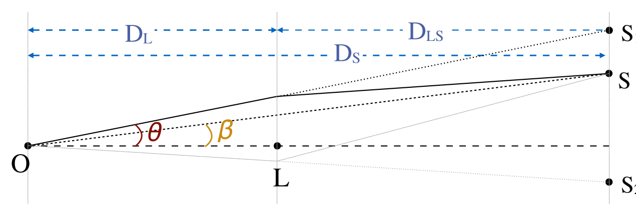
■ Scientific Justification

We propose here an optimized snapshot program to find the first ever multiply-imaged supernova (SN), exploiting a new HST capability enabled by the growing archive of deep WFC3-IR imaging on strong-lensing galaxy clusters. Along with the accompanying small GO follow-up program (PI:Strolger), we will use this unprecedented discovery to set the stage for the first ever use of a SN for time delay cosmography – a prospect initially conceived some fifty years earlier (Refsdal, 1964). Even with just a single SN time delay, we will be able to measure H_0 to about 10% precision *without any reference to the local distance ladder.* This first SN time delay will therefore be a unique and valuable test of systematic biases in other H_0 constraints, and will serve as a pathfinder for future large samples of lensed SN (e.g. from LSST), that could become a powerful new cosmological tool.

Motivation As light from a distant source passes through a galaxy cluster, strong gravitational lensing causes multiple images to appear to the observer. The massive clusters in our target list all have dozens of multiple images known, and it is from these multiply imaged galaxies that we derive our primary constraints for cluster mass models (REFERENCE??). When a SN inevitably appears within one of these multiply-imaged galaxies, it will of course be multiply-imaged itself. Unlike the effectively static backgrond galaxies, a lensed SN is a transient source, so we will observe the multiple images appear to us separated by a time delay

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

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



and 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. In Eq. 2 for the time delay potential (ϕ), 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. The distance ratio $D_L D_S/D_{LS}$ in Eq. 1 carries a factor ${H_0}^{-1}$, so if the lensing potential ϕ is well known, this ***time delay cosmography provides a direct measurement of the Hubble constant – completely independent of the local distance ladder.***

After several decades of substantial effort and slow progress, this field is now rapidly maturing (see Jackson, 2007; Treu, 2010, for recent reviews). The complete sample comprises ∼20 time delay measurements, exclusively from *quasars*. These are typically lensed by a single foreground galaxy, with only a few magnified by galaxy clusters (Inada et al., 2003, 2006; Oguri et al., 2008; Dahle et al., 2013). As techniques for measuring the time delay Δt and modeling the lensing potential ψ 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).

The distances derived from these time delay measurements are particularly complementary to high-z cosmological probes like the Cosmic Microwave Background (CMB; Linder, 2011). Time delay distances provide an especially powerful check for unknown systematics, because – unlike SN Ia– 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 LSST era.*

Additionally, Unlike a multiply-imaged SN which is inherently single-peaked allowing to avoid phase-ambiguity, multiply-imaged quasars can require a long monitoring time for the time-delay to be well measured, albeit this has been done most successfully (Fohlmeister **). Discovering here the first multiply-imaged SNe, will not only enable a complementing and different independent meaure of the time-delay and the Hubble parameter, thus supplying independent tests of crucial systematic biases in other time-delay measueremnts and other cosmological probes, but may also reveal systematics in the lens models themselves hidden otherwise (e.g. Oguri et al. **). These systematics are a crucial factor in current Director's Discretionary Time studies of the high-redshift, magnified Universe such as the Frontier Fields program with HST[1], for which the lens-magnification models are key. Finally, if the lensed SN is of Type Ia (a likely prospect), then light curve fitting can provide a luminosity distance measurement with ∼8% precision (Phillips, 1993), and this lensed SN Ia could easily be among the most distant SN Ia ever seen.

The use of a multipy-imaged SN to measure H_0 was first proposed 50 years ago (Refsdal, 1964), but no multiply-imaged SN has yet been found.

Ground-based surveys and even HST/ACS programs have looked for SN in and around galaxy clusters, but by searching in optical bands none of these have had the capability to detect even highly magnified SN at $z > 2$ (e.g. Sharon et al., 2007; Dawson et al., 2009; Sharon et al., 2010; Sand et al., 2011). However, The lack of a detection in

Despite the long-standing prediction, to date, no multiply-imaged SN has found. The lack of multiply-imaged SNe can be attributed a low number of lenses properly analyzed until recently, and the short visibility window for any given high-z SN event (∼a few weeks). Only recently were the first few magnified SNe detected behind galaxy clusters: Amanullah et al. ** deteced a magnified SN behind the lensing cluster A1689, and three other magnified SNe were uncovered by us in the CLASH program (Patel et al. 2013/4**, see also Nordin et al. 2013/4**), yet all of these are too far away from the center to be multiply-imaged.

