■ Scientific Justification

Over the past decade, the deep *HST* Treasury surveys (GOODS, CANDELS, CLASH) have proven to be the most effective programs for locating and studying Supernovae (SNe) at high redshift. These surveys have all enabled "piggyback" SN searches, which have collectively accumulated scores of SN detections, including many of the most distant SNe known (Riess et al., 2007; Dahlen et al., 2008; Graur et al., 2014; Rodney et al., 2014). Continuing in this line of highly successful deep *HST* surveys, the Hubble Frontier Fields (HFF) director's discretionary program (PI:Lotz) now provides a powerful new tool for the discovery of high-z SNe. What sets the HFF program apart from previous surveys is the extraordinary depth of each visit; with ∼4 orbits per filter per epoch, we can reach $m_{lim,3\sigma}(F160W) \approx 27.9(AB)$, nearly 1 mag deeper than CANDELS/CLASH per epoch. Gravitational lensing in the prime fields also magnifies SN fluxes by factors $\mu \gtrsim 2$, making it possible to detect background events at extreme redshifts.

In Cycle 21 the TAC awarded us 60 orbits and 15 non-disruptive ToO triggers over 3 cycles to use in follow-up observations of SNe discovered in HFF imaging and supplementary surveys. We are on pace to expend all of these orbits in the first 2 years, primarily due to the unexpected (and unprecedented) discovery of a multiply-imaged SN, gravitationally lensed into an Einstein Cross (Figure 3, Kelly et al. 2015). **We propose to extend our FrontierSN program into Cycle 23, so we can continue to provide the necessary follow-up observations to maximize the scientific return of this rich Frontier Fields SN sample.**

Testing SN Progenitor Models with High Redshift Rates

Through the first two years of the HFF program, our team has searched for SNe in all imaging of the Frontier Fields clusters and parallel fields. We have also searched the 10 complementary cluster and parallel fields observed in the Grism Lens Amplified Survey from Space (GLASS, PI:Treu, PID:13495), working jointly with the GLASS team. We have discovered 39 transients, primarily normal Type Ia or Core Collapse SNe at redshifts reaching to $z = 1.5$. Roughly half of these discoveries have come from the GLASS program, and half from the HFF imaging.

Our primary science goal with this complete SN sample is to measure SN Ia rates to $z \sim 2.5$, yielding improved constraints on SN Ia progenitor models. With the CLASH and CANDELS surveys we have shown that measurements of the Type Ia SN rate beyond $z \sim 1$ can be used to measure the fraction of SN Ia that explode within ∼500 Myr after formation (Graur et al., 2014; Rodney et al., 2014). The FrontierSN program will improve this measurement even if no new SNe are discovered at $z > 1.5$. Our lack of such high-z detections in the first two years already strengthens the case for a low fraction of SN Ia that explode promptly, as suggested by the CANDELS and CLASH programs. To first order, this low rate supports the hypothesis that the SN Ia population is dominated by double white dwarf progenitor systems, and very few have progenitors systems with main sequence or giant branch donor stars.

