■ Scientific Justification

The seminal work of Refsdal (1964) first showed how a gravitationally lensed supernova (SN) resolved into multiple images could be used as a cosmological tool. Now, some 50 years later, HST is playing an integral role in the long-awaited first observations of such gravitationally lensed SNe (Figure 1). HST observations caught the first multiply-imaged SN, called "SN Refsdal"—a core-collapse SN lensed by both a galaxy cluster and a single galaxy (Kelly et al. 2015). This was soon followed by the first multiply-imaged Type Ia SN (iPTF16geu), resolved with HST imaging (Goobar et al. 2016). As the light for each of the multiple images follows a different path through the expanding universe and through the lensing potential, the SN images appear delayed by hours (for galaxy-scale lenses) or years to decades (for cluster-scale lenses). For SN Refsdal, measurement of this time delay can be used as a precise test of cluster lens models (Treu et al., 2015). For iPTF16geu, the lensing potential is simple enough that we can convert the time-delay measurement into a direct constraint on the Hubble constant–completely independent of the local distance ladder. Preliminary time delay measurements have been made, but for both SNe these are limited by the need to include complex microlensing effects (Rodney et al., 2016; More et al., 2016). **We propose to re-analyze the HST observations for these two lensed SNe, improving the photometry and including the significant yet previously ignored effects of microlensing. We will develop an open-source software package in the course of this work, optimized for multiply-imaged SNe, that will enable precise time delay measurements to be made for dozens or hundreds of lensed SNe in the LSST/WFIRST era.**

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" (Dressel, 2012), our re-analysis will use foreground stars within the MACS1149 imaging datasets to define a variable PSF model (Cox & Niemi, 2011). **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

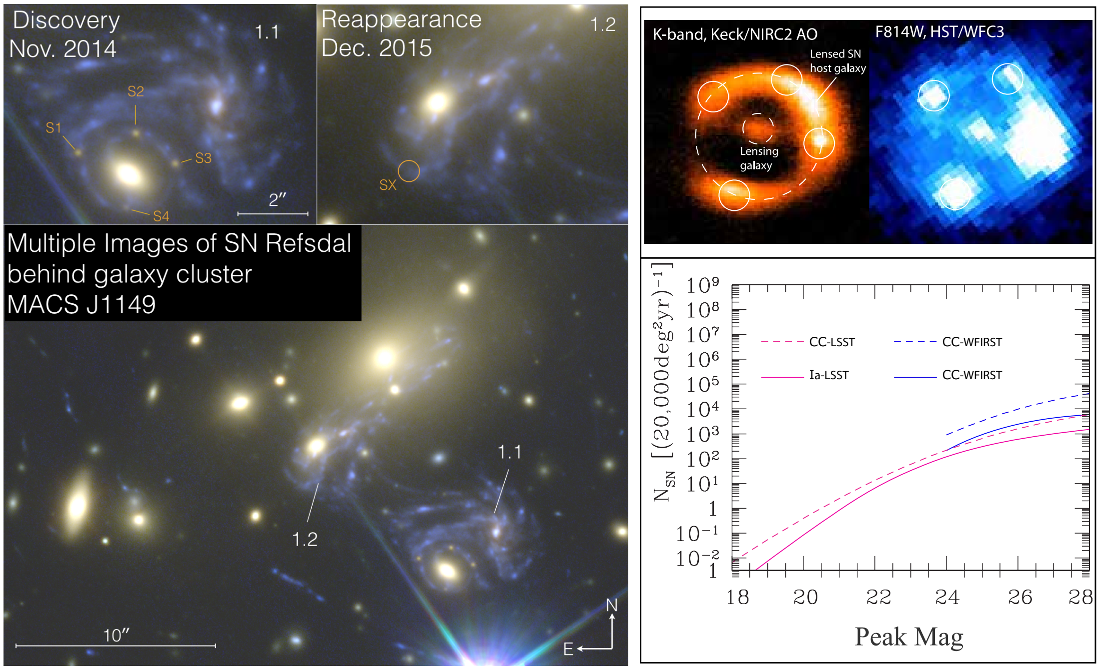

Figure 1: (Left) MACS J1149.6+2223 field, showing the positions of the three primary images of the SN Refsdal host galaxy. SN Refsdal appears as four point sources in an Einstein Cross configuration in the southeast spiral arm of image 1.1. (Right) Expected numbers of Type Ia and Core Collapse SNe for LSST ($i_{peak,lim}$) and WFIRST ($H_{peak,lim}$), adapted from Oguri & Marshall (2010).