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; **?**; **?**; **?**). Co-PI Zitrin has had a leading role in this recent burst, principally through the light-traces-mass (LTM)

[1]for which the co-PI A. Zitrin acted as an external lensing-science advisor, and in which we have (PI: Rodney) a program to search for general SNe

lens modeling technique (?), which particularly excels at describing the strong-lensing regime of cluster lenses in great detail. Through the CLASH program (PI:Postman), this approach is being used to generate precise mass models for 25 clusters, dramatically expanding the number of well-studied strong-lensing clusters (e.g. ?). As detailed below, the combination of deep WFC3-IR imaging and precise mass models for over 2 dozen clusters now makes it feasible for the first time to find a multiply imaged SN and use it for time delay cosmography.

Detecting The First Multiply-Imaged SN In Cycle 22, HST has just achieved a new capability for the discovery of a multiply-imaged 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 (Rodney et al., 2012; Jones et al., 2013).

multiply-imaged SN in the past, but none have had (e.g. Sharon et al., 2010). 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. CLASH, for example, collected WFC3-IR imaging of 25 clusters over 3 years, but the time separation between the first and last IR image on any single cluster was typically only ∼40 days, so in practice each cluster only had one epoch suitable for a lensed SN search rendering serendipiuos detection extremely unlikely. However, CLASH and other programs have now provided the second critical advance: deep IR template imaging of massive clusters from which to construct difference images for SN discovery. Our snapshot program will capitalize on this rich new treasury, focusing on a carefully-chosen cluster target list (Table 1).

In optimizing the target list, one has to take into account the trade-off between the lensing power of a lens and the time-delay, which we have now investigated. Very massive clusters, will generally multiply-lens more background objects, increasing the chances of detecting a SN in one of the few-dozen backrgound galaxies being multiply-imaged. However, very massive clusters will also, on avarage, yield time delays which are hard to measure on a reasonable time scale (can be up to thousands of years), and only a smaller portion of the multiple-image pairs (down to $\sim 10{-}20\%$ following our calculations) would yield desired time delays of a few-months to few-years timescale (allowing for more precise measurements of Δt and with ample time to prepare for the appearance of the second image). As a counter-example, galaxy-scale lenses also produce useful time-delays that can be measured on a timescale of days or weeks, but these lenses each comprises typically only one background galaxy and it would take an immense effort to find a multiply-imaged SNe in them. Therefore, optimal targets, as a rule of thumb (i.e. there is also depndence on the exact structure and redshift of the lens), for a timescale of months to few-years time delays, are medium-to-large sized lenses (Einstein radii of roughly $\sim 10 - 30''$) comprising each few to few-dozen multiply-imaged galaxies. We have now compiled a list of well-studied clusters, the majority of which are CLASH or Frontier Fields (PI: Lotz) clusters which we have studied in detail, and in which many multiple-images of background galaxies are apparent. For all of these clusters we have in hand state-of-the-art lens models (Zitrin et al., ****, 2014 in prep for the full CLASH sample) which are crucial for the accurate determination of H_0. Our list contains in total ** lenses spread neatly across the sky, the bulk of which is designed to follow the selection criteria specified above, but supplemented by 2-3 more massive clusters for completeness comprising an order of a hundred multiple images each (Table 1).

The HST Snapshot Search Strategy To estimate the number of snapshots we need, we start with a tabulation of the number of known multiply-imaged galaxies in the fields of our target clusters (Table 1 ** we need to list the number of images, maybe not only the useful fraction?). 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 $N_{SN} = SNR_M \times M_{gal} \times N_{gal} \times t_{vis}$. Here 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, so we assume that our average lensed galaxy is generating SN at a rate similar to an Sc galaxy in our local universe: $SNR_M \sim 0.2(100\text{yr})^{-1}(10^{10}\text{M}_\odot)^{-1}$ for SN Ia and $0.7(100\text{yr})^{-1}(10^{10}\text{M}_\odot)^{-1}$ for Type II (Mannucci et al., 2005). We adopt an average stellar mass of $M_{gal} = 10^{10.7}\text{M}_\odot$ (**?**), and use the census of multiply-imaged systems in Table 1 to predict an average of $N_{gal} \sim 35$ lensed galaxy images per cluster[2]. Using simulated SN light curves in 240 multiply-imaged galaxies (Figure 1), we find an average $t_{vis} \sim 30$ days for SN Ia and ~20 days for SN II.

With these relatively conservative estimates, we get $N_{SN} \sim 0.1$ SN per snapshot, including both Type Ia and II. To give this program a good chance at discovering a strongly lensed SN in Cycle 22, we request 200 snapshots. Assuming a realistic snapshot execution rate of ~30%, this program should yield a sample of $\sim 6 \pm 4$ SN in one year. Even if our yield prediction is biased high by a factor of ~2, we still have a better than 68% chance to catch at least one. Given the intrinsic value of each lensed SN, 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 mainly for discovery. Follow-up observations will come from accompanying GO program (PI: Strolger), 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.