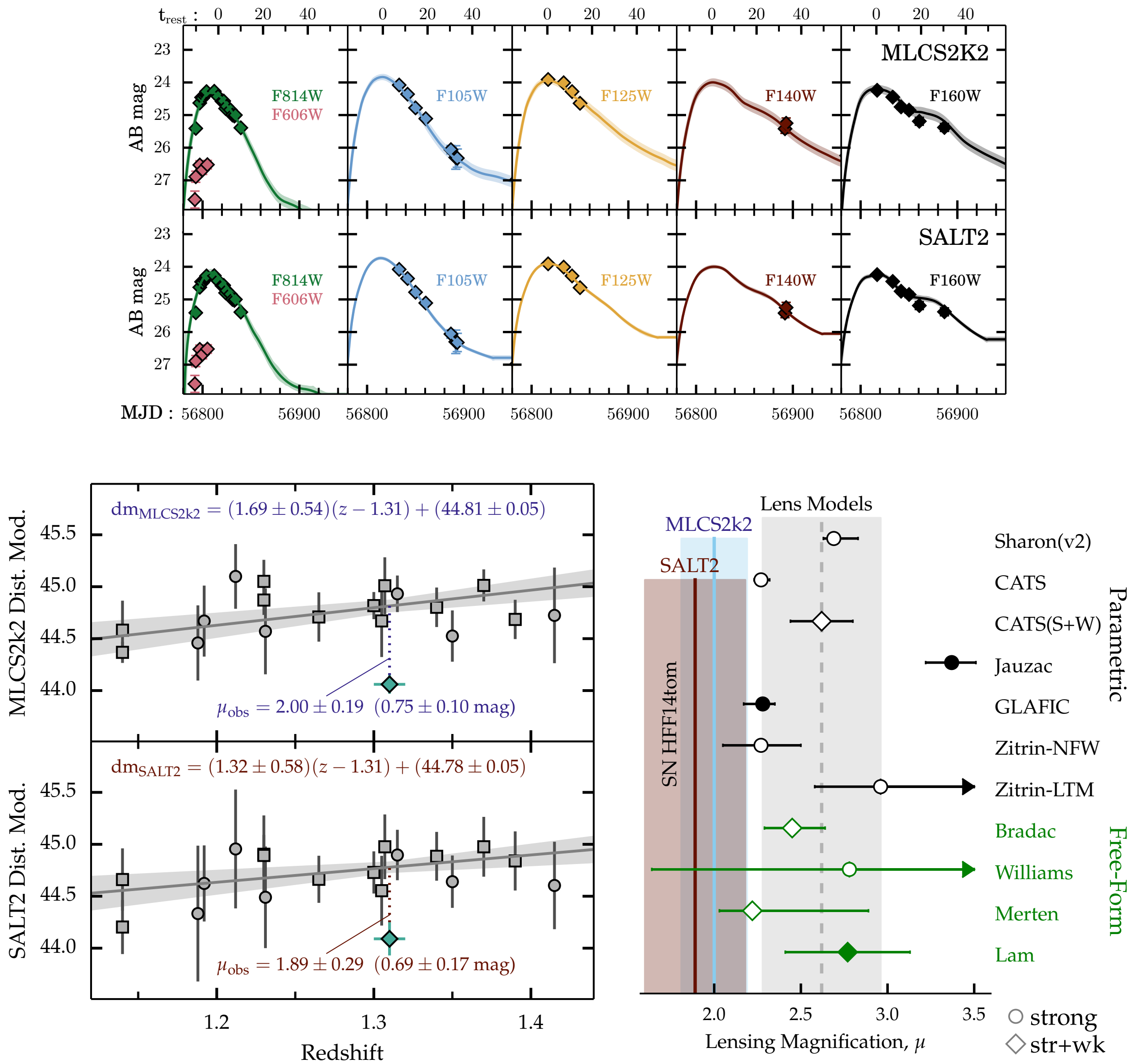

Figure 1: **Testing Cluster Mass Models with Lensed SN Ia.** SN HFF14tom is a spectroscopically confirmed Type Ia SN at $z = 1.33$, discovered by the FrontierSN program behind the galaxy cluster Abell 2744 (z=0.308). *(Top)* This SN is well matched by a normal SN Ia light curve template with little extinction, using either the MLCS2k2 or SALT2 light curve fitters. TODO: drop one of the fitters for simplicity *(Bottom Left)* To define a cosmology-independent "true" distance modulus, we use a linear fit to the distances from un-lensed SNe at similar redshifts (Riess et al., 2007; Suzuki et al., 2012). The separation between the best-fit line and our lensed SN gives us a measurement of the lensing magnification with ∼10% precision. *(Bottom Right)* The vertical red and blue bars indicate the measured magnification from the SN, and data points show the predicted values from all publicly available lens models, with the sample mean as a dashed vertical line. Collectively these models are *systematically overestimating* the magnification.

Illuminating Dark Lenses with Highly Magnified Transients

The FrontierSN program in Cycle 23 will also continue to discover unique *strongly-lensed transients* behind the HFF clusters. Of primary interest are lensed Type Ia SNe, with which we can directly measure the true lensing magnification μ and confront the predictions from existing lens models (Riehm et al., 2011; Patel et al., 2014; Nordin et al., 2014). Figure 1 shows a Type Ia SN with a magnification $\mu = 2.00 \pm 0.19$ found in Cycle 21 (Rodney et al., 2015b). The magnification of this SN is systematically *overestimated* by all existing mass models, with some discrepant by $> 5\sigma$. **Though small, our sample of lensed SNIa is already proving to be a very valuable tool for testing galaxy cluster dark matter models,** which will be particularly valuable for the study of $z > 8$ galaxies magnified by these clusters (e.g. Zheng et al., 2012; Coe et al., 2013; Bouwens et al., 2014; Zitrin et al., 2014).

