# Strongly Lensed Type Ia Supernovae

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## 1 Scientific Motivation

Strongly lensed Type Ia supernovae (SNe Ia) are rare systems that probe the mass profiles of elliptical galaxies at sub-kiloparsec scales. As cosmological probes, they provide a novel method of measuring $H_0$, $\Omega_m$, and $w$ via time delays, and their magnifications enable studies of supernova evolution to high redshift ($z \approx 1.8$ in ZTF). Studying them can reveal clues about the nature of dark energy, resolve tension between the local and CMB values of $H_0$, and constrain feedback mechanisms that regulate galaxy evolution.

### 1.1 Strongly Lensed SN Ia Cosmology with ZTF

When a SN Ia is strongly lensed by an elliptical galaxy, multiple images of the event, usually separated from one another by less than $1''$, are formed. Light rays from each image take a different amount of time to propagate to the observer, causing a relative time delay that can be measured with moderate-cadence, high-resolution imaging. The time delay, which is typically between 1 and 100 days, depends on the cosmological parameters (primarily $H_0$) and the gravitational potential of the lens. Because SNe Ia are standard candles, their magnifications (and thus their lens potentials) can be measured directly by comparing their observed brightnesses to the brightnesses of unlensed SNe Ia. Thus by measuring a time delay and a magnification, one can constrain the cosmological parameters.[1] This is the essence of strongly lensed SN Ia cosmology.

Such a measurement has never been achieved. Currently, only one strongly lensed SN Ia with resolved images has been discovered: iPTF16geu (Goobar et al., 2016). Although iPTF16geu is a testament to the power of ZTF's predecessor for discovering strongly lensed SNe Ia, it possesses sub-day time delays and significant brightness fluctuations from lens galaxy substructure that will make cosmology a challenge (More et al., 2016). To do precision cosmology with strongly lensed SNe Ia, more systems, with larger time delays and simpler lens potentials, must be discovered. ZTF is the only upcoming survey that provides the cadence, depth, and area necessary to achieve this goal. It does not have the spatial resolution necessary to resolve individual images, so our intention is to use ZTF as a photometric discovery engine for strongly lensed SNe Ia, with the goal of doing time delay extraction, lens modeling, and cosmology with targeted follow-up observations in space and with adaptive optics (AO) on the ground.

**Galaxy science** By constraining the lens potentials of elliptical galaxies at a variety of radii, strongly lensed SNe Ia can produce a data-driven elliptical galaxy mass profile template that extends to small radii. This will be useful for understanding the role of feedback in galaxy evolution (e.g., Sharma et al., 2012; Voit et al., 2015), and for correcting for the effects of microlensing by lens galaxy substructure in future strongly lensed SN Ia analyses.

In conclusion, ZTF has the opportunity to launch the field of strongly lensed SN Ia cosmology, providing the discoveries that will enable the first cosmological results with this probe, as well as interesting ancillary science.

[1] Assuming a well-determined lens potential, the fractional uncertainty on $H_0$ is equal to the fractional uncertainty on the time delay, which for typical delays can be measured to 1% or better.

### 1.2 Figures of merit

Since this program employs ZTF primarily as a triggering mechanism for higher spatial resolution, higher cadence follow-up observations, the figure of merit we have adopted for a ZTF lensed SN Ia program is simply the multiply imaged SN Ia yield.

### 1.3 Real-time discoveries

Real time discoveries will be essential for this program, because time delay extraction requires high spatial-resolution follow-up observations of lensed SNe Ia while they are active. The key to identifying strongly lensed SNe Ia photometrically is to take advantage of an optical illusion: in ZTF, lensed SNe Ia will appear as point sources spatially coincident with elliptical galaxies, but their brightnesses and light curve shapes will reveal that they must actually be located at higher redshift, implying that the apparent host (the elliptical) is acting as a lens. On average, strongly lensed SNe Ia should be ∼10 times brighter than unlensed SNe Ia at the same redshift, though significantly larger magnifications are possible. Because the redshift distribution of strongly lensed SNe Ia in ZTF peaks around $z \sim 1$, the SNe should be expected to evolve ∼2× more slowly than most unlensed ZTF SNe Ia, exhibiting a typical light curve duration of ∼200 days.