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.

The discovery of SN iPTF16geu suggests that the **rate of strongly lensed Type Ia 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 (Goobar et al. (2016),More et al. (2016)). If the number of lensed Type Ia SNe observed in the LSST/WFIRST 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.

Analysis Plan

Datasets:

There are 64 relevant datasets in the HST archive that will be used in this work: 58 intersecting the coordinates of MACSJ1149, and 8 intersecting the coordinates of SN iPTF16geu. will be used in this work. The data intersecting MACSJ1149 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. The data intersecting SN iPTF16geu are from the WFC3-IR instrument, and span October 20-November 17, 2016 with HST Project ID 14862.

The required HST datasets amount to a relatively small volume of data. All datasets will be requested from the archive at once, at the start of the project. We will start with the FLT files, and will process them through a modified version of the HST data processing pipeline that was originally developed for the CANDELS and CLASH SN surveys (Rodney et al., 2014). This pipeline uses a custom processing sequence with AstroDrizzle and TweakReg to segregate the data into epochs, combine each epoch of HST imaging exposures, register them to a common co ordinate system, and generate difference images suitable for SN detection and photometric measurements. This pipeline was updated for use in SN searches related to the Frontier Fields, and is now publicly available (https://github.com/srodney/sndrizpipe).

This pipeline will be revised and improved again for this work, adding additional steps to remove persistence artifacts that might impact the photometry of the SN targets and/or the foreground stars that will be used to define a time-varying PSF model. For the initial measurement of the time delays of SN Refsdal, special data processing steps were required to address contamination of the SN by diffraction spikes from a 15th-magnitude star in the foreground (Rodney et al., 2016). Revision and improvement of this contamination removal will be a critical step for increasing the precision of the photometry for SN Refsdal.

All data processing will be executed on the University of South Carolina research computing clusters (`http://rci.cec.sc.edu/`).

Management Plan

The first stage of this project is to produce an open-source software package called Supernova Time Delays (SNTD). There are currently two software packages that form the basis of this product: Python Curve Shifting (PyCS; Tewes et al. 2013) used for quasars, and Supernova

Cosmology (SNCosmo; (Barbary, 2014)). This will proceed in three steps: 1) Integrate SNCosmo and PyCS, giving researchers a tool that can model SN light curve data with the abilities present in either software package; 2) Extend and optimize the lensing and microlensing algorithm present in PyCS for SNe; 3) Simulate a large number of multiply-imaged SN light curves using SNCosmo and test the ability of SNTD to simultaneously determine SN and lensing parameters. This work will be done primarily by graduate student PI Roberts-Pierel, under the guidance of Co-I Rodney at USC. We anticipate this will require 4-6 months of full time effort from the PI.

In parallel with the software development, we will improve the photometry of the two multiply-imaged SNe (Refsdal and iPTF16geu) by 1) reprocessing the HST images using the most up-to-date AstroDrizzle software; 2) developing new time-variable PSF models, based on stellar sources within each image; and 3) deriving new photometric time series, using multiple photometry packages to extract photometry from both the template-subtracted difference images and directly from the FLT files. Although SN Refsdal appeared in the Hubble Frontier Fields, for this work it is necessary to reprocess the data separately from the official HFF products, because we need to break it up into separate epochs. This component will require 4-6 months of part-time work from the two Co-I's, supplemented by additional effort from the grad student PI.

For the conclusion of this project, we will use the new SNTD package to measure improved gravitational lensing parameters for SN Refsdal and iPTF16geu. The software is being developed as an open-source project, and is already publicly accessible on github (`https://github.com/jpierel14/sntd`). We anticipate that the SNTD package and the results of the new lensing analyses will be separately published within 18 months of the start of this project.

