Observing and understanding gravitationally lensed objects is a new and exciting field of study. The first example of a strongly lensed supernova (SN) resolved into multiple images was SN "Refsdal" in 2014 (Figure 1,(1)). Subsequent work was done to classify Refsdal, as well as to measure time delays and magnification ratios (2). To date, there is no optimally designed software package to analyze correlated data sets from multiply imaged lensed SNe and simultaneously determine SN class, time delays, and magnification ratios. The lack of a standard resource leaves researchers to write and implement their own ad hoc programs, which increases uncertainty and decreases efficiency. It's clear that an optimized software package with the ability to analyze a light curve for these and other parameters would be extremely valuable to a wide range of research using current and next generation telescopes.

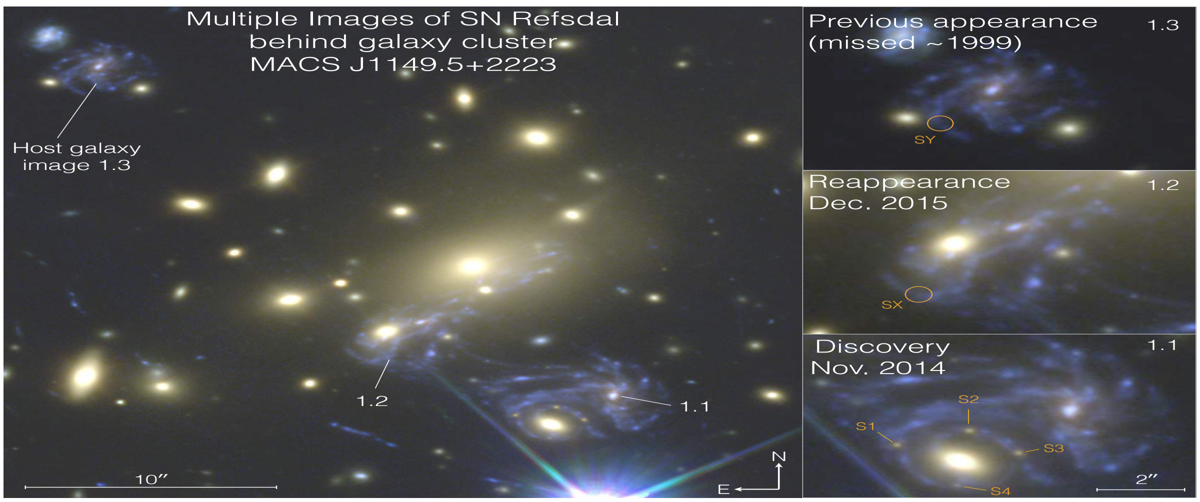

Figure 1: MACS J1149.6+2223 field, showing the positions of the three primary images of the SN Refsdal host galaxy (labeled 1.1, 1.2, and 1.3). SN Refsdal appears as four point sources in an Einstein Cross configuration in the southeast spiral arm of image 1.1 (2)

The purpose of this work is to produce an open-source software package called Supernova Time Delays (*SNTD*) that will address the SN modeling needs of the research community and lead to a first-author publication that furthers our understanding of lensed SNe (Figure 2). There are currently two software packages, written in Python, which are relevant to this product: Python Curve Shifting (PyCS), and Supernova Cosmology (SNCosmo). There will be four components to this research: 1) Integrate SNCosmo and PyCS, giving researchers a tool that can model SN light curve data with the tools present in either software package; 2) Extend and optimize lensing and microlensing algorithm present in PyCS for SNe; 3) Simulate a large number of SN light curves using SNCosmo and test the ability of *SNTD* to determine SN parameters; and 4) Explore the abilities of *SNTD* in analyzing POP III SNe using modeled light curves in anticipation of JWST and WFIRST observations.