The unique combination of deep imaging, strong lensing, and rapid cadence in the HFF program has also provided two very exciting discoveries of *multiply-imaged* transients. In January and August of 2014, **we observed two short transient events in separate images of the same strongly lensed galaxy at $z = 1.0$.** Collectively nicknamed "Spock", both of these events are too faint to be a normal SN and too bright to be a stellar flare. The light curves are also faster than expected from a He shell explosion on a white dwarf (a ".Ia" event Bildsten et al., 2007; Shen et al., 2010), and fainter than any of the "fast optical transients" yet seen in wide-field ground-based surveys (e.g. Kasliwal et al., 2010; Poznanski et al., 2010; Ofek et al., 2010; Drout et al., 2014; Vinkó et al., 2015).

Lens models (and Occam's razor) suggest that these two events are most likely *spatially coincident* on the source plane. If the two events were also *coincident in time*, then this could be an example of an extremely rare neutron star collision (a "kilonova"; Tanvir et al., 2013; Kasen et al., 2014; Metzger et al., 2015). If not, these may be two separate outbursts from an extremely bright nova with a remarkably fast recurrence timescale of ∼1 year (Figure 2; Rodney et al., in prep). This would be a unique nova, as it would have a recurrence timescale on par with the most extreme examples known (Tang et al., 2014) and would also be at least an order of magnitude more luminous than a typical nova.

In November of 2014 we discovered another exciting transient, this time with four distinct sources appearing ∼simultaneously in a strongly lensed spiral galaxy at $z = 1.5$. Dubbed "SN Refsdal," this is the **first ever example of a strongly lensed SN with multiple resolved images (Figure 3; Kelly et al. 2015).** The Einstein Cross configuration shown in Figure 3 is generated by a galaxy-scale lens, but the SN host galaxy is also multiply imaged by the cluster, so **we expect to see SN Refsdal return elsewhere in the cluster field in 1-5 years** (Oguri, 2015; Sharon & Johnson, 2015). Measurements of the relative magnifications and time delays among these multiple images will soon deliver an unprecedented suite of powerful new mass model constraints.

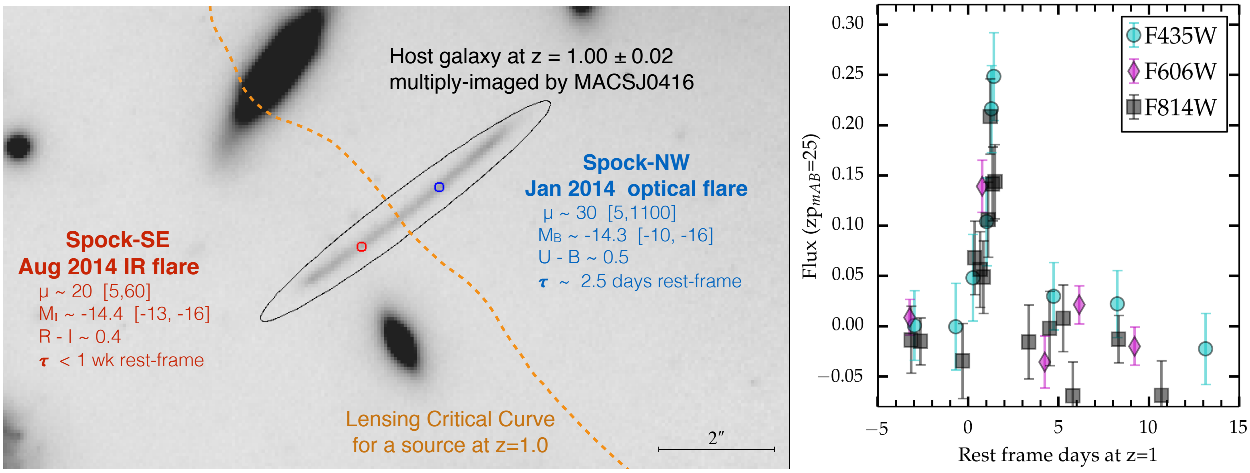

Figure 2: **Spock, a peculiar pair of events.** *Left:* A template *HST* image in the F814W band showing the locations of two transient sources (nicknamed "Spock-SE" and "Spock-NW") that separately appeared in adjacent images of a strongly-lensed galaxy at $z = 1.0$ behind the Frontier Field cluster MACSJ0416. Lens models indicate that a critical curve passes roughly mid-way between them, and they are magnified by $\mu \sim 20 - 30$ (3-4 mags). *Right:* The light curve of the Spock-NW event was captured in high-cadence HST-ACS imaging, and the entire episode lasted only ~ 3 rest-frame days.

