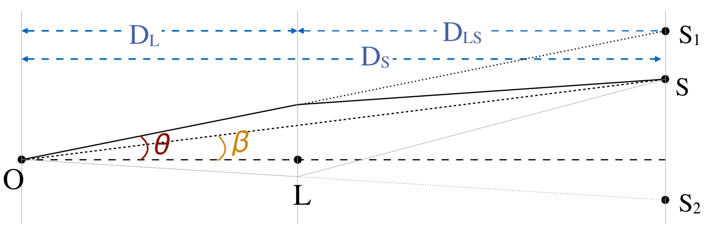
## ■ Scientific Justification

Exactly fifty years ago, Refsdal (1964) first imagined the use of multiply-imaged supernovae (SNe) to measure the Hubble constant, $H_0$, through time delay cosmography (see inset, below). Over the intervening 5 decades, no multiply-imaged SN has been found. With this program we propose to use a WFC3-IR snapshot survey of strong lensing galaxy clusters, providing the first truly viable opportunity to find a multiply-imaged SN. This project is newly possible with HST because we can now capitalize on a treasury of well-studied strong lensing clusters with deep WFC3-IR template imaging. This provides the critical advantage that we can detect SN at $z \sim 2$ where we have a large sample of known multiply-imaged galaxies in an era when the universe was near peak efficiency for generating SN explosions.

**The First Multiply Imaged SN:** After several decades of substantial effort and slow progress, the time delay field is now rapidly maturing (see Jackson, 2007; Treu, 2010, for recent reviews). There already exists a sample of ∼20 time delay measurements for multiply-imaged *quasars*, which are typically lensed by a single foreground galaxy, with only a few that are known to be lensed by galaxy clusters (Inada et al., 2003, 2006; Oguri et al., 2008; Dahle et al., 2013). As techniques for measuring the time delay $\Delta t$ and modeling the lensing potential $\psi$ have improved, there are now a few of these lensed quasars that can jointly deliver an $H_0$ constraint with ∼6% precision (e.g. Suyu et al., 2010, 2013). Additionally, time delay distances provide an especially powerful check for unknown systematics, because each separate time delay measurement can be individually quite precise and largely independent of the rest of the sample (Suyu et al., 2013; Treu et al., 2013).

A measured time delay from even a single multiply-imaged SN would be a valuable addition, and would provide a critical first step towards future samples with over 100 SN time delays in the




**Time Delay Cosmography:** As light from a distant source passes through a gravitational lens, each subsequent image will appear to the observer delayed by

$$\Delta t = \frac{(1+z_L)}{c}\frac{D_L D_S}{D_{LS}}\left(\frac{1}{2}(\theta-\beta)^2 - \psi(\theta)\right) \qquad (1)$$

(relative to the unlensed travel time). Here, $z_L$ is the redshift of the lens, while $D_L$, $D_S$, and $D_{LS}$ are angular diamater distances from the observer to the lens, observer to source, and lens to source, respectively. The time delay has a geometric component due to light rays following different path lengths to the observer, plus a general relativistic component, $\psi$, due to differing values of the gravitational potential along each path. The distance ratio $D_L D_S / D_{LS}$ in Eq. 1 carries a factor ${H_0}^{-1}$, so if the lensing potential $\psi$ 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.***

JWST/LSST era. Additionally, if the lensed SN is of Type Ia (a likely prospect for our survey strategy), then light curve fitting can provide a luminosity distance measurement with ∼8% precision (e.g. Phillips, 1993; Jha et al., 2007). With a known luminosity distance, the source magnification can be directly measured, providing powerful additional leverage for breaking degeneracies in the lens model (Kolatt & Bartelmann, 1998; Oguri & Kawano, 2003). Finally, a lensed SN discovered with this program could easily be among the most distant SNe ever seen, very valuable in its own right.

**How many SNAPs?** To estimate the number of snapshots we need, we start with an optimized list of target clusters (Table **??**). We then tabulate all the known multiply-imaged galaxies behind those clusters. These are our potential SN host galaxies, and we count each separate image of a multiple-image set except the last one (one cannot measure a time delay from the last appearance). The time delay between each image is of order months or years, so each snapshot visit is essentially observing the same galaxy at several widely-spaced epochs that can be treated as independent. We then limit this list to count only those image pairs that would have a time delay of $\Delta t$<5 years leaving us with an average of ∼ 15 potential lensed SN host galaxies per cluster.[1]

For each lensed galaxy, we can then compute the total number of detectable core collapse (CC) and Type Ia SN (SN Ia) per snapshot as

$$N_{\rm det} = (SNR_{Ia} \cdot t_{vis,Ia} + SNR_{CC} \cdot t_{vis,CC})(1+z)^{-1}, \tag{2}$$

where SNR is the SN explosion rate per year (separately computed for each galaxy and segregated by SN type), $t_{vis}$ is the fraction of a year that an average SN is brighter than our snapshot detection limits (see Table 1, below), and the factor of $(1+z)^{-1}$ corrects for time dilation at the redshift of the galaxy. Using simulated SN light curves in 240 multiply-imaged galaxies (Figure 2), we find an average $t_{vis} \sim 30$ days for SN Ia and ∼20 days for SN II.