Description of the Observations

[2]Note that 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 is essentially observing the same galaxy at several widely-spaced epochs that can be treated as independent.

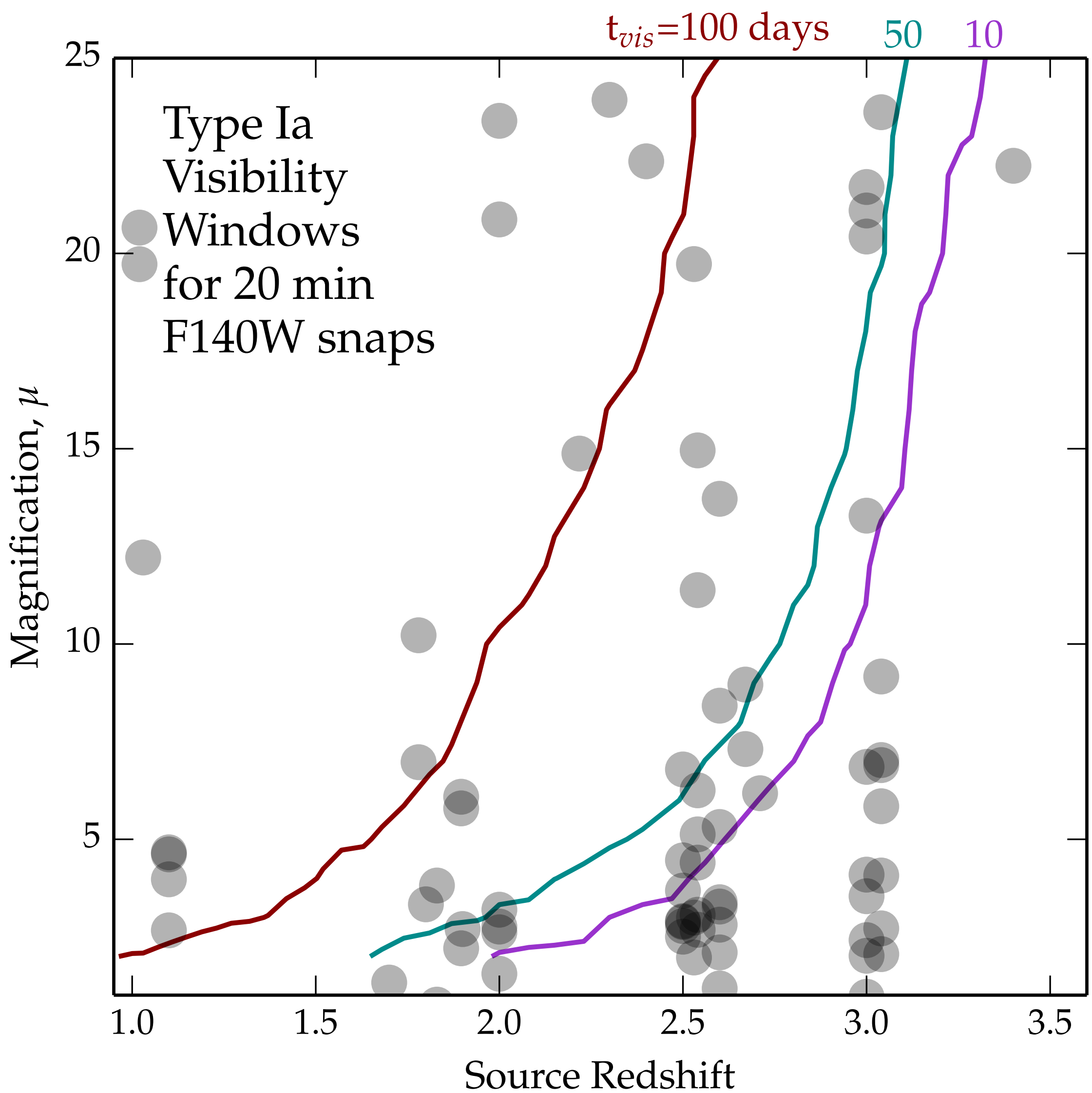


Figure 1: Visibility time contours in the redshift-magnification plane. Using simulated light curves of an average lensed Type Ia SN, we have measured the expected visibility window (a.k.a the control time): the number of days that the SN is above our detection threshold for a 20-minute snapshot. Solid lines plot contours of constant visibility time in the $z-\mu$ plane at t_{vis} =100, 50, and 10 days. Grey points mark the measured magnifications and redshifts for 50 strongly-lensed galaxy images from three of our primary cluster targets.

Table 1: 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 ∼25, but we expect this weighted snapshot allocation to result in an actual mean of $N_{im} \sim 35$.

Special Requirements

Justify Duplications

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■ Past HST Usage

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