■ Scientific Justification

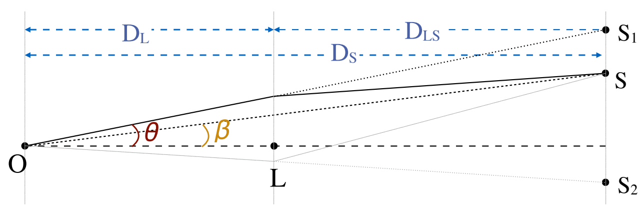
The HST archive now holds a deep trove of WFC3-IR imaging on strong-lensing galaxy clusters at redshifts $z \sim 0.5$. Many of these clusters have dozens of multiply-imaged background galaxies at redshifts $1 \lesssim z \lesssim 6$, which have been used to produce well-constrained models of the cluster lensing potential. When a supernova (SN) inevitably appears within one of these multiply-imaged galaxies, it will of course be multiply-imaged itself. ***With this snapshot survey, we propose to use WFC3-IR to discover the first ever multiply-imaged SN behind a strong lensing galaxy cluster.*** Along with the accompanying GO proposal for ToO follow-up, ***this program will set a new gold standard for future gravitational lens time delay measurements.*** With even just a single lensed SN time delay, we will constrain H_0 to better than 6% precision, provide powerful new constraints on dark energy parameters, and deliver a unique test of systematic biases in other cosmological probes.

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, 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 Equation 1 is known as the *time delay distance*, and it carries a factor of ${H_0}^{-1}$. Thus, if the lensing potential ϕ is well known, then a time delay measurement provides a direct measurement of the Hubble constant – independent of the local distance ladder. The distance ratio 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 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 (e.g. Suyu et al., 2010, 2013). 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 stochastically variable, often requiring years of stable monitoring for the time delay measurement. 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 (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; Sharon et al., 2010; 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. 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. 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. These HST programs have also led to an explosion of detailed mass modeling for strong-lensing clusters, which is crucial for evaluating a multiply-imaged SN when one is found.

Our snapshot program will capitalize on this rich new treasury, focusing on well-studied massive clusters that act as especially strong lenses (Table **??**). 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. **????**Zitrin et al., 2013). 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 most quasar time-delay lenses.

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 (Filippenko, 1997; Blondin & Tonry, 2007). Thus the time delay measurement does not require continuous long-term monitoring, and can be made with minimal systematic uncertainties. Finally, 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), and this lensed SN Ia could easily be among the most distant SN Ia ever seen.

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 **??**). 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: $SNR_M \sim 0.2(100\mathrm{yr})^{-1}(10^{10}\mathrm{M}_\odot)^{-1}$ for SN Ia and $0.7(100\mathrm{yr})^{-1}(10^{10}\mathrm{M}_\odot)^{-1}$ for Type II (Mannucci et al., 2005). 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 **??** to predict an average of $N_{gal} \sim 35$ lensed galaxy images per cluster.[1] Using simulated SN light curves in 240 multiply-imaged galaxies (Figure **??**), we find an average $t_{vis} \sim 30$ days for SN Ia and ∼20 days for SN II.

With these relatively conservative estimates, we estimate $N_{SN} \sim 0.1$ 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 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.

Description of the Observations

Special Requirements

Justify Duplications

[1]Note that we count each separate image of a multiple-image set except the last one (we can't 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.

References

Blondin, S., & Tonry, J. L. 2007, ApJ, 666, 1024
Dawson, K. S., et al. 2009, AJ, 138, 1271
Filippenko, A. V. 1997, ARA&A, 35, 309
Jackson, N. 2007, Living Reviews in Relativity, 10, 4
Jones, D. O., et al. 2013, ApJ, 768, 166
Linder, E. V. 2011, Phys. Rev. D, 84, 123529
Mannucci, F., et al. 2005, A&A, 433, 807
Phillips, M. M. 1993, ApJ, 413, L105
Refsdal, S. 1964, MNRAS, 128, 307
Rodney, S. A., et al. 2012, ApJ, 746, 5
Sand, D. J., et al. 2011, ApJ, 729, 142
Sharon, K., et al. 2010, ApJ, 718, 876
Suyu, S. H., et al. 2013, ApJ, 766, 70
—. 2010, ApJ, 711, 201
Zitrin, A., et al. 2013, ApJ, 762, L30

Past HST Usage

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