To estimate SNR$_{Ia}$, we start with the volumetric SN rate as a function of redshift, SNR$_{Vol}$, as measured out to $z \sim 2.5$ (Graur et al., 2014; Rodney et al., 2014). Dividing by the measured cosmic luminosity density (Reddy & Steidel, 2009), we convert this volumetric rate to a SN rate per unit B-band luminosity SNR$_B$. We then multiply by the observed luminosity of each galaxy to get SNR$_{Ia}$ for Eq. 2.

For core collapse SN, which are even more tightly correlated to star formation than are SN Ia, we use the observed rest-frame UV luminosity to define each galaxy's star formation rate, using $SFR = 9.3 \times 10^{-29} \cdot L_{UV}$ M$_\odot$yr$^{-1}$ (Dahlen et al., 2007), and then convert to SN rate using $SNR_{CC} = 0.007 \cdot SFR$, as appropriate for a Schechter luminosity function and consistent with observations (Dahlen et al., 2012).

Folding in these values for all multiply-imaged galaxies in a representative sample from

[1]Note that this computation of the SN yield by counting known galaxies is a relatively conservative approach. It is quite possible to detect a multiply-imaged SN even if the host galaxy remains undetected. Such apparently "hostless" SN could boost our actual probability of a successful detection by as much as ∼20%.

our target list of clusters, we find $N_{det} = 0.01$ SN discoveries per snapshot observation.[2]. This means that we need only ∼100 executed snapshots to have a good chance at catching the first ever multiply imaged SN. Factoring in an anticipated execution fraction of ∼30%, we request 300 snapshots to deliver this valuable cosmographic tool.

## Description of the Observations

In Cycle 22, HST has just achieved a new capability for the discovery of a multiply-imaged SN. Three key ingredients will make this program feasible for the first time in this cycle: (1) the use of WFC3-IR, (2) a SNAP survey strategy with repeated shallow visits over many clusters, and (3) a carefully optimized target list of clusters with both IR template imaging and excellent mass models.

Table 1: SNAP Detection Limits

| WFC3/IR Filter | Exp.Time [min] | $m_{lim}$ * [AB mag] |
|---|---|---|
| F110W | 12 | 26.3 |
| F110W | 20 | 26.6 |
| F110W | 30 | 26.9 |
| F140W | 12 | 25.9 |
| F140W | 20 | 26.2 |
| F140W | 30 | 26.5 |

* Apparent magnitude that yields S/N of 5 (optimum S/N∼10) in the given exposure time.

**1. WFC3-IR:** Ground-based surveys and even HST/ACS programs have looked for lensed SN (e.g. Sharon et al., 2007; Dawson et al., 2009; Sharon et al., 2010; Sand et al., 2011), but none of these have had the capability to detect SN at $z \sim 2$, even with substantial magnification, so many multiply-imaged galaxies were effectively unreachable to them. Amanullah et al. (2011) demonstrated the value of searching for high-$z$ SN at IR wavelengths, where one samples rest-frame optical bands at the peak of the SN SED. Using a K-band survey from the VLT with HAWK-I[3] they discovered of a lens-magnified SN at $z \sim 1.7$ behind the galaxy cluster Abell 1689. With the CANDELS and CLASH programs, we have taken this IR search strategy above the atmosphere, showing that WFC3-IR is capable of discovering even un-lensed SNe at $z > 1.5$ (Rodney et al., 2012; Jones et al., 2013), and finding three more lens-magnified SNe (Patel et al., 2013; **?**). The ongoing Hubble Frontier Fields (HFF) program (PI:Lotz) is gathering deep WFC3-IR imaging of 6 galaxy clusters, and with our multi-cycle GO program (PI:Rodney) we have already found 8 SN in the HFF data, including 2 with significant magnification. However, all of these magnified SN are too far away from the cluster center to be multiply-imaged.

