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. 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). These gravitationally lenses are also important tools for observing pair-instability (PI) and Population III (Pop III) SN in the early universe (high-z), as **understanding these first stars is crucial to a wide range of cosmology including the formation of primeval galaxies and the origin of supermassive black holes**[3]. As 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 be essential to making precise measurements of lens properties and time delays for the hundreds of multiply-imaged SN observations expected over the next decade (Figure 1). My research will have two major components: 1. Using SNTD and multiply-imaged SN as a cosmological probe. 2. Observing and understanding the physical properties of very high-z PI and POP III SN.

<u>*Intellectual Merit*</u> : After completing SNTD, I will use the software to make more precise time delay measurements for the two currently documented multiply-imaged SN. 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[5;6] or as a probe to test cosmological models[7]. As SN iPTF16geu is Type Ia, achieving more accurate measurements will provide both an important milestone in breaking degeneracies in the lens model and a result for the Hubble constant H_0 that is completely independent of the local distance ladder[8;9]. The methodology and software I develop will be **critical to future SN surveys** for analyzing multiply-imaged SN and tightening the constraints found in the course of this work.

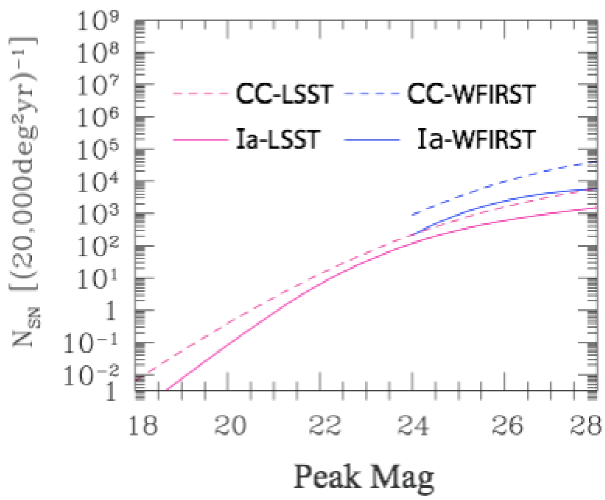

Figure 1: Expected numbers of lensed SN Ia and Core Collapse SN for LSST ($i_{peak,lim}$) and WFIRST ($H_{peak,lim}$) after one year of observations. With this huge volume of lensed CC and Ia SN observations expected in the next decade, the open-source SNTD package will be widely used and essential for analyzing this large WFIRST/LSST SN sample (adapted from Oguri & Marshall 2010[4]).

Over the next 2 years, working with my advisor Dr. Steven Rodney, I will be able to search for high-z and strongly lensed SN in the 101-orbit HST program BUFFALO, which will image the massive galaxy clusters of the Hubble Frontier Fields that have delivered three of the most prominent examples of strongly lensed transients: SN Refsdal[1], the HFF14Spo transients[10], and the lensed star M1149-LS1[?] . Beginning in 2019, I will be collaborating with the team of Dr. Rogier Windhorst on the JWST Guaranteed Time Observations (GTO) program 1176. This program will apply 110 hours of cadenced imaging on massive galaxy clusters as well as a deep field at the North Ecliptic Pole. This could deliver between 1 and 10 high-z detections of PISN[11](Figure 2A). I will include theoretical light curve templates for both Pop III and PI SN in SNTD, so that future observations can be identified and both lens properties and progenitor physics studied.

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 PI and POP III SN to the SNTD package, and utilize the BUFFALO (HST) and GTO 1176 (JWST) programs to study the physics of these first stars. From this last component of my research, I will complete two further publications: one detailing the catalog of PISN and POP III SN and their physical properties, and the other making lens and time delay measurements for any strongly lensed or multiply-imaged SN discovered. These **four publications**, as well as the vetting and extensive use of the open-source SNTD package by the entire community in future work with the next generation of space telescopes, will be **clear measures of the success of this work.**

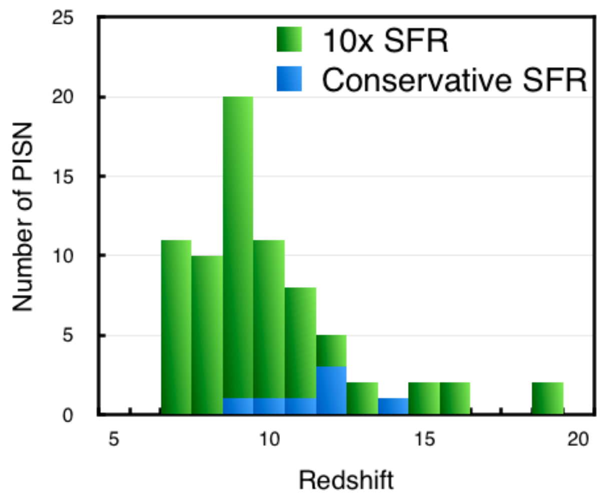

Figure 2: Histogram showing the dozens of expected PISN observations as a function of redshift for a single JWST survey realization, covering 0.06% of the sky. Roughly 7 or 73 PISN observations with S/N>2 are expected per field when conservative and 10× star formation rates (SFR) are used respectively, over the course of 5 years. Therefore, we expect roughly 1-10 PISN observations during the GTO survey (Figures adapted from Souza et al. 2013[11]).

Broader Impacts: I will use my previous STEM outreach experiences (see personal statement) to **increase the participation of young students in astronomy and other STEM fields from a community comprised of 88% minorities underrepresented in STEM.** My research is a terrific gateway into STEM because it is naturally exciting and interesting: space telescopes, pictures of galaxies, exploding stars, and gravitational lensing are surefire topics to capture the attention and imagination of a young learner, and I have already created a plan with the local after-school program leader. First, I will take the kids to our local University observatory and lead them through a series of exciting and educational astronomical exercises. Once I have garnered their attention and enthusiasm, I will have each student work on a relatively simple astronomy project with me and at home, and then present their results to community members. By creating a passion for STEM and having participants choose and investigate a research question, this outreach program will **improve the well-being of the students by encouraging higher learning in STEM, and increase public scientific literacy and public engagement with STEM** by teaching the students and engaging the parents via the research projects and presentations.

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