Goldstein & Nugent (2017) proposed a new method for photometrically identifying strongly lensed SNe Ia in wide-field surveys based on these considerations. The idea of their method is to look for supernovae that appear to be hosted by elliptical galaxies, but that have absolute magnitudes implied by the apparent hosts' photometric redshifts that are far brighter than the absolute magnitudes of normal SNe Ia (the brightest type of supernovae found in elliptical galaxies). Importantly, this purely photometric method does not require the ability to resolve the lensed images for discovery. Active galactic nuclei, the primary sources of contamination that affect the method, can be controlled using catalog cross-matches and color cuts. Highly magnified core-collapse SNe will also be discovered as a byproduct of the method.

For ZTF we have developed an improvement on this method that takes into account all of the information in the multi-band light curves of the supernovae to identify lensed SN Ia candidates. The technique is to fit the light curves of supernovae that are spatially coincident with elliptical galaxies with the SALT2 spectral template (Guy et al., 2007) fixed at the photometric redshift of the galaxy and with $M_B$ fixed between -18.5 and -20, a liberal range for SNe Ia. Lensed SN Ia candidates are created from any objects with light curves at least $5\sigma$ off from the best fit. Thus every lensed SN Ia considered in this work is incompatible at $> 5\sigma$ with being a normal SN Ia in the apparent host. An example of this procedure is shown in Figure 1. Human scanning of the images and light curves of the objects that meet these criteria will be a precursor for follow-up observations. Photometric redshifts of lens galaxies can be obtained from SDSS.

## 2 Proposed Observations

By carrying out detailed Monte Carlo simulations of the source (SN Ia) and lens (quiescent galaxy) populations, we determined that the nominal $g + R$ MSIP survey would yield just a few (∼2-3) strongly lensed SNe Ia over the lifetime of the survey. However, we found this yield could be increased dramatically (by a factor of 5 to 10) with the addition of cadenced $R$ or $i$ band observations of the low airmass ($< 2$) extragalactic MSIP fields. Assuming ∼30% of the lensed supernovae will be unaffected by microlensing in the lens galaxy (Dobler & Keeton, 2006), these observations would significantly increase the number of "golden" lensed SNe Ia discovered by the search. For this program, *we therefore request cadenced R or i-band observations (but not both) from the ZTF partnership* of the 7,500 to 10,000 square degrees of low airmass, extragalactic MSIP fields.

## 2.1 Pointings, Cadence, and Filters

An essential component of our search strategy is stacking observations taken within a 9 day window to boost our detection efficiency. To avoid inaccurate stacks from outliers and small number statistics, we require at least 5 observations during each 9-day period. This can be achieved with a dedicated survey at this cadence in $i$ or a supplementary $R$-band survey that reaches this cadence when combined with MSIP data. To achieve the same FoM, more observations are required in $R$-band than $i$-band because $i$-band captures more of the rest frame peak of the SED of high redshift SNe Ia than $R$-band. Based on our calculations, 11.5 strongly lensed SNe Ia can be expected from 1 hour of $i$-band or $R$-band observations on 7,500 square degrees of extragalactic sky per night ($+/-0.5$ mag variations in the limiting magnitudes of $gRi$ change these numbers to 24 and 6 SNe in both filters). When 10,000 square degrees are surveyed, $R$-band is able to maintain the cadence necessary for stacking and the yield increases to 15 (30 / 8.36 for magnitude variations), whereas it drops to 8 in $i$-band as the cadence falls below the limit for stacking.

*We therefore propose that the ZTF partnership survey 7,500 square degrees in R or i band or 10,000 square degrees in R band for one hour per night. We support the option that has the greatest synergy with other ZTF science proposals.* While the large-area $R$-band survey can improve the lensed SN Ia yield, the $i$-band survey is more sensitive to higher-redshift SNe Ia, and it could provide a valuable data set of high S/N spectra at redshifts where SNe Ia are not normally visible, even from space (see Figure 2). This would be a extremely useful for understanding whether and how SNe Ia evolve as a population with redshift.