**2. Snapshots:** A primary reason that recent WFC3-IR surveys have not found any multiply-imaged SN is because they are optimized for depth and wavelength coverage instead of cadence. CLASH, for example, collected WFC3-IR imaging of 25 clusters over 3 years, but many orbits were allocated to ACS and WFC3-UVIS, and the time separation between the first and last IR image on any single cluster was typically only ∼40 days. Thus, in practice

[2]Note that this predicted yield is unchanged if we instead use observed SN rates from the local universe (e.g. Mannucci et al., 2005; Li et al., 2011), appropriately scaled to account for the increased star formation at $z \sim 2$

[3]VLT: Very Large Telescope; HAWK-I: High Acuity Wide-field K-band Imager

each cluster only had one epoch suitable for a lensed SN search, making any detection extremely unlikely. The HFF program only exacerbates this problem, by drilling even deeper on a much smaller number of clusters. However, CLASH, HFF and other programs have now provided deep IR template imaging of many massive clusters from which to construct difference images for SN discovery.

Our snapshot program will capitalize on this rich archival treasury by delivering hundreds of shallow visits across ∼25 clusters. We will use snapshots with 12, 20 and 30 minutes of total exposure time to provide maximal flexibility for scheduling. The stochastic snapshot scheduling process will typically ensure that our visits are spread over a long time baseline, maximizing our chance of catching a new multiply-imaged SN in action. However, if multiple snapshots on the same cluster do get scheduled together, then the added depth simply makes that epoch more sensitive to faint SN. We will use a mix of F110W and F140W snapshots so that same-epoch snaps will also provide some minimal color information that can aid in preliminary SN classification. Anticipated detection limits are given in Table 1, and Figure 2 shows that our snaps will be deep enough that SN Ia will be visible for long periods in most of the lensed galaxy images for our sample.

**3. Cluster Target Selection:** The HST archive now holds a deep trove of ACS and (most notably) WFC3-IR imaging on strong-lensing galaxy clusters at redshifts $z \sim 0.2-0.7$. This valuable data set has led to an explosion of high quality cluster lens models, thanks to much effort in supplemental observations and modeling (e.g. Kneib et al., 2004; Smith et al., 2005; Limousin et al., 2008; Bradač et al., 2008; Richard et al., 2009). Co-PI Zitrin has had a leading role in this recent burst, principally through the light-traces-mass (LTM) lens modeling technique, which particularly excels with its predictive power for the discovery of multiply-imaged galaxies (Broadhurst et al., 2005; Zitrin et al., 2009b). Through the CLASH program, this approach has been used to generate precise mass models for a few dozen clusters, dramatically expanding the number of strong lensing clusters with many known multiple-image systems (e.g. Zitrin et al., 2009b,a, 2011a,b,c; Merten et al., 2011; Zitrin et al., 2012a,b, 2013b,a; Coe et al., 2012, 2013). The quality of our lens models will translate directly into the uncertainty in our determination of $H_0$. We find that reaching ∼10% precision on $H_0$ is a very plausible benchmark (Figure **??**), consistent with past estimates (Bolton & Burles, 2003; Oguri & Kawano, 2003; Riehm et al., 2011).

To build our target list, we have taken into account the trade-off between the number of lensed galaxies and the length of their time delays. Very massive clusters will generally provide more multiply-imaged background galaxies that could host a SN during our survey. However, very massive clusters will also on average yield time delays which are too long to be of practical use hard to measure on a reasonable time scale ($\Delta t$ can be $\sim 10^{2-3}$ years). In some cases only $\sim 20\%$ of the multiple-image pairs behind these monster lenses would yield desirable time delays on the scale of months to years. Therefore, the optimal cluster lens targets are medium-to-large lenses with Einstein radii of roughly $\sim 10 - 30''$. There is also some dependence on the exact structure and redshift of the lens, but as a rule of thumb such lenses will each have about $\sim 10 - 40$ multiple galaxy images with useful time delays.

Table **??** presents our list of 25 cluster targets, which are spread across the sky to optimize snapshot observability. The list is dominated by moderate-to-large lenses, but supplemented with some more massive clusters that contain more multiple images.

## Special Requirements

This snapshot program is designed exclusively for SN discovery. Follow-up observations will come from an accompanying GO program (PI: Strolger), which should be evaluated in concert with this proposal.

## Justify Duplications

This program necessarily re-visits fields with substantial HST imaging. We rely on the existing WFC3-IR data to provide template imaging for SN discovery.

