■ 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.** We propose to perform a comprehensive reanalysis of SN Refsdal in order to refine our constraints on the lensing parameters. 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.

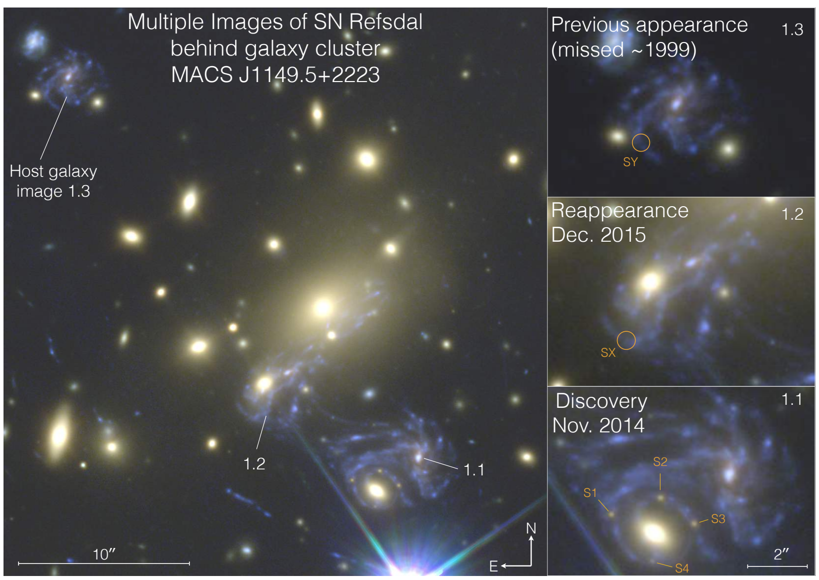

Figure 1: MACS J1149.6+2223 field, showing the positions of the three primary images of the SN Refsdal host galaxy (labeled 1.1, 1.2, and 1.3). SN Refsdal appears as four point sources in an Einstein Cross configuration in the southeast spiral arm of image 1.1 (Rodney et al., 2016)

A New Software Package:

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.** The lack of a standard resource leaves researchers to write and implement their own ad hoc programs, which will become increasingly inefficient as the number of observed lensed SNe increases. 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.

There are currently two software packages that form the basis of this product: Supernova Cosmology (SNCosmo), and Python Curve Shifting (PyCS) used for quasars. Unlike quasars, SNe of a given class always have consistent and well-known light curve shapes. This will allow for physically motivated, less flexible models that will be more likely than PyCS to correctly identify SN microlensing effects and produce simpler time delay measurements. By allowing certain constraints to float as free parameters, these models will also produce best-fit synthetic light curves from which time delays, magnifications, SN class, and redshift can be derived. By simulating large numbers of SNe with these synthetic light curves, we will be able to quantify the accuracy and efficiency of the software.

Microlensing Effects:

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. After the discovery of Refsdal in 2014, subsequent work was done to classify the SN (Kelly et al., 2016), as well as measure time delays and magnification ratios (Rodney et al., 2016). These previous analyses completely ignored microlensing; therefore we will **fully analyze the effects of microlensing on a multiply-imaged SN for the first time.**

Lensed SNe are affected by microlensing caused both by transverse motion of stars in the lensing galaxy (type 1), and as the expanding photosphere of a SN interacts with an increasing volume of the caustic web (type 2). The latter form, which precipitates microlensing effects described by Dobler & Keeton (2006) that can cause fluctuations of $\sim$0.2 to $>$0.5 magnitude, is unique to lensed SNe and has never been fully classified or considered in lensed SN analysis. Therefore, an algorithm will be developed following the methodology of Dobler & Keeton (2006) and released as a component of the open-source software packaged being developed in the course of this work. In preparing this proposal, we have already used flexible functions to preliminarily measure the effects of the type 1 microlensing (Figure 2), and it's **clear that microlensing must be taken into account** in order to ensure accurate time delay and magnification measurements.

