■ Scientific Justification

The observation of the first multiply-imaged, gravitationally lensed supernova (SN) in 2014, SN "Refsdal", was a critical step forward for the SN cosmology community (Figure 1; Kelly et al. (2015b)). As light from a distant source passes through a gravitational lens, each subsequent image will appear to the observer delayed relative to the unlensed travel time. If the lensing potential is well known, then the **time delay measurement provides a direct constraint on the Hubble constant that is completely independent of the local distance ladder.** There are certain degeneracies associated with obtaining these constraints directly from time delays, which are broken in the case of a Type 1a "standard candle" SN (Kolatt & Bartelmann, 1998). The very first multiply-imaged Type 1a SN (iPTF16geu) was discovered by Goobar et al. (2016), but attempts to constrain the time delays have been only moderately successful citing the need for a comprehensive mechanism that includes microlensing effects as a primary source of uncertainty (More et al., 2016). We propose to perform a complete reanalysis of SN Refsdal in order to refine our constraints on the lensing parameters and define a rigorous methodology for use in the case of SN iPTF16geu and future lensed SNe. We will improve upon previous work by making substantial improvements to the photometry, and including the significant yet previously ignored effects of microlensing. Additionally, we will produce an open-source software package in the course of this work, optimized specifically for multiply-imaged SNe.

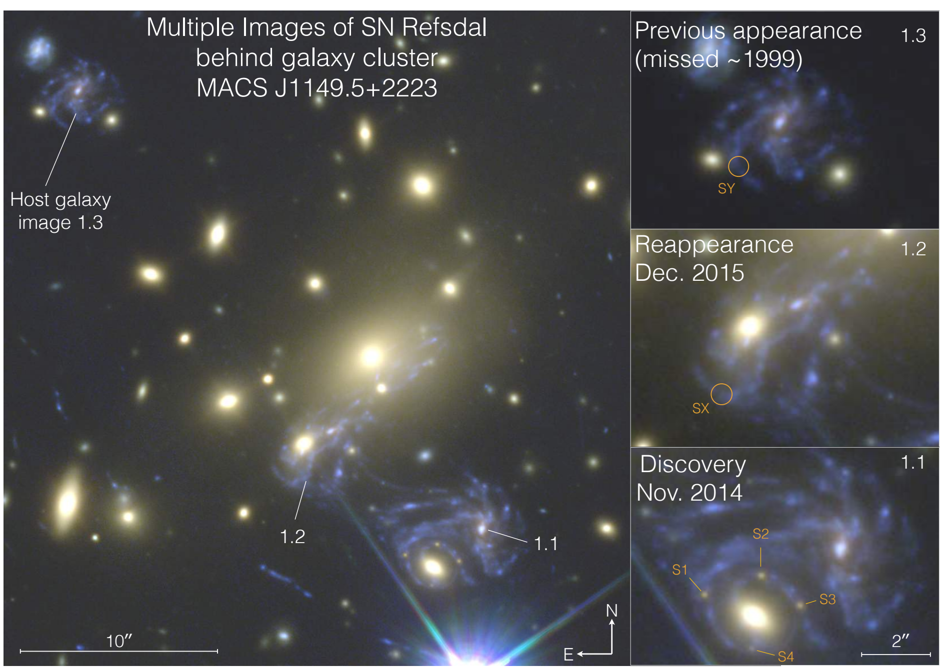

Figure 1: MACS J1149.6+2223 field, showing the positions of the three primary images of the SN Refsdal host galaxy (labeled 1.1, 1.2, and 1.3). SN Refsdal appears as four point sources in an Einstein Cross configuration in the southeast spiral arm of image 1.1 (Rodney et al., 2016)

As a previously ignored check against systematic biases, our reanalysis will use both the *PythonPhot* and the *DOLPHOT* packages to perform photometric measurements. We will also measure the photometry in single-exposure images, allowing us to check for any deviations at very short timescales, indicative of very rapid microlensing events. Rodney et al. (2016) measured flux using a single empirical point-spread function (PSF) fixed in time, derived from standard stars. However, as we know that the HST PSF does undergo subtle variations due to telescope "breathing" (**CITE**), our re-analysis will use foreground stars within the MACS1149 imaging datasets to define a variable PSF model. **The reduction of systematic biases in the photometry and our improvements to the PSF will provide drastically ameliorated flux calculations, which in turn will increase the accuracy and precision of time delay measurements.**

Microlensing refers to small-scale gravitational lensing perturbations due to massive objects along the light path of any one image of a multiply-imaged SN. The effect of microlensing is to cause distortions in the SN light curves that significantly limit the precision that can be achieved in the measurement of their time delays (Dobler & Keeton, 2006). Despite noting this significant source of uncertainty, the analyses performed for SN Refsdal and SN iPTF16geu have completely ignored microlensing due to its complexity (More et al. (2016); Rodney et al. (2016)). In preparing this proposal, we have already used flexible functions to preliminarily measure the effects of the type 1 microlensing on SN Refsdal (Figure 2), and it's **clear that microlensing must be taken into account** in order to ensure accurate time delay and magnification measurements. Therefore, we will **fully analyze the effects of microlensing on a multiply-imaged SN for the first time** and ensure they can be accurately accounted for in future SN analysis.