## 2.2 Sensitivity to calibration and variations in cadence of filters

**Calibration** As we are using ZTF solely as a triggering mechanism, our science does not depend sensitively on calibration, a few percent in each filter is sufficient.

**Variations in cadence of filters** See §2.1.

## 2.3 Suitable periods for the observations

Not applicable.

# 3 Supporting Observations

## 3.1 Use of other photometric facilities

Supporting photometric observations will be critical for time delay extraction and cosmology. We plan to apply for time on WFC3 on HST and AO on Keck, and, if collaborations with members of Caltech are possible, potentially RoboAO to do higher-cadence follow-up observations for time delays. We note that the median image separation of our recovered systems is $0.9''$, and thus good quality photometric follow-up observations are well within reach of many ground based facilities.

## 3.2 Feasibility of relaxed cadence and filter requirements

Given the fact that our proposed ZTF survey will cover more than 3,000 square degrees per night, it is physically impossible to do this survey on any other instrument currently available on planet Earth. For example, DECam, with a minimum exposure, readout, and slew of 30 seconds, would need eight hour nights all year long to just cover 2,000 square degrees in a single band. Additionally, DECam and ZTF do not overlap in the extragalactic sky by much.

### 3.3 Spectroscopic classification

Spectroscopic classification will be necessary to confirm candidates as lensed SNe Ia and to measure their redshifts (and the redshifts of the lenses). For bright systems, SEDM can be used for classification. We would require $S/N \geq 10$ in each spectral resolving element. Keck, Lick, NOT, etc. will be used for the fainter supernovae. For these $R \sim 1000$ instruments, $S/N \geq 2$ is sufficient for classification. 20% calibration accuracy across the entire instrument is sufficient for our needs.

### 3.4 External resources

While we only expect to find 10 to 20 of these objects, they are extremely scientifically valuable, and each merits extensive UVOIR follow-up observations. Therefore, we will be putting in ToO proposals at several facilities in space and on the ground to prepare for this program.

## 4 Expertise and tools

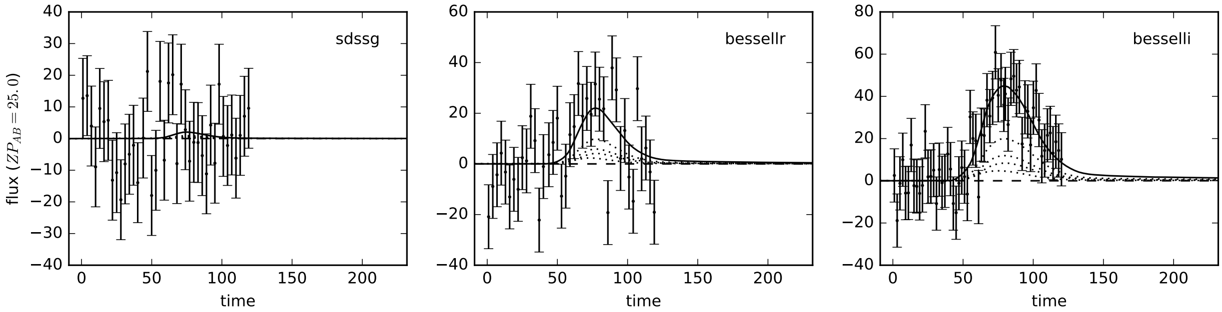
**Expertise** The authors have the expertise to carry out the detection, follow up, time delay extraction, and cosmology components of this program.

**Tools** To execute our search, we require that the candidate identification technique described in §1.3 be implemented in the ZTF follow-up marshal. We also require that the procedure for stacking multiple observations be added to the photometry pipeline. If this is not feasible, both can be carried out at NERSC. Thus we would only require that the data be transferred from IPAC in as near real-time as possible.