While PyCS currently uses flexible functions to account for microlensing of quasars caused by transverse motion of stars in the lensing galaxy, there is a second form of microlensing unique

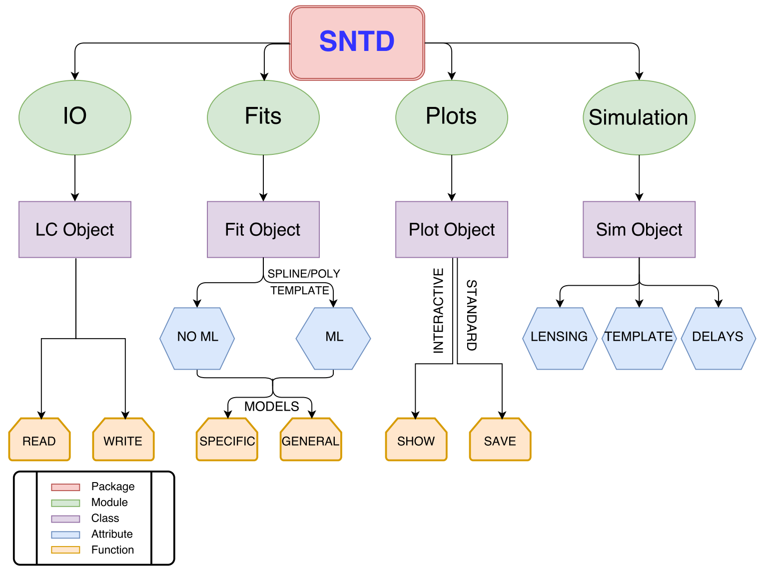

Figure 2: A visual representation of the capabilities of SNTD. The python package will have a simple framework in which each module creates a respective object, which can then be edited by the user. This structure is extremely organized, computationally efficient, and user-friendly.

to lensed SNe. The expanding photosphere of a SN interacts with intervening matter, causing microlensing effects described by Dobler and Keeton 2006a that can exhibit magnitude fluctuations of $\sim$0.2 to >0.5 on timescales of weeks to months. This proposed work has already integrated the flexible function method (Figure 3), and will seek to include both types of microlensing effects to increase the precision of time delay measurements. No software package currently exists with this capability, therefore the algorithm will be developed following the methodology of Dobler and Keeton 2006a. In general, *SNTD* will be much more likely to correctly identify SN microlensing effects and produce simpler time delay measurements because, unlike for quasars, researchers already have a robust set of intrinsic light curve shapes to describe a range of different SN classes that will allow for physically motivated, less flexible models. By allowing certain constraints to float as free parameters, these models will also produce best-fit synthetic light curves, from which time delay, 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.

The era of JWST will yield a drastic increase SN observations at z<5 (4), and WFIRST will arrive shortly thereafter in the mid 2020s. In addition, recent simulations of PI SN light curves indicate that various solar mass PI and POP III Type IIn SNe will be visible to both JWST (z>30 and z$\sim$15 respectively) and WFIRST (z$\sim$20 and z$\sim$5 respectively) (5). Whether it is a follow-up observation of a ground based detection, or a discovery made by one of these space telescopes, having flexible software in place to analyze any SN light curve will be essential to SN cosmologists. We expect this research to yield multiple publications about the methodology of the software itself and the simulation results for low and high redshift SNe, as well as advancements in our understanding of lensed SNe resulting from the use of *SNTD*. There are also plans to use this package for follow-up measurements of SN Refsdal and the PTF Type Ia SN parameters, including the previously ignored microlensing effects. *SNTD* will be written in Python, a free and open-source programming language, and distributed to SN researchers with extensive documentation including descriptive tutorials. This combination will make *SNTD* a free, widely accessible, and invaluable tool in the SN research community.

