this issue has been discussed in e.g., [44,45]. On the positive side, the image flux ratios observed can be used to infer limits on the possible dark matter contribution from e.g., primordial black holes over a wide mass range [20].

8. gLSNe in the LSST era

Thanks to the wide-field coverage and faint photometric limit of the Legacy Survey of Space and Time (LSST) survey at the Vera Rubin Observatory, the discovery rate of strongly lensed supernovae is expected to increase dramatically. Simulation studies have shown that hundreds of lensed SNe should be found [22], many of which will be spatially resolved [46]. For SNe Ia, [47] found that a 'gold sample' of ~ 10 lensed SNIa per year can be expected, with time delay above 10 days caught before peak, and sufficiently bright (below 22.5 mag) for spectroscopic follow-up observations. In three years of LSST operations, such a sample can yield a 1.5% measurement of the Hubble constant.

9. Conclusion

The rapid developments in time-domain astronomy, including wide-field imaging from the ground and very sensitive near-IR space instruments has led to an exciting development in the discovery of strongly lensed supernovae: the era of time-delay cosmography with supernovae has begun! Ground-based searches have uncovered a population of compact lens systems, where micro and millilensing effects are very important to characterise, also since they provide tests for the nature of dark matter. Lessons learned from searches to date give rise to great optimism, as instruments to be deployed in the immediate future will greatly enhance the feasibility and science reach of cosmology and astrophysics with lensed supernovae.

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