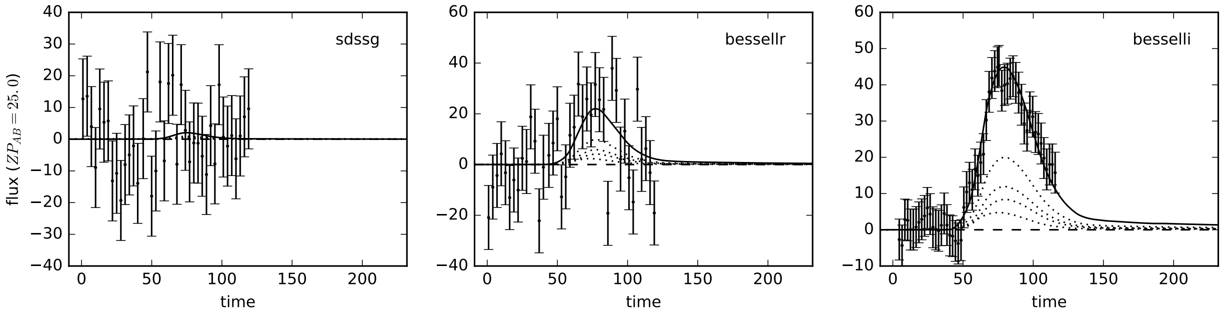
## 5 Manpower

**Manpower and timeline** This project will be led and carried out by the authors of this paper. Upon the discovery of suitable supernovae in the first year data, we will publish a paper detailing the discoveries and presenting their cosmological constraints in what may be the first analysis of its kind. Longer term projects include ancillary galaxy science and our key deliverable: a measurement of the Hubble constant with the full strongly lensed SN Ia sample from ZTF.

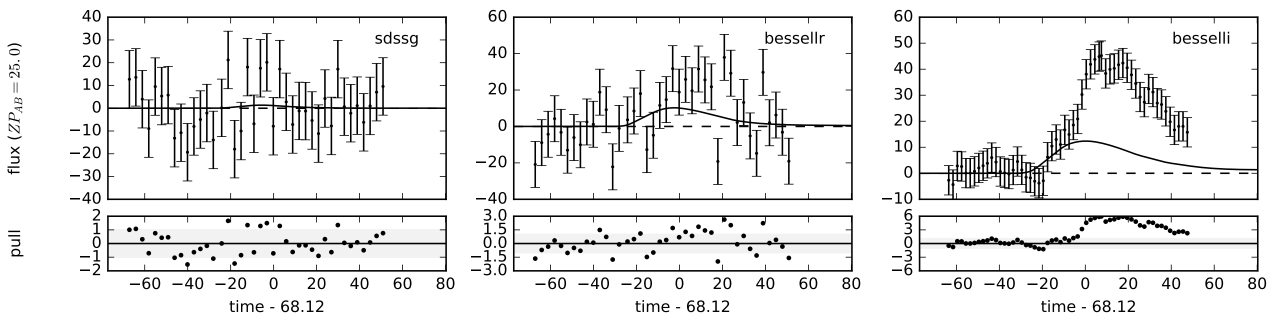
**Thesis projects** Any of the above projects completed before May 2018 will form part of Danny Goldstein's thesis.




(a) Simulated $gRi$ ZTF photometry (points with error bars) of a strongly lensed SN Ia ($z = 1.1$; $z_l = 0.55$; $\mu = 24.7; t_d \sim 4$d; true light curve shown as solid line), itself the sum of four unresolved lensed images (true light curves shown as dotted lines) from our proposed MSIP+1hr 7,500 square degree $i$-band survey. The MSIP data ($g + R$; left two columns) show no signal of the transient, but there is a weak signal from the $i$-band data.




(b) Stacking the higher-cadence $i$-band data over a 9 day window increases its S/N.




(c) Fitting the data with a SALT2 template fixed to the redshift of the lens (solid line), and constrained to obey -18.5 $> M_B >$ -20, a liberal SN Ia magnitude range, shows the object is inconsistent at $6\sigma$ with being an SN Ia hosted by the lens. The $i$-band data (right column) are essential to this conclusion.

