■ 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 that first multiply-imaged SN with a small, single-cycle snapshot program.*

0.1 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

$$\Delta t = \frac{D_l D_s}{D_{ls}}(1 + z_l)\phi \qquad (1)$$

where 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 redshift of the lens is z_l, and ϕ is the time delay potential, which includes a geometric component due to light rays following different path lengths to the observer, plus a general 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, we have only just begun to realize the potential in this technique with the recent measurement of a few dozen *quasar* time delays (Jackson, 2007), including just a handful with particularly high precision (Suyu et al., 2010, 2013). These quasar lenses generally suffer from a number of serious concerns, notably: (1) the lensing potential (typically a single foreground galaxy) is poorly constrained; (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.

This snapshot program will open the door for a much cleaner time delay distance measurement with the discovery of a strongly lensed SN behind a galaxy cluster. We will target well-studied, massive clusters that all have dozens of known multiple-image systems, meaning that the lensing potentials ϕ are exquisitely well defined. Typical time delays through these clusters are months or years, allowing for more precise measurement of Δt, with ample time to prepare for the appearance of the second image. A SN also provides an inherently better time-delay source: 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.

Furthermore, with a cluster lens and SN source there is 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 also 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.

Description of the Observations

Special Requirements

Justify Duplications

References

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Table 1. 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 1 lists the HST programs from recent cycles that include PI Rodney.