■ Scientific Justification

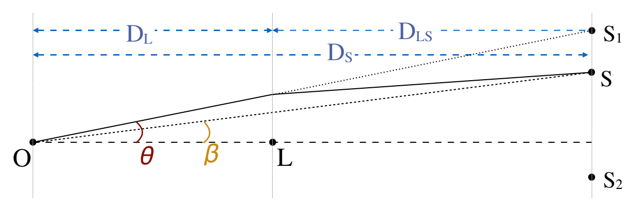
With this snapshot program, we propose to use HST's WFC3-IR detector to discover the first multiply-imaged SN behind a strong lensing galaxy cluster, setting the gold standard for future strong lensing time delay measurements. In recent years HST programs such as CLASH and the Hubble Frontier Fields 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

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

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



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 (Linder, 2011).

Refsdal (1964) 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 (Jackson, 2007). Among these, only a handful have time delays measured with particularly high precision (Suyu et al., 2010, 2013, 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.

Furthermore, with a cluster lens and SN source ***we will open up the possibility of measuring independent distances to both components.*** Cluster distances can be estimated using the Sunyaev-Zeldovich effect and x-ray cluster luminosities (Silk & White, 1978). If the SN is of Type Ia (a likely prospect), then light curve fitting can provide a luminosity distance measurement with ∼8% precision (Phillips, 1993). A multiply-imaged SN Ia would therefore be a unique chance to apply the distance-duality test: comparing the luminosity distance $D_S^{(L)}$ inferred from light curve fitting against the angular diameter distance $D_S^{(A)}$ derived from the time delay. If the ratio $\eta_{DD} = D_S^{(L)}/(D_S^{(A)}(1 + z_S)^2)$ deviates from unity, then this would signal systematic errors in one or more distances, or a fundamental flaw in the concordance cosmology.

HST Getting Better with Age

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 ther SED profile in rest-frame optical bands (Rodney et al., 2012; Jones et al., 2013). 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. Dawson et al., 2009; Sand et al., 2011). 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 capatalize 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, all with dozens of known multiply-imaged galaxies (Table 1). ***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 potential for 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 (Filippenko, 1997; Blondin & Tonry, 2007) – so the time delay measurement does not require continuous long-term monitoring.

The lenses in our target list are also much better than existing time-delay lenses. For all of our potential targets we have state-of-the-art lens models in hand (e.g. **????**Zitrin et al., 2013). The large angular separations between our lensed sources and their unlensed sight-lines will allow for very precise astrometry that is free of systematics due to source blending. Together, these advantages will provide much better constraints on the lensing potential ($\phi(\theta, \beta)$, Eq. 2). This fore-knowledge will also be crucial for quickly evaluating any lensed SN candidates we discover, to weed out impostors before investing precious follow-up time.

Maximizing Search Efficiency

Typical SN light curves for strongly lensed SN of Type Ia and II are shown in Fig 1

Visibility time for SN Iaand II is shown in Fig 2

SN rate per unit mass (Mannucci et al., 2005)

high star formation rate at z∼2

typical galaxy mass at z∼2

Calculating the expected number of SN per 200 snapshots

factor in 30% completion.

Conservative estimate, because (1) this only counts the lensed galaxies we see. SN could be found in as-yet-unseen lensed dwarf galaxies. (2)

Follow-up observations will come from outside this program. This program only does discovery. HST DD time would be needed for immediate confirmation and classification. With magnification, most lensed SN we might discover (and their hosts) would be observable with large ground-based telescopes (using ground-based DD time) allowing us to get precise spectroscopic redshifts of the source if needed.

We request to waive the proprietary period, and plan to announce all candidate strongly lensed SN discoveries immediately to the community through ATEL.

Other discoveries of interest that do not rise to the level of DD time (e.g. SN with mu 2 but no multiple images) could be followed up with our FrontierSN program using HST/Gemini/VLT/Keck

Secondary science : 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) again, classification and light curve measurement could be done with FrontierSN follow-up orbits

Table 1. Cluster Target List

Cluster	R.A.	Decl.	N_{lensed}*
A1689			165
A1703			50
M1206			47
M0416			∼50
A2744			∼60
M1149			41
M0647			28
RXJ2248			∼40
RXJ1347			∼20
M0744			∼20
M2129			∼20
M1931			∼15
A2261			∼20-30
A383			∼25
A611			∼15
M0329			∼15
MACS1423			∼15
MACS1720			∼15
CL1226			∼10-15
RXJ2129			10-15
MS2137			∼10
MACS0717a			∼25
MACS0717b			∼25
bullet cluster a			∼15
bullet cluster b			∼15
Abell 2218			>25
Macs0454			13-17
Macs0451, cl0024			∼25-30
ms1358			∼15-20
El Gordo			>15
frye and broadhurst lens			
Locuss check			

* Number of known strongly-lensed galaxy images within the WFC3-IR FOV, counting all instances of each lensed galaxy.

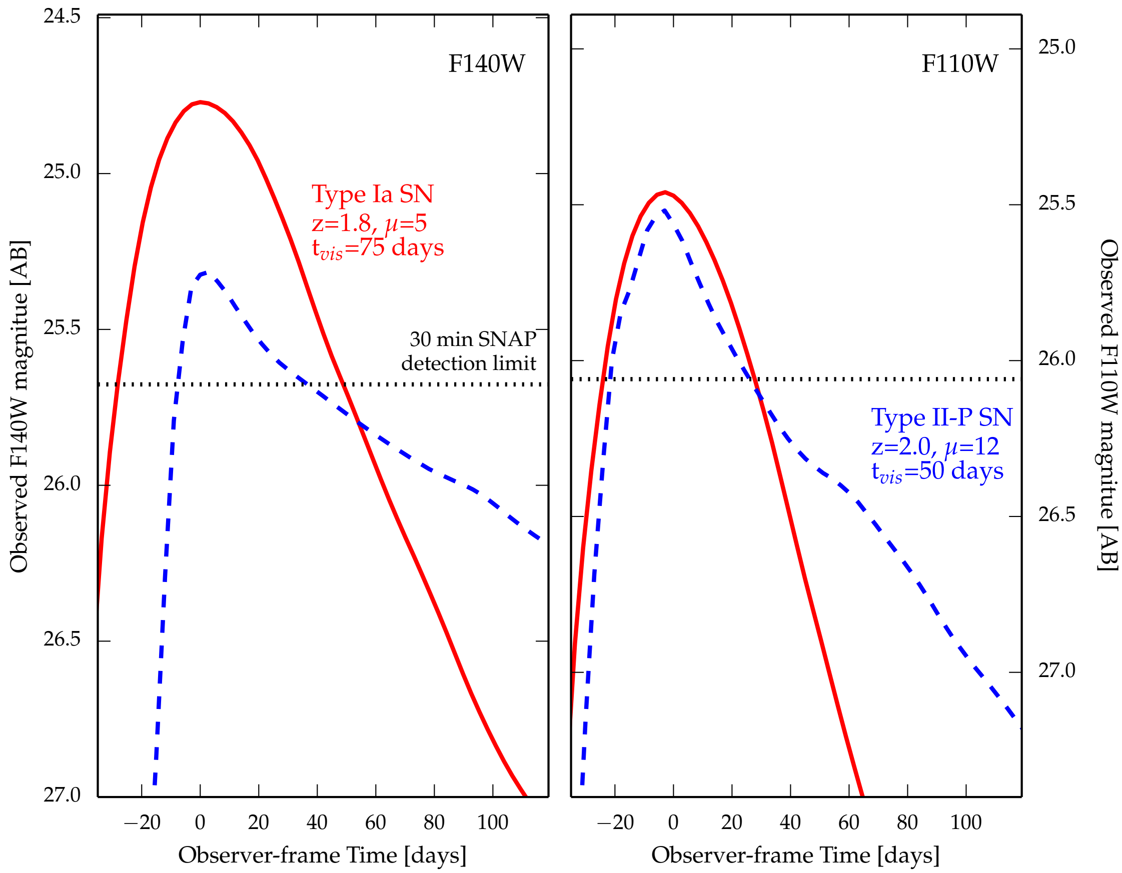


Figure 1 Lensed SN light curves

Description of the Observations

Special Requirements

Justify Duplications

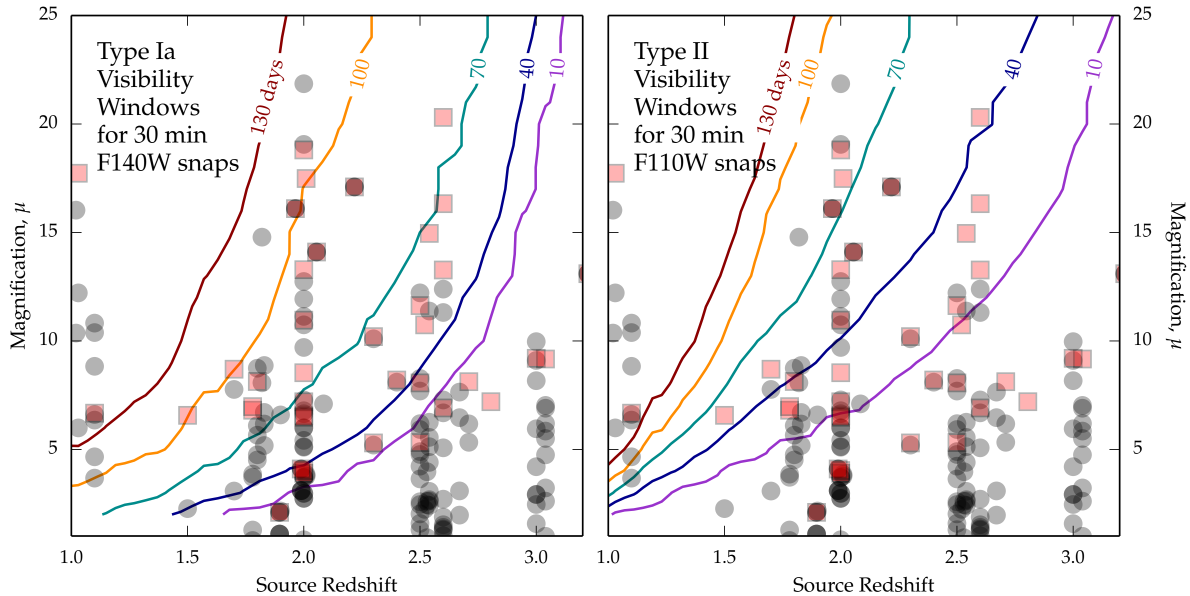


Figure 2 Visibility time for lensed SN.

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Table 2. Past HST Usage for PI

PID	Title	Status	Selected Publications*
12060-64, 12440-45	CANDELS	Cycle 18-20 MCT; ~90% complete.	Grogin et al. 2011 Trump et al. 2011 van der Wel et al. 2011
12065-69, 12100-04, 12451-60	CLASH	Cycle 18-20 MCT; ~90% complete.	Postman et al. 2012 Coe et al. 2013
12099, 12461, 13063	C+C SN Follow-up	Cycle 18-20 MCT; ~90% complete.	Rodney et al. 2012 Frederiksen et al. 2012 Jones et al., 2013
13046	RAISIN	Cycle 20 ToO; collecting data	···

*Listed publications are those with direct input from PI Rodney and the CANDELS+CLASH SN team. Total CANDELS+CLASH publications ≈63.

Past HST Usage

Table 2 lists the HST programs from recent cycles that include PI Rodney.