Improving Photometry:

Measuring photometry with a single photometric tool, as was done in Rodney et al. (2016), means that potential systematic errors may be disregarded. As a check against systematic biases, our reanalysis will use both the *PythonPhot* and the *DOLPHOT* package 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 in our reanalysis.**

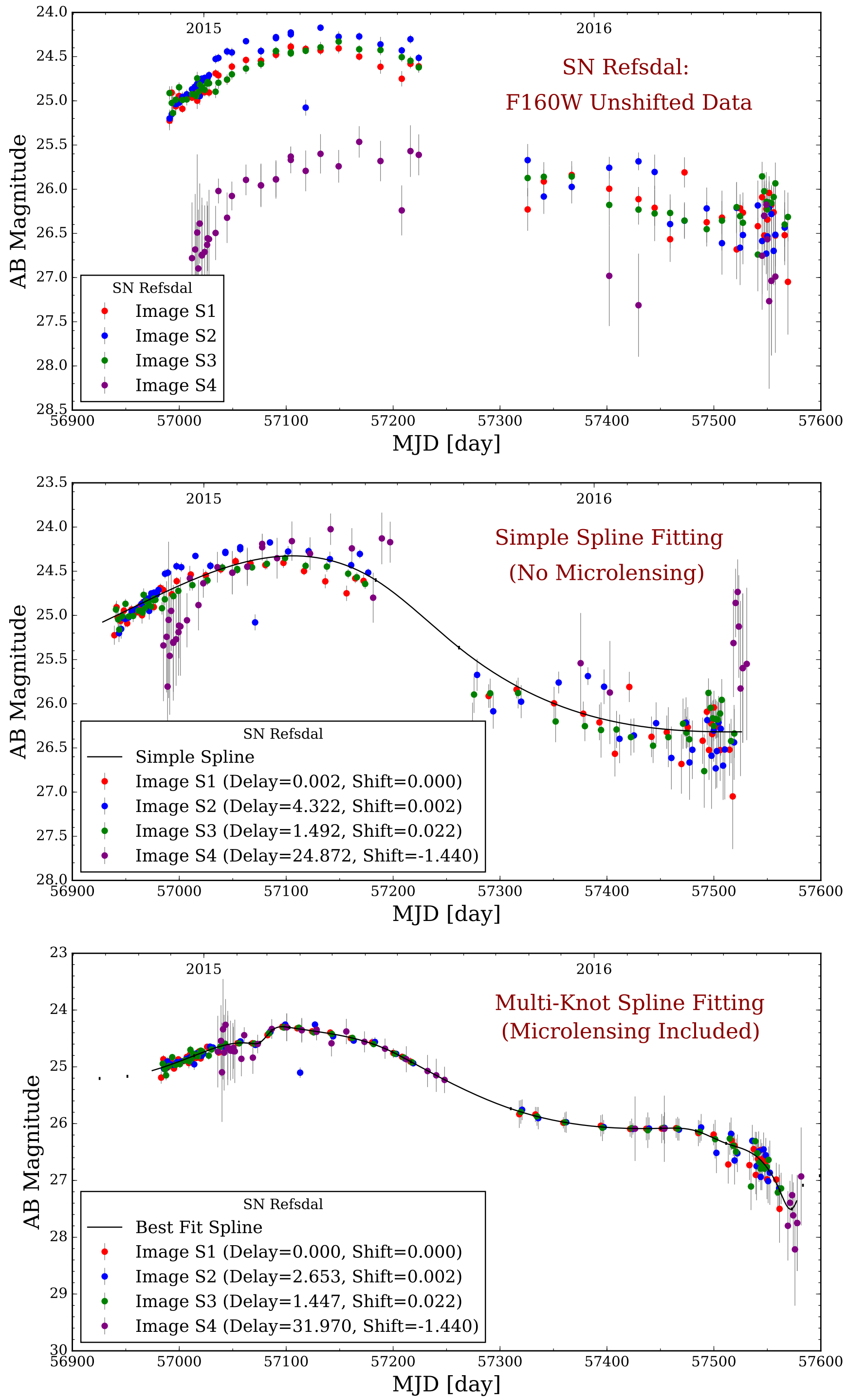

Figure 2: (Top) HST F160W data representing the four images of SN Refsdal (Figure 1), with no lensing or time shifts. (Middle) Method of fitting the SN Refsdal light curves from Rodney et al. 2016, which did not consider microlensing effects. (Bottom) Preliminary results from this work using a multi-knot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

Barbary, K. 2014, sncosmo v0.4.2

Dobler, G., & Keeton, C. R. 2006, ApJ, 653, 1391

Kelly, P. L., et al. 2015a, ArXiv e-prints, arXiv:1512.09093

—. 2015b, Science, 347, 1123

—. 2016, ApJL, 819, L8

Oguri, M., & Marshall, P. J. 2010, 2593, 2579

Rodney, S. A., et al. 2016, ApJ, 820, 50

Strolger, L.-G., et al. 2015, ApJ, 813, 93