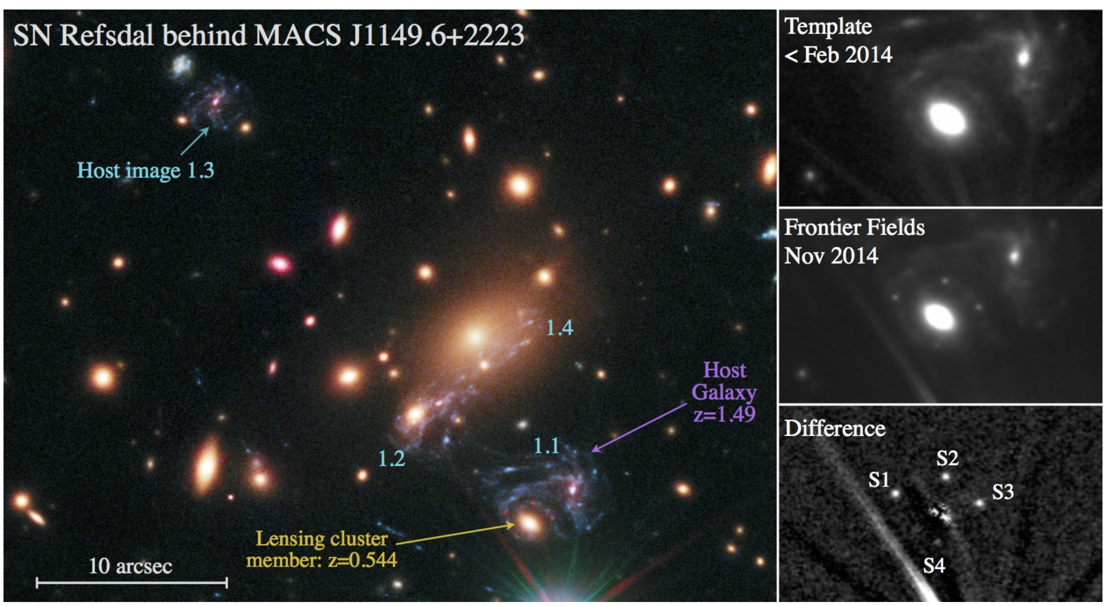

Figure 3: **Refsdal, the first multiply-imaged supernova.** The left panel shows a composite UV+optical+IR image of the central region of the galaxy cluster MACSJ1149 at $z = 0.544$. Cyan labels mark the locations of a multiply imaged face-on spiral galaxy at $z = 1.49$. The three panels at right partially enclose image 1.1 of this system, showing the appearance of 4 new point sources in WFC3-IR imaging collected in November, 2014 (Kelly et al., 2015).

Description of the Observations

In Cycle 23 the SN discoveries that this program will follow up will come primarily from the HFF imaging of the final two cluster fields: Abell 370 and Abell S1063. In addition, we are submitting a separate Cycle 23 proposal (PI:Kelly) to provide regular monitoring of the MACSJ1149 field with HST imaging. That Cycle 23 program is needed to measure time delays between the 4 images of SN Refsdal (Figure 3) and catch it's predicted reappearance). If that MACSJ1149 program is approved, it will effectively provide a third SN survey field in Cycle 23. Our FrontierSN team will search for any *new* SNe, lensed or otherwise, that appear in the MACSJ1149 cluster field or the associated parallels.

Based on our simulations of the HFF survey and the actual yield in the first two years, we expect to find another 8-12 SNe in Cycle 23, with uncertainty dominated by poisson statistics for the small number of events in any single survey year. As our first two years have shown, it is extremely difficult to prognosticate the actual number of orbits that will be required for effective follow-up of this final-year HFF SN sample. Using the first two years as a guide, **we request a new allocation of 20 orbits for Cycle 23.**

We anticipate spending ∼6 orbits on 2-5 candidate SNe that might be at high redshift ($z > 1$) or significantly magnified ($\mu > 2$). The deep and frequent HFF imaging visits will provide a high S/N and well-sampled light curve in either ACS optical bands or WFC3 IR bands. Our follow-up imaging will provide the complementary bands needed for optical-NIR colors, which are critical for photometric classification and redshift estimation of $z > 1$ SNe (Riess et al., 2004; Rodney et al., 2012). A typical target in this category might have an AB magnitude of 26.5, requiring a single-orbit visit to get 2-3 filters from the same camera. In some cases multiple epochs of observations are warranted to improve the classification and redshift estimate.