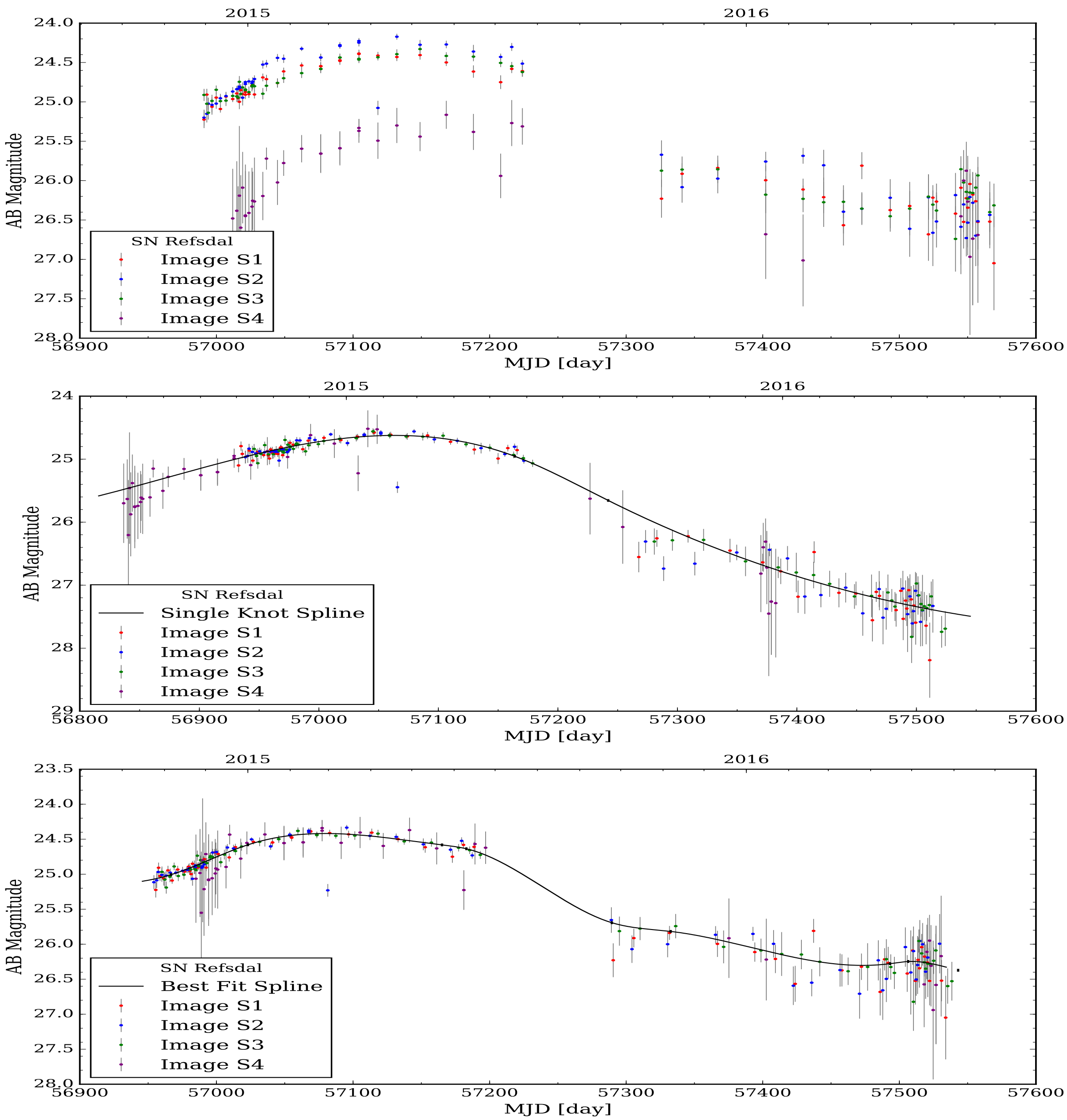

Figure 3: (Top) Colorized are the F160W data representing the four images of SN Refsdal (Figure 1), with no lensing or time shifts. (Middle) Method of fitting the SN Refsdal light curves from Rodney et al. 2016 (Bottom) Preliminary results from *SNTD* using a multi-knot spline to fit the data, with lensing and time delays considered.

Works Cited

1. Kelly, Patrick L, Steven A Rodney, Tommaso Treu, Ryan J Foley, Gabriel Brammer, Kasper B Schmidt, Adi Zitrin, et al. 2015. "Multiple Images of a Highly Magnified Supernova Formed by an Early-Type Cluster Galaxy Lens." Science 347 (6226): 1123-26. doi:10.1126/science.aaa3350.

2. Rodney, S. A., L.G. Strolger, P. L. Kelly, M. Bradac, G. Brammer, A. V. Filippenko, R. J. Foley, et al. 2016. "SN Refsdal: Photometry and Time Delay Measurements of the First Einstein Cross Supernova" The Astrophysical Journal 820 (1): 50. doi:10.3847/0004-637X/820/1/50.

3. Dobler, Gregory, and Charles R Keeton. 2006. "Microlensing of Lensed Supernovae." Astrophysical Journal.

4. Mesinger, Andrei, and Benjamin D Johnson. 2006. "The Redshift Distribution of Distant Supernovae and Its Use in Probing Reionization", 80-90.

5. Magg, Mattis, Tilman Hartwig, Simon C O Glover, Ralf S Klessen, and J Whalen. 2016. "A New Statistical Model for Population III Supernova Rates?: Discriminating Between Λ CDM and WDM Cosmologies" 12 (June): 1-12.