The next decade is expected to yield observations of over 100 lensed SNe that will require analysis (Oguri & Marshall, 2010), yet **there is no public software package for analyzing multiply-imaged SNe.** In the course of this work, we are producing an open-source software package written in Python for use in this and future SN analysis. Specifically, efforts to measure the time delays of SN iPTF16geu, critical to a new measurement of H_0, have not been successful beyond broad constraints (Goobar et al. (2016), More et al. (2016)). This new tool, developed and tested in the course of reanalyzing SN Refsdal, will be used to make a time delay measurement in parallel to the Goobar et al. team when they make follow-up observations later this year, providing an important independent check of such a measurement for the first time.

Goobar et al. (2016) concluded that the **rate of strongly lensed Type 1a SNe is likely much higher than previously thought**, with implications for our constraints on H_0, the study of galaxy sub-structures, and tests of theories of modified gravity. If the number of lensed Type 1a SNe observed in the JWST/LSST era follows these predictions, then it will be absolutely essential to have a publicly available, standardized tool in place to accurately produce time delay and magnification measurements. The reanalysis of SN Refsdal offers a **unique chance** to develop the software and methodology necessary in the coming years for analyzing new SNe **to obtain exciting scientific results**, including constraints on dark energy parameters and a direct probe of the expansion rate of the universe, H_0.