Figure 1: Procedure for photometrically identifying a strongly lensed SN Ia. Note that the $i$-band data (right column) from one of the surveys proposed in this paper, is critical for detecting this object. The MSIP data alone (left and center columns) would not be sufficient.

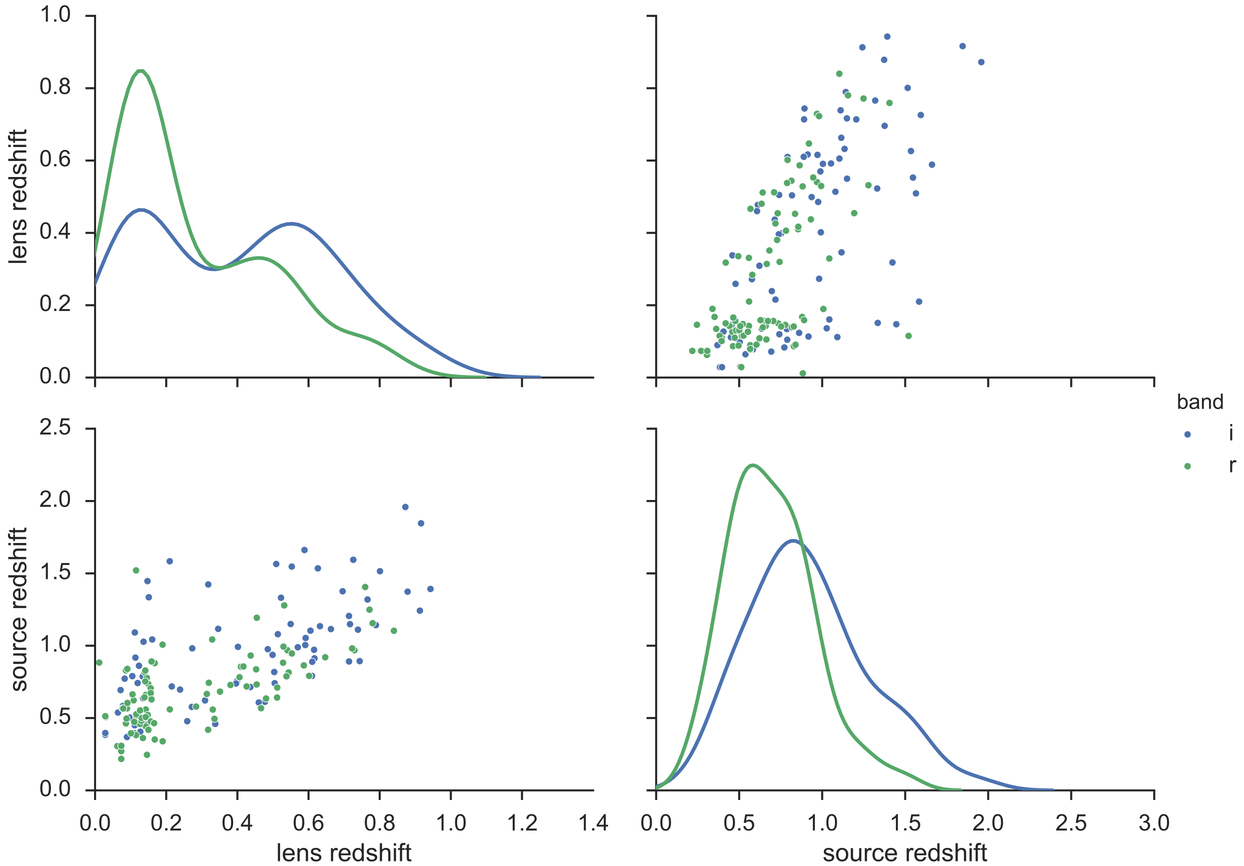



Figure 2: Supernova and lens redshift distributions of strongly lensed SN Ia systems detected with 1 hour of $R$ or $i$-band follow-up observations of 7,500 square degrees of the extragalactic MSIP fields. The $i$-band survey is more sensitive to high-$z$ SNe.

# References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