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 [1], and subsequently the first Type Ia SN iPTF16geu [2], 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). The next decade is expected to yield observations of tens to hundreds of multiply-imaged SNe [3], yet there is no public software package for analyzing multiply-imaged SNe.

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). I will use SNTD to make more precise time delay measurements for the two currently documented multiply-imaged SNe. Properties of dark energy and dark matter are still poorly understood and inadequately constrained, but accurate measurements of the lensing magnification and time delays for SN Refsdal can be used to test models for the dark matter distribution in the lensing object [4, 5] or as a probe to test cosmological models [6]. As SN iPTF16geu is Type Ia, providing more accurate time delay and luminosity distance measurements will accomplish two critical goals. First, directly measuring the source magnification will provide an important milestone in breaking degeneracies in the lens model [7, 8]. Second, precise determinations of the time delays for a multiply-imaged Type Ia SN will provide a measurement of the Hubble constant H_0 that is completely independent of the local distance ladder, and the methodology and software I develop will be **essential to future SN surveys** for tightening those constraints.

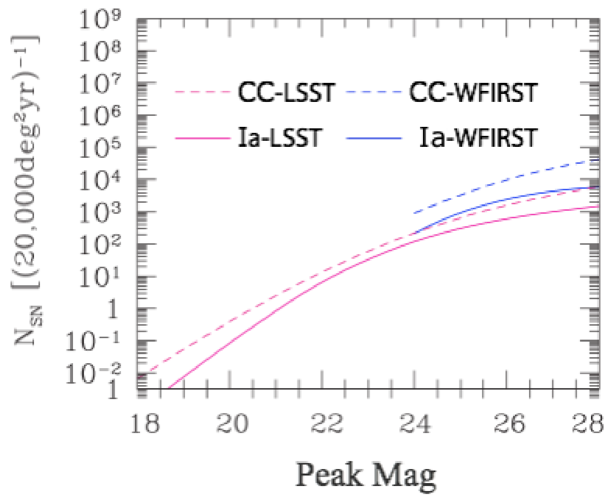

Figure 1: Expected numbers of lensed SNe Ia and Core Collapse SNe for LSST ($i_{peak,lim}$) and WFIRST ($H_{peak,lim}$) after one year of observations. With this huge volume of lensed CC and Ia SNe observations expected in the next decade, the open-source SNTD package will be widely used and essential for analyzing this large WFIRST/LSST SN sample (adapted from Oguri & Marshall 2010 [3]).

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, as **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** [9]. Therefore, I will collect a sample of high-z and gravitationally lensed SNe, and begin discerning the properties of these poorly understood objects via powerful lensing. With the SNe identified as weakly lensed, I will produce careful magnification measurements and make small corrections to the Hubble diagram. In addition to searching for PI and Pop III SNe and studying their physical properties, I will include theoretical light curve templates for both objects in SNTD, so that future observations can be identified and both lens properties and progenitor physics studied.

<u>*Research Summary*</u>: 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 adjustments. 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 detailing the 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 vital for future work using the next generation of space telescopes.

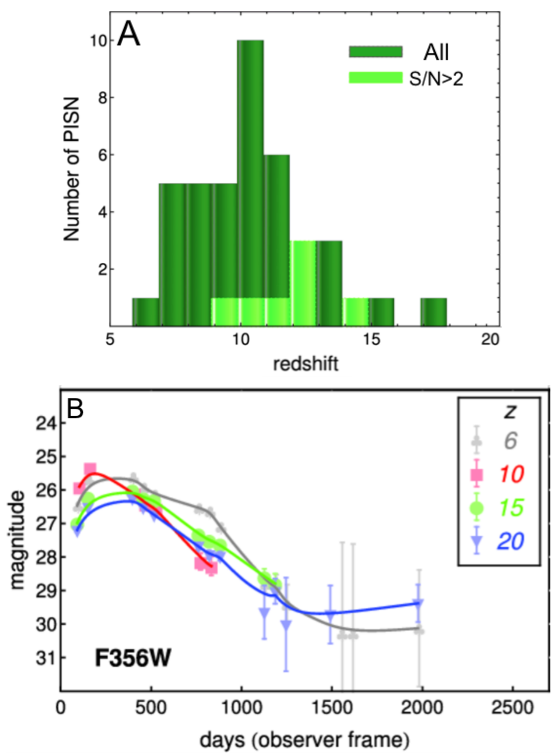

Figure 2: (A) Histogram showing the dozens of expected PISN observations as a function of redshift for a single JWST survey realization, covering 0.06% of the sky over the course of 5 years. (B) Colored curves depict simulated JWST NIRCam PISN observations in the F356W filter. These light curves show that the PISNe will be visible for thousands of days, making observations extremely likely in each field, which makes their inclusion in SNTD essential to future work with JWST (Figures adapted from Souza et al. 2013 [10]).

<u>*Broader Impacts Summary*</u>: Due to my academic experience at a young age, I am committed to ensuring that no child's love of astronomy will go unfostered in my community. It is crucial that childen who love STEM, and specifically astronomy, are reinforced that this is a valid future career and that a graduate degree is possible for them. Growing up in rural Maine, graduate degrees were few and far between, and even the percentage of high school graduates attending a 2-4 year college was only around 50%. In my current community within Columbia, SC according to City-Data.com, **only** 27% **of people graduated from high school,** 13% **have a bachelor's degree,** 3% **have a master's degree, and** 0% **have a PhD.** I will use my STEM outreach experiences with NASA's ARSET program, as well as the techniques I learned volunteering in elementary school math classrooms in college and tutoring high school students while at Goddard, to help foster excitement for STEM in my community. I have already discussed

my plans with the local after-school program leader, who was very excited to implement a framework to encourage astronomy and STEM learning. By taking kids to our local University observatory, and leading them through a series of exciting and educational astronomical exercises throughout the year, I hope to convince these students that **achieving higher degrees is possible and valuable**, and break the viscious cycle of supressed academic opportunities forming in my community.

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