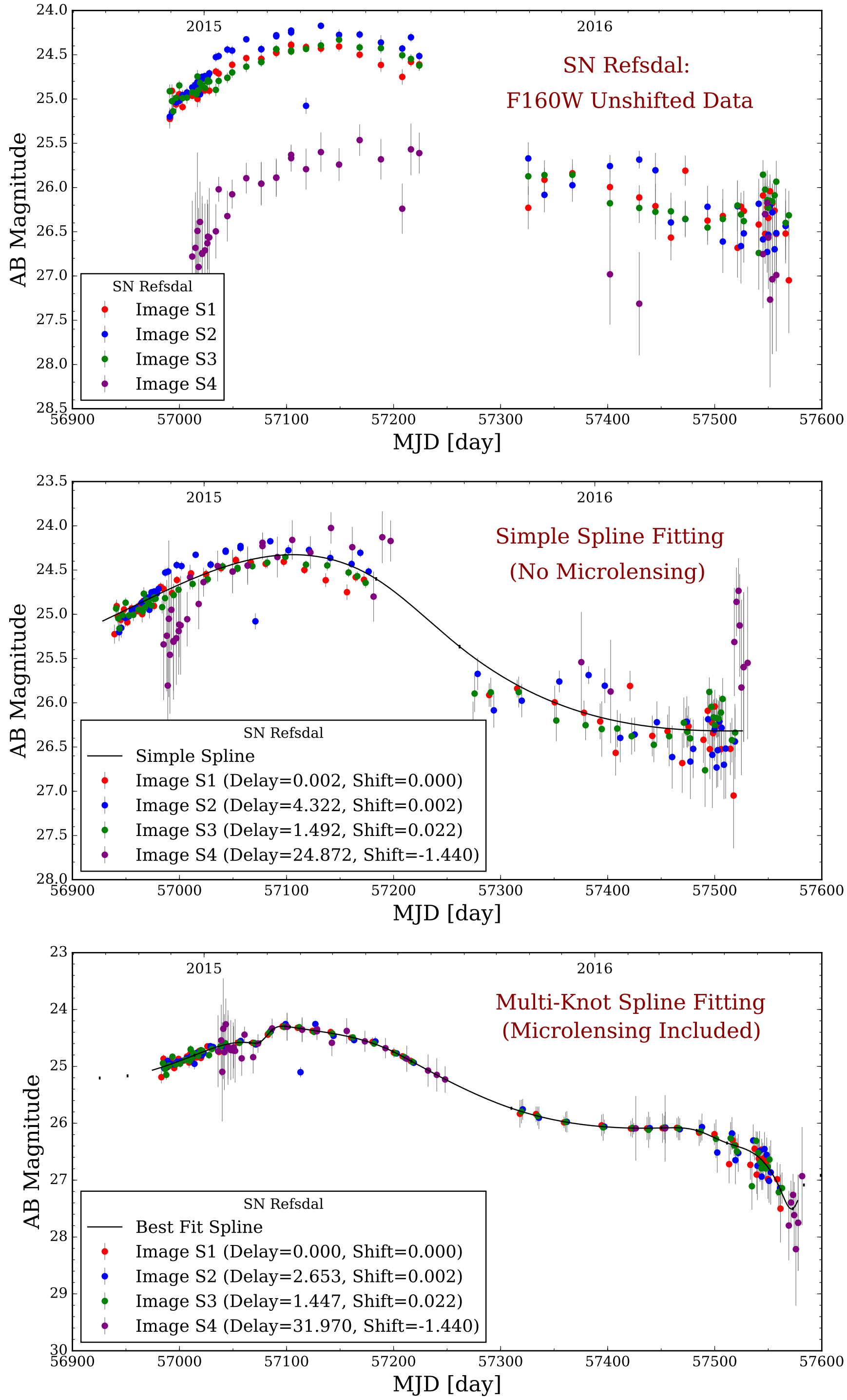

Figure 2: (Top) HST F160W data representing the four images of SN Refsdal (Figure 1), with no lensing or time shifts. (Middle) Method of fitting the SN Refsdal light curves from Rodney et al. 2016, which did not consider microlensing effects. (Bottom) Preliminary results from this work using a multi-knot spline to fit the data. This method includes microlensing effects, which leads to a slight adjustment in time delay measurements.

Analysis Plan

Datasets:

There are 58 relevant datasets in the HST archive intersecting the coordinates of MACSJ1149 that will be used in this work. The data are from the WFC3-IR and ACS-WFC instruments, and span April 22, 2004-October 30, 2016 with HST Project IDs: 9722, 10493, 12068, 12197, 13504, 13459, 14041, 13790, 14199, and 14208. NEED TO ADD HOW WE'RE GETTING THE DATA, HOW LONG IT'LL TAKE, ETC.

Analysis:

First, as described in the scientific justification, previous photometry will be improved by using both the *PythonPhot* and *DOLPHOT* packages, which will minimize potential systematic errors in either method. In addition, foreground stars within the MACS11489 datasets described above will be used to define a variable point spread function (PSF) model, which will account for known subtle variations due to telescope "breathing" (**CITE**).

For lensed SNe, it is possible to classify the SN based on photometry and spectroscopy, and then identify a well-matched SN light curve template. In contrast to quasar time delay measurements that use a flexible function fitting method, the template method provides a strong informative prior for the intrinsic light curve shape. In the case of SN Refsdal, the initial analysis concluded that a SN 1987A-like template fits the data best (Kelly et al., 2015a), and we will confirm this with our own new analytical software package being developed in this work. The SN 1987A template will be corrected to match the redshift of SN Refsdal, measured to be $z = 1.488 \pm .001$(Rodney et al., 2016), and then a Bayesian parameter estimation framework will be implemented to estimate the color corrections, time delays, and magnifications for all four SN Refsdal images. Previously ignored microlensing effects will be considered by analyzing achromatic deviations from the light curve templates in conjunction with a Bayesian prior that describes microlensing probability as a function of time. Microlensing effects identified by the model are corrected so that the inherent light curve can be compared to the template, and the correct template parameters derived. The model light curves are defined using

$$m(\lambda', t') = M(\lambda, t) + K(\lambda, t; \lambda') + C_\lambda, \tag{1}$$

where the time t is the rest-frame age relative to the date of peak brightness in the rest-frame R band, and is a free parameter in the model. The model apparent magnitude in an observed passband, $m(\lambda', t')$, is governed by a model absolute magnitude in a model passband at the model's rest- frame age, $M(\lambda, t)$, corrected to an observed passband with $K(\lambda, t; \lambda')$ (Strolger et al., 2015). Finally, a magnitude shift C_λ is added as a separate free parameter for each photometric passband, which accounts for both cosmological dimming and any color difference between the model and SN Refsdal due to dust extinction or intrinsic color differences. Linear interpolation will be used to infer model magnitudes between observed points in the template light curves.

To take into account the gravitational lensing effects, we will include six more free parameters that are applied as corrections to the observed data: time shifts Δt_i, and achromatic magnitude shifts Δm_i that give the time delays and magnifications of the the Refsdal sources relative to a reference source. The model light curves are then simultaneously compared to all SN Refsdal sources to derive a likelihood distribution from each light curve template T_k, using:

$$p(D|T_k,\theta) = \prod_i \frac{p_i(\theta)}{\sqrt{2\pi}\sigma_i} e^{-(m_{obs(t_i)} - m_k(\lambda_i,t_i))^2/(2\sigma_i^2)}. \tag{2}$$

Here θ denotes the set of free parameters, and $p_i(\theta)$ are the Bayesian prior distributions. In contrast with previous analysis done on SN Refsdal, a microlensing parameter will be added to the set θ, and the related Bayesian prior distribution will not be flat. In order to sample the likelihood distributions defined by Equation (2) over the multidimensional parameter space, we will use the Markov Chain Monte Carlo ensemble sampling tools from the *SNCosmo* software package (Barbary, 2014).

Management Plan

References

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