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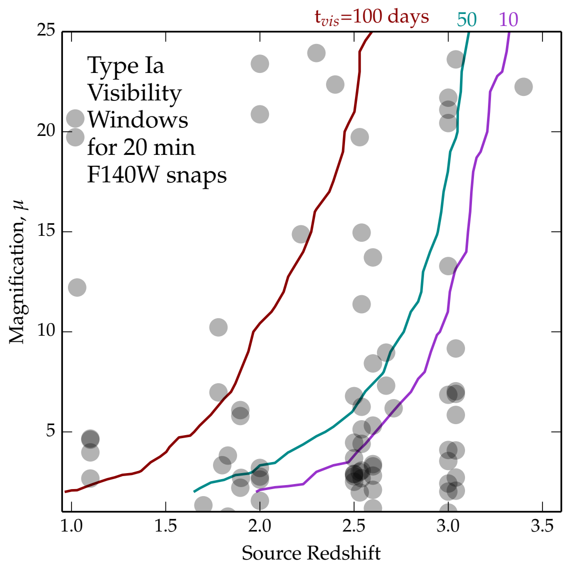


Figure 1: Visibility time contours in the redshift-magnification plane. For any given redshift and magnification, we estimate $t_{vis}$, the number of days that an average SN Ia would be detectable in a 20-minute snapshot. Solid lines plot contours of constant visibility time in the $z - \mu$ plane at $t_{vis}$ =100, 50, and 10 days. Grey circles mark the magnifications and redshifts for 50 strongly-lensed galaxy images from three of our primary cluster targets. Thus, if a galaxy lies to the left of the 50-day line, then it is visible to our survey for at least 50 days.

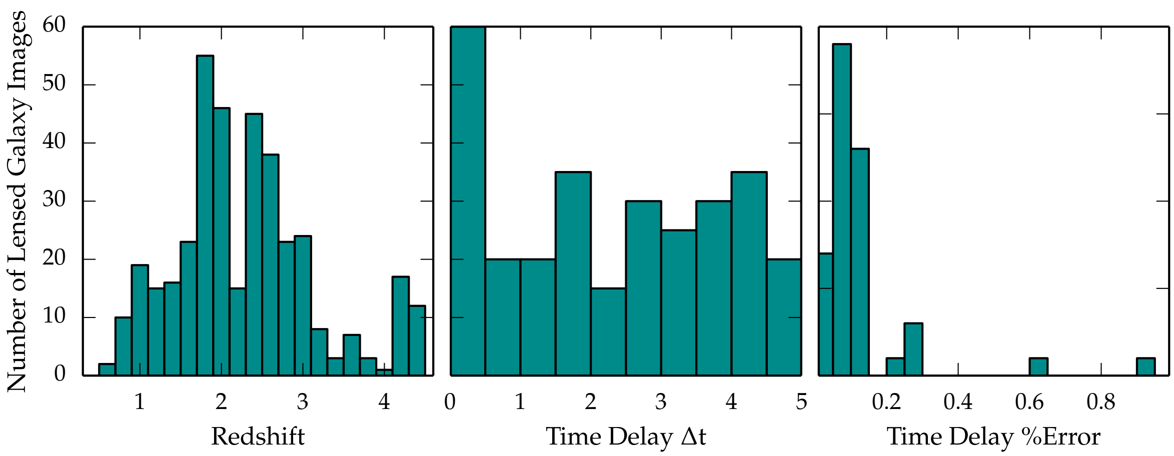


Figure 2: Histograms showing the distribution of a representative sample of lensed galaxy images over redshift (left), time delay (middle) and time delay precision (right).

## Past HST Usage

Table 2 lists the HST programs from recent cycles that include one or both co-PIs Rodney and Zitrin.

Table 2: Past HST Usage for co-PIs

| PID | Title | Selected Publications |
|---|---|---|
| 12060-64 | CANDELS | Grogin et al. 2011 |
| 12440-45 | | Trump et al. 2011 |
| | | van der Wel et al. 2011 |
| 12065-69 | CLASH | Postman et al. 2012 |
| 12100-04 | | Coe et al. 2013 |
| 12451-60 | | |
| 12099 | CANDELS+CLASH SN Follow-up | Rodney et al. 2012 |
| 12461 | | Graur et al., 2014 |
| 13063 | | Rodney et al., 2014 |
| 13046 | RAISIN | ... |
| 13279 | Characterizing the Young Galaxies at Cosmic Dawn | Zheng et al., 2014 |
| 13317 | Infrared Grism Confirmation of a Strongly Lensed z$\sim$11 Candidate: MACS0647-JD | Coe et al., 2013 |
| 13386 | Frontier Field Supernova Search | ... |
| 13236 | Galaxy Evolution at the Frontier | ... |
| ... | Frontier Fields Map Making | Zitrin & Merten (2013) |