■ 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. (2015)). 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 Ia "standard candle" SN (Kolatt & Bartelmann, 1998). The very first multiply-imaged Type Ia 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 including 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 estimates of the lensing parameters, which alone will allow for improved constraints on dark matter modeling parameters. We will improve upon previous work by making substantial improvements to the photometry, and including the significant yet previously ignored effects of microlensing. This reanalysis will define a rigorous methodology that we will use in the case of SN iPTF16geu to attempt the first measurement of H_0 from a lensed SN. Additionally, we will develop open-source software package in the course of this work, optimized specifically for multiply-imaged SNe, that will enable precise measurements to be made for future lensed SNe.

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

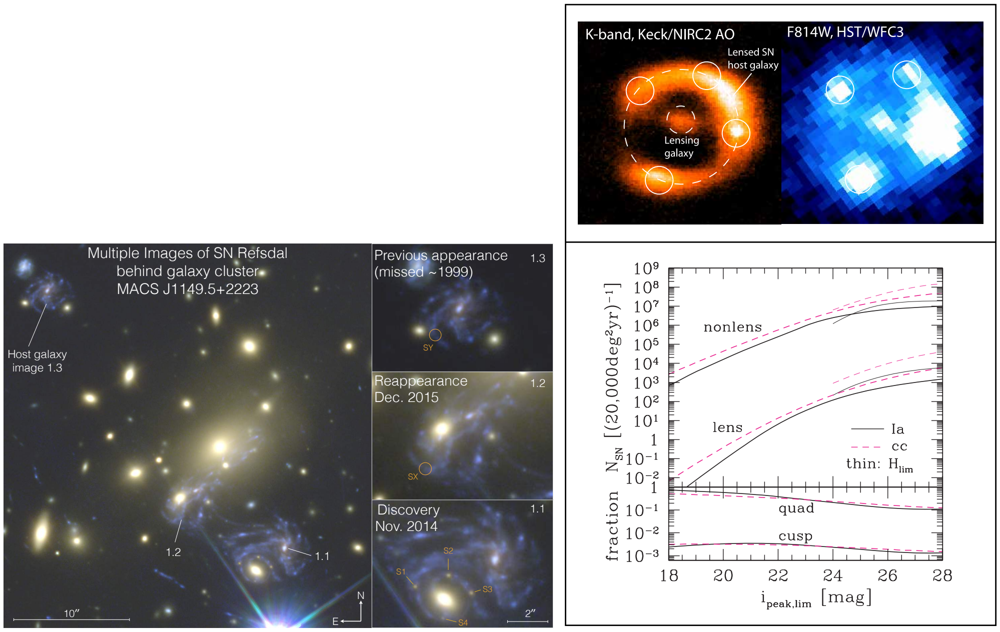

Figure 1: (Left) MACS J1149.6+2223 field, showing the positions of the three primary images of the SN Refsdal host galaxy. SN Refsdal appears as four point sources in an Einstein Cross configuration in the southeast spiral arm of image 1.1 (Rodney et al., 2016). (Right) Expected numbers of SN Ia and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

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 (**?** 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 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.

Management Plan

References

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

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

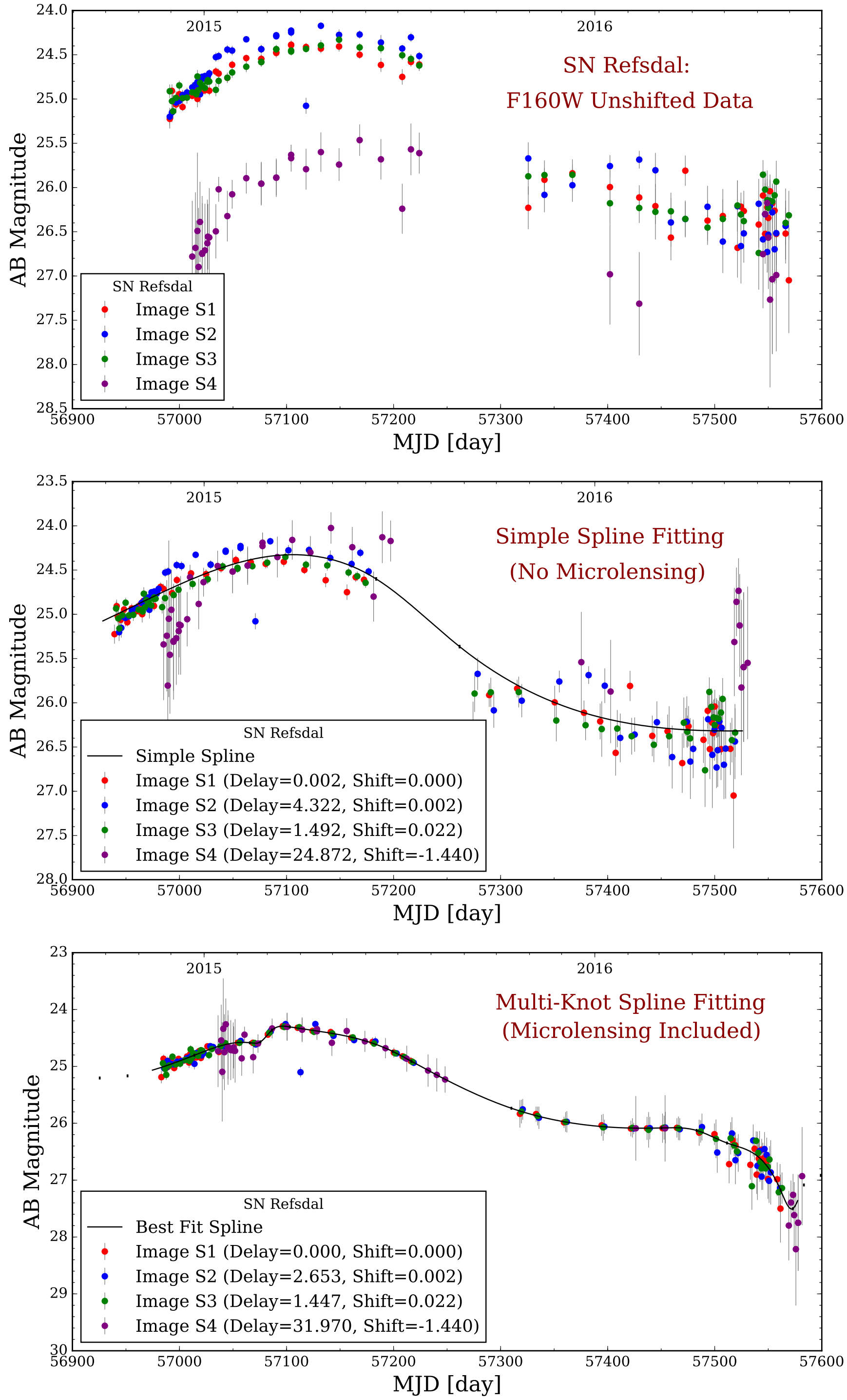

Figure 2: (Top) HST F160W data representing the four images of SN Refsdal (Figure 1), with no lensing or time shifts. (Middle) Method of fitting the SN Refsdal light curves from Rodney et al. 2016, which did not consider microlensing effects. (Bottom) Preliminary results from this work using a multi-knot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