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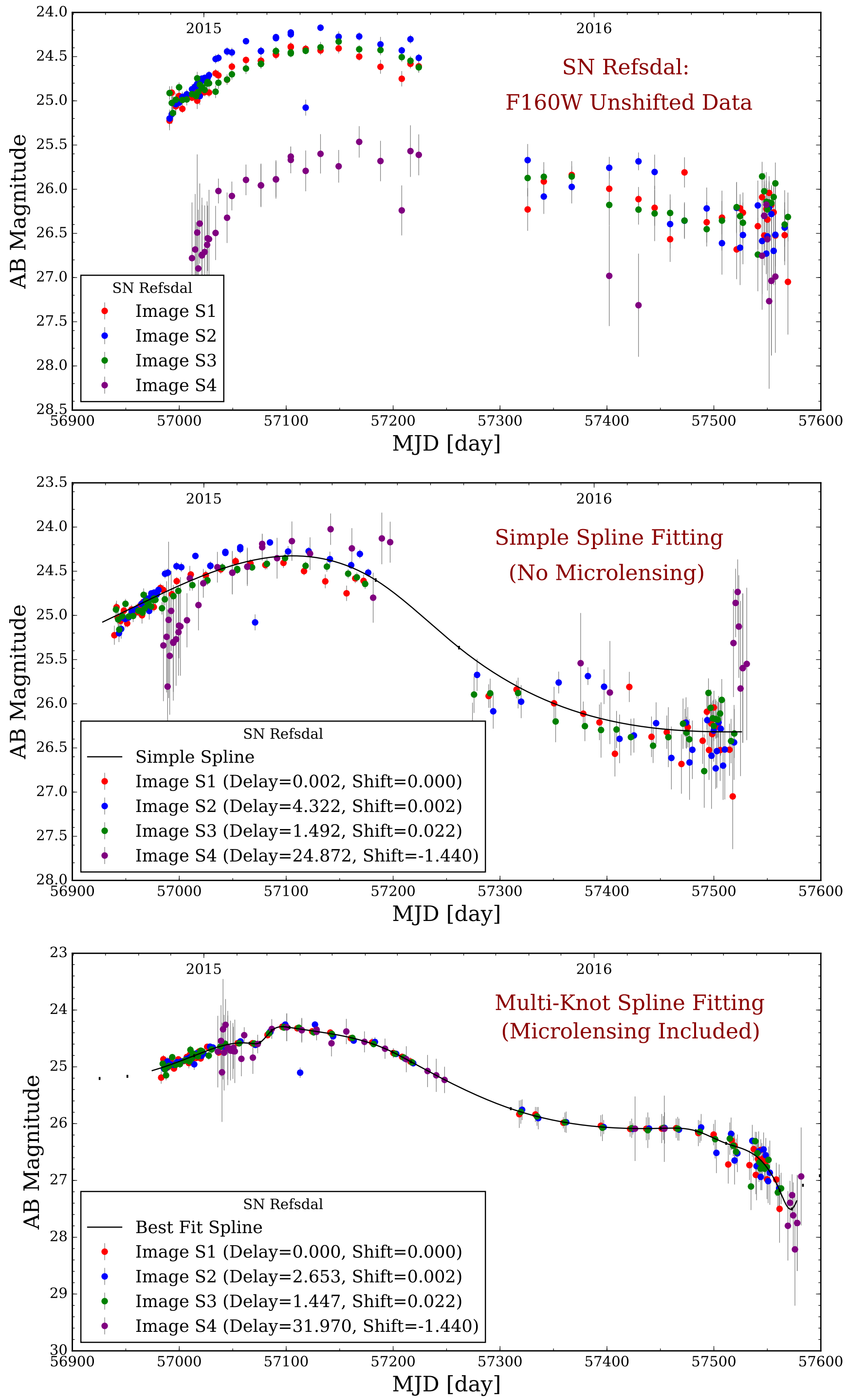

Figure 2: (Top) HST F160W data representing the four images of SN Refsdal (Figure 1), with no lensing or time shifts. (Middle) Method of fitting the SN Refsdal light curves from Rodney et al. 2016, which did not consider microlensing effects. (Bottom) Preliminary results from this work using a multi-knot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