It has been over half a century since renowned astrophysicist Sjur Refsdal first hypothesized the use of a supernova (SN) resolved into multiple images as a cosmological tool. In recent years, the first multiply-imaged core-collapse (CC) SN Refsdal (Kelly et al., 2015), and subsequently the first Type Ia SN iPTF16geu (Goobar et al., 2016), have been discovered (Figure 1A-C). 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 (for cluster-scale lenses). For objects like SN Refsdal, measurement of this time delay can be used as a precise test of cluster lens models (Treu & Ellis, 2015). For a SN like iPTF16geu, the time delay can lead to a **direct constraint on the Hubble constant** H_0, that is completely independent of the local distance ladder. The next decade is expected to yield observations of tens to hundreds of multiply-imaged SNe (Oguri & Marshall, 2010), yet there is no public software package for analyzing multiply-imaged SNe.

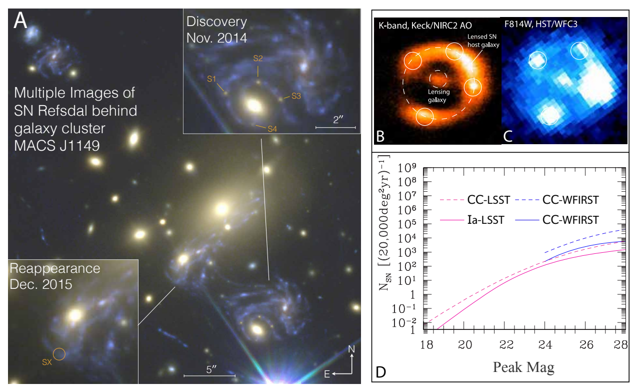

Figure 1: (A) MACS J1149.6+2223 field, showing the positions of the three primary images of the SN Refsdal host galaxy. SN Refsdal appears as four point sources in an Einstein Cross configuration in the southeast spiral arm of image 1.1. (B) HST/WFC3 observation of iPTF16geu, revealing four point sources and (C) NIR Keck observation, with the Einstein ring of the host galaxy clearly visible, adapted from Goobar et al. (2016). (D) Expected numbers of Type Ia and Core Collapse SNe for LSST ($i_{peak,lim}$) and WFIRST ($H_{peak,lim}$), adapted from Oguri & Marshall (2010).

Intellectual Merit : As the PI on an ongoing HST Archival Research Grant, **I am developing the first open-source software package** in Python (*Supernova Time Delays* [SNTD]) that will enable a user to precisely measure lens properties and time delays for the hundreds of multiply imaged SNe expected in the LSST/WFIRST era (Figure 1D). Properties of dark energy and dark matter are still poorly understood and inadequately constrained, but measurement of the lensing magnification and time delays can be used to test models for the dark matter distribution in the lensing object (Rodney et al., 2015, 2016) or as a probe to test cosmological models (Suyu et al., 2014). To that end, I will first use SNTD to make more precise time delay measurements for the two currently documented multiply imaged SNe. SN iPTF16geu is Type Ia, so by providing a more accurate time delay and luminosity distance measurement, I will be able to accomplish two critical goals. First, directly measuring the source magnification will provide an important milestone in breaking degeneracies in the lens model (Kolatt & Bartelmann, 1998; Oguri & Kawano, 2003). Second, precise determinations of the time delays for a multiply imaged Type Ia SN will provide a constraint on H_0, and the methodology and software I develop will be **essential to future SN surveys** for tightening those constraints. Between SN iPTF16geu and SN Refsdal, I will be able to validate SNTD and the methodology I am developing for time delay measurements, and provide these tools for the next generation of observations with JWST, WFIRST, and LSST.

Observations either by way of gravitational lensing, or by the next generation telescope JWST, will provide a sample of extremely high redshift SNe (Figure 2). Of interest in the early universe are pair-instability (PI) and Population III (Pop III) SNe. **Understanding these first stars is crucial to a wide range of cosmology, including the formation of primeval galaxies, initial stages of cosmological reionization, and the origin of Supermassive black holes** (Whalen et al., 2013).Therefore, I will collect a sample of current high-z and gravitationally lensed SNe, and begin discerning the properties of these first stars. In addition to searching for, and studying the physics of PI and Pop III SNe, I will include theoretical light curve templates for both objects in the open-source software I am developing, so that future observations can be identified and both lens properties and progenitor physics studied. Not all SNe found and analyzed will be strongly lensed and valuable for identifying lens and dark energy properties or dark matter distribution. Therefore, I will also collect a sample of these weakly lensed SNe, and carefully measure their magnification in order to make small corrections in the Hubble diagram.

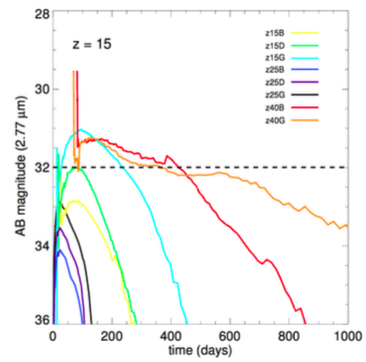

Figure 2: JWST will measure light curves for some of the earliest SN explosions in the universe. Colored curves depict theoretical explosions from Pop III SNe, and a dashed horizontal line shows the nominal detection limit for JWST. These simulated light curves show that these first stars are detectable by JWST, which makes their inclusion in SNTD essential to future work(Figure adopted from Whalen et al. 2013b).

Research Summary: First, I will complete the python software package SNTD, and write a publication presenting its capabilities and validation. Next I will perform the reanalysis of SN Refsdal and SN iPTF16geu using SNTD, writing a second publication presenting the more precise time delay measurements, detailing the methodology required for these analyses, and obtaining a constraint on H_0 from iPTF16geu. Finally, I will add theoretical light curves for PISN and POP III SNe to the SNTD package, and obtain a gravitationally lensed SN sample to study the physics of these first stars. With the weaker lensed objects, I will perform Hubble diagram magnification adjustment. From this last component of my research, I will complete two further publications: one describing magnification corrections for Hubble diagram SNe and their affect on H_0, and the other the detailing search for, and ideally discovery of, PISNe and POP III SNe and their physical properties. These four publications will be a clear measure of the success of this work, and the software and methodologies developed during the course of my research will be crucial tools for future work using the next generation of space telescopes.

Broader Impacts Summary: The SNTD software package will be a crucial tool in years to come, as the next generation of telescopes drastically increases our catalogue of multiply imaged SNe. Improving our understanding of the first stars will be essential to various branches of cosmology such as the origin of supermassive black holes, and I will pave the way for future PISN and POP III SN observations by including their theoretical templates in SNTD, and search for the first POP III SN observation by forming a sample of strongly lensed SNe. Finally, by documenting SNTD and my improved measurement of the Refsdal and iPTF16geu time delays, I will provide a constraint on H_0 and a standardized methodology that will be used for future SN observations to tighten constraints on H_0 and dark energy properties.

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