CLASH Summary and Science Priorities: The Cluster Lensing and Supernova survey with Hubble (CLASH) couples the gravitational lensing power of 25 massive intermediate redshift galaxy clusters with HST’s newly enhanced panchromatic imaging capabilities (WFC3 and a restored ACS) to test structure formation models with unprecedented precision. The HST observations, combined with existing wide-field imaging from Subaru, represent a giant advance in the quality and quantity of strong lensing data, enabling the measurement of dark matter (DM) mass profile shapes and mass concentrations from hundreds of multiply imaged sources that, in turn, provide precise (detect deviations between data and theory as small as ~15% at a 99% confidence level) observational challenges to scenarios for the DM mass distribution. The strongly lensing clusters in our sample give us a tenfold advantage over field surveys in identifying galaxies with $z > 7$ for which spectra can be obtained with large ground-based telescopes. In parallel with this lensing survey, we will use both ACS and WFC3/IR to detect type-Ia supernovae (SNe Ia) in the space-unique redshift range $1 < z < 2.5$. Because the SNe Ia will be detected when these cameras are in parallel, they will be far from the cluster core where the effects of lensing are small (and correctable), making the SNe usable for improving the limits on the redshift variation of the dark energy equation of state. Our top 4 science priorities for CLASH are, thus:

1. Map, with unprecedented accuracy, the distribution of dark matter in galaxy clusters using strong and weak gravitational lensing.

2. Detect Type Ia supernovae out to redshift $z \sim 2$, allowing us to test the constancy of dark energy's repulsive force over time and look for any evolutionary effects in the supernovae themselves.

3. Detect and characterize some of the most distant galaxies yet discovered at $z > 7$ (when the Universe was younger than 800 million years old - or less than 6% of its current age).

4. Study the internal structure and evolution of the galaxies in and behind these clusters.

CLASH Program Status: We obtained the first CLASH observations for Abell 383 on November 18, 2010. Observations of 10 of the 25 CLASH clusters will be performed in cycle 18. As of today (March 25, 2011) we have completed all observations for 2 of these 10 cycle 18 targets (Abell 383 and MACS1149+2223) and have begun to observe our 3rd cluster – Abell 2261. Figure 1 shows a color image of the core of Abell 383 made from the 16-filters. The observations are executing very well and we have had no major glitches to date. The schedule for
cycle 18 is shown in Figure 2. We currently are planning to observe 10 more clusters in cycle 19 and the remaining 5 clusters in cycle 20. We don’t foresee any issues with staying on track with this schedule.

We (and the community at large) have been making good progress scientifically:

- The first scientific paper to use CLASH data was published by researchers not on the CLASH science team. The paper (Richard et al. 2011; astro-ph/1102.5092) reported the discovery of a lensed z=6.03 galaxy behind Abell 383. This was a new discovery enabled by the far-red ACS and WFC3/IR data. A spectrum of the galaxy was obtained with Keck and shows a probable Ly-α emission line. The spectrum was enabled by the 11.4x magnification, one of the many desired objectives of the CLASH program.
- The first scientific paper written by the CLASH science team is being submitted
to ApJ the week of March 28 (Adi Zitrin et al.). This paper presents a detailed analysis of the total mass distribution in A383 as derived from our strong and weak lensing constraints. Zitrin (the first author) is a graduate student nearing completion of his Ph.D. from Tel Aviv University. The CLASH data have revealed 13 new multiply-lensed images (not previously known), so that a total of 27 multiple-images of 9 systems are used to tightly constrain the cluster’s inner mass profile. The critical radius of Abell 383 is modest by the standards of other lensing clusters, $r_{\text{Einstein}} = 16 \pm 2''$ (for $z_{\text{Source}} = 2.55$), so the relatively large number of lensed images uncovered here with precise photometric redshifts validates our imaging strategy.

- The supernova search program has yielded a total of 6 candidates in our first two clusters. Three of these are $z \sim 1$ or greater and the rest are $z < 0.4$. One of the $z \sim 1$ candidate supernova was co-discovered both by the CLASH team and by Saul Perlmutter’s team. For the SNe that can be followed up from the ground (typically when $z < 0.7$), we have been posting their positions and finding charts on the SkyAlert and VOalert networks. See http://www.skyalert.org/events/all/50/.

![Figure 2: The current cycle 18 CLASH observation schedule.](image)

**CLASH Science Team:** The CLASH science team now consists of 41 researchers at 19 institutions. We do not envision any major growth to the size of our team but 2 or 3 new additions are possible. