■ Scientific Justification

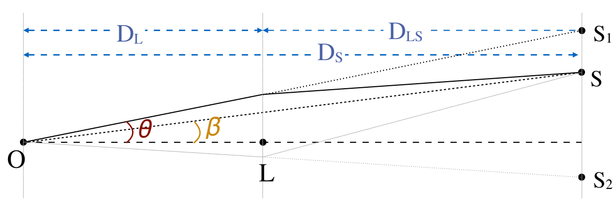
With this snapshot program, we propose to use HST's WFC3-IR detector to discover the first multiply-imaged SN behind a strong lensing galaxy cluster, setting the gold standard for future strong lensing time delay measurements. In recent years HST programs such as CLASH and the Hubble Frontier Fields have built up a deep trove of WFC3-IR imaging on strong-lensing galaxy clusters at redshifts $z \sim 0.5$. Many of these clusters have dozens of multiply-imaged background galaxies at redshifts $1 \lesssim z \lesssim 6$, which have been used to produce well-constrained models of the cluster lensing potential. When a SN inevitably appears within one of these multiply-imaged galaxies, it will of course be multiply-imaged itself. With that SN we could measure a time delay distance with better than 6% precision, providing a unique and powerful constraint on H_0 and dark energy. With deep template imaging for over 25 rich clusters in hand, ***we now have a viable pathway to discover the first ever multiply-imaged SN with a small, single-cycle snapshot program.***

Time Delay Cosmography

As light from a distant source passes through a galaxy cluster, strong gravitational lensing causes multiple images to appear to the observer, with a time separation between the images given by

$$\Delta t = \frac{D_L D_S}{c\, D_{LS}}(1+z_L)\phi \qquad (1)$$

$$\phi = \frac{1}{2}(\theta-\beta)^2 - \psi(\theta) \qquad (2)$$



where the redshift of the lens is z_L, 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 potential, ϕ, is given in Eq. 2. The first term gives the geometric delay due to light rays following different path lengths to the observer, and the second term, ψ, is the relativistic component due to differing values of the gravitational potential along each path.

Each of the distances in Equation 1 carries a factor of $H_0{}^{-1}$, so if the lensing potential ϕ is well known, then a time delay measurement provides a direct measurement of the Hubble constant. The distance ratio $D_L D_S / D_{LS}$ also has unusual sensitivities to cosmological parameters as a function of redshift that make this technique a particularly useful probe of dynamic dark energy models (**?**).

? first proposed the use of SN time delays as a means to measure H_0. Now 50 years later, this has not yet been achieved, primarily due to the small number of very well analyzed gravitational lenses (∼dozens), and the short visibility window for any given high-z SN event (∼a few weeks). Only recently have we begun to realize the potential in this technique with the recent measurement of a few dozen time delays of quasars, being lensed typically by a single foreground galaxy (**?**). Among these, only a handful have time delays measured with particularly high precision (**??**, e.g.). These quasar lenses generally suffer from a number of serious concerns, notably: (1) the lensing potential is poorly constrained due to inherent degeneracies and insufficient constraints; (2) the time delays and angular separations are quite small (tens of days, fractions of an arcsecond); and (3) the source is continuously variable, requiring many years of stable monitoring to resolve phase degeneracies. Wide-field surveys in the coming decade could deliver >100 quasar time delays, but these problems represent unavoidable systematic biases for this sample.

The SN Time Delay Advantage

In Cycle 22, HST has just achieved a new capability for the discovery of a strongly-lensed SN. The first key advancement was the availability of WFC3-IR, which allows HST imaging surveys to capture high-z SN at the peak of their SED profile in rest-frame optical bands (**??**). Ground-based surveys and even HST/ACS programs have searched for multiply-imaged SN in the past, but none have had the capability to detect even highly magnified SN at $z > 2$ (e.g. **??**). With WFC3-IR, *Hubble* now has access to a much larger survey volume with each pointing.

A WFC3-IR program targeting massive clusters, such as CLASH or the Hubble Frontier Fields, could in principal have caught a strongly lensed SN already, but in practice the likelihood of such a find was vanishingly small. The CLASH team collected WFC3-IR imaging of 25 clusters over 3-years, but the time separation between the first and last image on any single cluster was never more than a few months. However, these programs – along with other WFC3-IR cluster imaging campaigns – have now provided the second critical advance: deep IR template imaging of massive clusters from which to construct difference images for SN discovery. These HST programs have also led to an explosion of detailed mass modeling for strong-lensing clusters, providing well-defined lensing potentials that will be crucial for evaluating a multiply-imaged SN when one is found.

Our snapshot program will capitalize on this rich new treasury of IR cluster imaging in the HST archive, opening the door for a pioneering time delay distance measurement with the discovery of one or more strongly lensed SN behind a galaxy cluster. We will target well-studied massive clusters that act as especially strong lenses (Table 2). For each of these clusters we have dozens of known multiply-imaged galaxies, and we already have state-of-the-art lens models in hand (e.g. **?????**). Wherever a multiply-imaged SN should appear, ***we will be starting out with much better constraints on the lensing potential*** ϕ than are available for existing quasar time-delay lenses. In addition to improving the quality of the time-delay cosmography, this fore-knowledge of the lensing potential will also be crucial for quickly evaluating any lensed SN candidates we discover, to weed out impostors before investing precious follow-up time.

Furthermore, ***the SN we discover behind these clusters will be inherently better time-delay sources*** than the existing sample of quasars. Typical time delays through our target clusters are months or years (not days or weeks as for many lensed quasars), allowing for more precise measurements of Δt, with ample time to prepare for the appearance of the second image. Also, the SN light curve has a single peak, so there is no possibility of phase ambiguity, and the age of a SN relative to explosion can be precisely defined from light curve shape and color, or from spectroscopic cross-correlation (**??**). Thus the time delay measurement does not require continuous long-term monitoring, and can be made with minimal systematic uncertainties.

The HST Snapshot Search Strategy

Since Cycle 17, HST surveys of strong lensing clusters (notably CLASH and the Frontier Fields) have been investing hundreds of orbits in deep WFC3-IR imaging. With these templates in hand, the most efficient way to discover high-z strongly lensed SN is through a relatively small snapshot program. To estimate the number of snapshots we need, we use a tabulation of the number of known multiply-imaged galaxies in the fields of our target clusters (Table 2). This is a conservative approach, as it is quite possible to detect a multiply-imaged SN even if the host galaxy is well below the current detection thresholds for these cluster fields. The total yield of strongly-lensed SN per snapshot is then

$$N_{SN} = SNR_M \times M_{gal} \times N_{gal} \times t_{vis}, \tag{3}$$

where SNR_{M^*} is the SN rate per unit mass, M_{gal} is the average mass of a multiply-imaged galaxy, N_{gal} is the number of multiply imaged galaxies in the field, and t_{vis} is the length of time that any given SN is visible to our snapshot survey. Most of the lensed systems in our target list are at $z \sim 2$, in an era near the peak of the cosmic star formation history. This should substantially enhance the rate of both Type Ia and Type II SN, but we conservatively assume that our average lensed galaxy is generating SN at a rate similar to an Sb galaxy in our local universe: $SNR_M \sim 0.1$ for both SN Ia and SN II (?). We adopt an average stellar mass of $M_{gal} = 10^{10.7}\mathrm{M}_\odot$ (?), and use the census of multiply-imaged systems in Table 2 to predict an average of $N_{gal} \sim 35$ lensed galaxy images per cluster.[1]

To maximize the flexibility for scheduling, we consider snapshots with 12, 20 and 30 minutes of exposure time (∼22, 30, and 40 min with overhead). These snapshots reach a depth of 25-26 AB mag in the F110W and F140W filters (Table 1). To describe a realistic distribution of SN visibility times, t_{vis}, we use a census of magnifications and redshifts from all multiply-imaged galaxies in three of our primary cluster targets (Figure 2). We then use simulated SN light curves to measure the length of time each SN stays above our detection threshold, finding an average $t_{vis} \sim 30$ days for SN Ia and ∼20 days for SN II.

Inserting these estimates into Eq. 3, we find $N_{SN} \sim 0.02$ SN per snapshot, including both Type Ia and II. To give this program a realistic chance at discovering a strongly lensed SN in Cycle 22, we request 200 snapshots,

Table 1: Detection Limits

WFC3/IR Filter	Exp.Time [min]	m_{lim} * [AB mag]
F110W	12	25.5
F110W	20	25.8
F110W	30	26.1
F140W	12	25.0
F140W	20	25.3
F140W	30	25.6

* Apparent magnitude to reach S/N of 10 in the given exposure time.

[1]Note that we count each separate image of a multiple-image set except the last one (typically the most highly magnified). The time delay between each image is of order months or years, so each snapshot is essentially observing the same galaxy at multiple widely-spaced epochs that can be treated as independent for the purpose of SN discovery. The last image is not counted because we can not measure a time delay from the last appearance of a multiply-imaged SN.

which would yield a sample of $\sim 4^{+3}_{-2}$ SN in one year if all snaps were executed. With a realistic snapshot execution rate of ∼30%, that sample drops to ∼one. These are perilously small sample sizes, but given the conservative estimates used in this prediction, we expect that a 200-snap allocation will be sufficient to deliver at least one strongly lensed SN in Cycle 22. Even just a single detection will nevertheless be an extraordinary step forward for time delay cosmography.

Finally, we note that this snapshot program is designed only for discovery. Follow-up observations will come from accompanying GO program, using 12 orbits with ToO observations for immediate confirmation of a SN candidate and measurement of the light curve. Sometime in the future, a return campaign to catch the next image would be needed to complete the time delay measurement, using HST, ground-based AO systems, or possibly JWST, depending on the length of the delay.

Lensed SN Ia Probing Cluster Models We could find lensed SN Ia with significant magnification that do not have multiple images, adding to the sample of SN lensing probes (Patel+ 2014, Nordin+ 2014). Classification and light curve measurement could be done with FrontierSN follow-up orbits

Description of the Observations

Special Requirements

Justify Duplications

Table 2: Cluster Target List

Cluster	R.A.	Decl.	z	N_{im} *	References
Abell 2744†	00:14:23.4	-30:23:26	0.31	43	Merten et al. 2011
CL0024	00:26:35.0	+17:09:43	0.39	20	Zitrin et al. 2009a
El Gordo	01:02:52.5	-49:14:58	0.87	11	Zitrin et al. 2013b
Abell 370†	02:39:52.8	-01:34:36	0.37	36	Richard et al. 2009, ZFF
Abell 383	02:48:03.4	-03:31:44	0.19	18	Zitrin et al. 2011b
MACS0416†	04:16:08.4	-24:04:21	0.40	36	Zitrin et al. 2013
MACS0647	06:47:50.3	+70:14:55	0.58	20	Zitrin et al. 2011, Coe et al. 2013
Bullet-a	06:58:37.9	-55:57:00	0.3	10	Bradac et al. **
Bullet-b	06:58:37.9	-55:57:00	0.3	11	Bradac et al. **
MACS0717-a	07:17:35.6	+37:44:44	0.55	18	Zitrin et al. 2009b, Limousin et al. 2012, Z14
MACS0717-b	07:17:35.6	+37:44:44	0.55	18	Zitrin et al. 2009b, Limousin et al. 2012, Z14
MACS0744	07:44:52.8	+39:27:24	0.70	14	Zitrin et al. 2011; 2014 in prep
Abell 611	08:00:56.8	+36:03:23	0.21	12	Newman et al. 2013, Z14
MACS1149†	11:49:35.7	+22:23:55	0.54	29	Zitrin & Broadhurst 2009, Zheng et al. 2012
MACS1206†	12:06:12.1	-08:48:04	0.44	33	Ebeling et al. 2009, Zitrin et al. 2012
Abell 1689†	13:11:34.2	-01:21:56	0.19	117	Broadhurst et al. 2005, Coe et al. 2010, Diego et
Abell 1703†	13:15:03.7	+51:49:27	0.28	36	Limousin et al. 200*, Zitrin et al. 2010
RXJ1347	13:47:31.1	-11:45:12	0.45	14	Köhlinger & Schmidt 2014
MS1358	13:59:48.7	+62:30:48	0.33	13	Zitrin et al. 2011c
Abell 1835	14:01:02.0	+02:52:45	0.25	17	Richard et al. 2010, Morandi et al. 2012
Abell 2218	16:35:54.0	+66:13:00	0.18	18	Kneib et al. 2004
Abell 2261	17:22:27.2	+32:07:57	0.22	18	Coe et al. 2012
MACS1931	19:31:49.6	-26:34:32	0.35	10	Z14
MACS2129	21:29:26.1	-07:41:28	0.57	14	Zitrin et al. 2011; Z14
RXJ2248†	22:48:44.0	-44:31:51	0.35	28	Monna et al. 2013

* Approximate number of known strongly-lensed galaxy images within the WFC3-IR FOV, counting all instances of each lensed galaxy except the last (i.e. all independent lensed galaxy images that could deliver a SN time delay measurement).
† Primary targets. We will allocate more snapshots to these clusters that have especially strong lenses with many multiply-imaged galaxies and particularly good lens models. The unweighted average N_{im} is $\sim$25, but we expect this weighted snapshot allocation to result in an actual mean of $N_{im} \sim 35$.

Past HST Usage

Table **??** lists the HST programs from recent cycles that include PI Rodney.

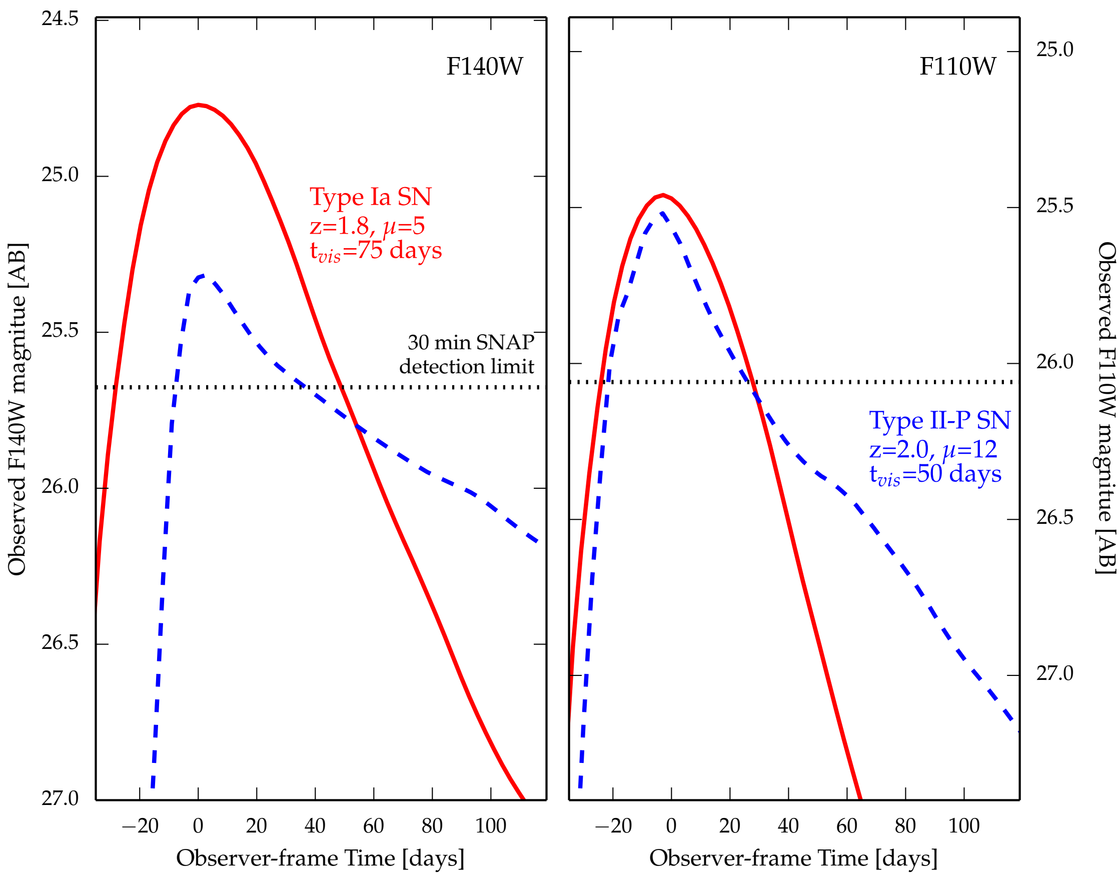


Figure 1: Lensed SN light curves

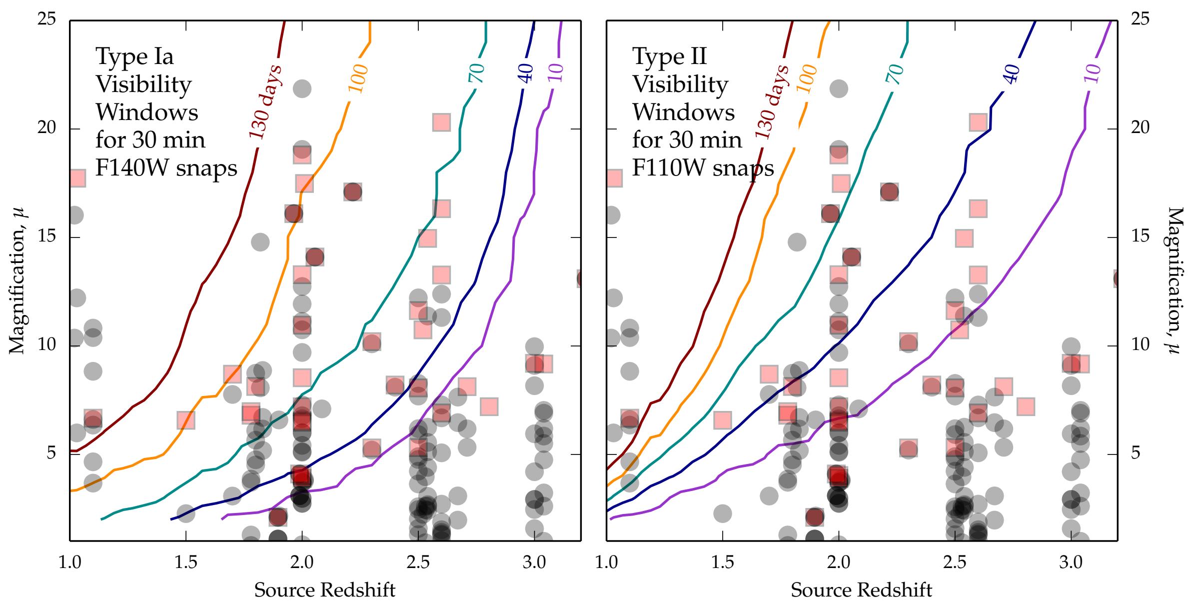


Figure 2: Visibility time for lensed SN.