We expect the other ∼14 orbits will be devoted to one or two objects of particular interest: very high redshift ($z > 1.5$) and/or strongly lensed ($\mu > 5$) transients like SN HFF14Tom, SN Refsdal, and Spock. These orbits will be used for optical/IR imaging or grism spectroscopy, as appropriate for the source redshift and class. As an example, SN HFF14Tom at $z = 1.3$ reached a peak brightness at ~ 24 AB mag in IR bands, and we followed the light curve down to 26.2 AB mag in F140W. The total cost of follow-up was 11 orbits: 5 orbits for ACS G800L grism and 6 single-orbit visits to collect the rest-frame optical light curve using WFC3-IR broad bands.

Special Requirements

This SN follow-up program requires ToO status, and we request 5 non-disruptive ToO triggers for the cycle. Most of our SN targets that warrant follow-up observations are at $z > 1$, with significant time dilation, and the deep Frontier Field imaging typically provides early detections for many of them. Therefore the non-disruptive time delay of 3 weeks is acceptable for all our triggers.

We additionally request a continuation of the fast-ftp delivery of our FrontierSN observations immediately after those data become available, as has been implemented for our program in

Cycles 21 and 22. Rapid delivery and analysis allows us to respond to new information from our follow-up observations and adjust future visits without requiring disruptive ToO's.

Recognizing the special nature of the Frontier Fields, and the value of early community access to transient data, we request no proprietary period for our ToO follow-up observations.

■ Coordinated Observations

When possible, we will choose the orient of our follow-up orbits such that the parallel camera (ACS or WFC3) falls back onto the Frontier Field footprint. In those cases we will use filters optimized for SN discovery, providing additional SN search epochs. When such an orient is not available, we will consult with the Frontier Field team at STScI to provide the most useful parallel observations (e.g. for improving cluster weak lensing constraints).

■ Justify Duplications

This program is essentially a resubmission of an approved multi-cycle ToO program from Cycle 21 (PI:Rodney, PID:13386,13790). The proposal in Cycle 21 anticipated a total sample of ∼20 SNe over 3 years, requiring 60 orbits of HST Target of Opportunity (ToO) follow-up observations. This forecast was based on the expected yield from the HFF survey alone. The approval of the GLASS program in Cycle 21 roughly doubled the effective survey volume, and as GLASS had no dedicated HST follow-up resources, we have used our FrontierSN orbits to follow the GLASS discoveries as well.

We have used **34 orbits** from our FrontierSN allocation for follow-up imaging and spectroscopy of 10 transient candidates found in the GLASS and HFF survey imaging. Of these 34 orbits, half were spent on just two objects of interest, SN Tomas (Figure 1) and Spock (Figure 2). This was in keeping with our initial expectations in the Cycle 21 FrontierSN proposal, where we anticipated roughly half of our 60-orbit allocation would be spent on such high-impact objects.

However, our predictions for HST follow-up needs were shattered by the unprecedented discovery of the multiply-imaged SN Refsdal. To classify this SN and confirm its redshift, we acquired a new allocation of 36 orbits for HST grism spectroscopy and optical imaging through a director's discretionary program. It was also necessary to commit another **24 orbits** from our FrontierSN program for IR imaging to collect the SN light curve, which enables a measurement of the gravitational lensing time delay. This leaves us with only 2 orbits left for follow-up of any SNe found in the remaining 5 months of HFF imaging in Cycle 22, plus the entirety of Cycle 23.

■ Past HST Usage

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

Table 1. Past HST Usage for PI

PID	Title	Status	Selected Publications*
12060-64, 12440-45	CANDELS	Cycle 18-20 MCT; 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; complete.	Postman et al. 2012 Coe et al. 2013
12099, 12461, 13063	C+C SN Follow-up	Cycle 18-20 MCT; complete.	Rodney et al. 2012 Frederiksen et al. 2012 Jones et al. 2013 Graur et al. 2014 Rodney et al. 2014 Rodney et al. 2015a
13046	RAISIN	Cycle 20 ToO; complete	...
13386,13790	FrontierSN	Cycle 21-23 ToO; precursor to this proposal	Kelly et al. 2015 Rodney et al. 2015b

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

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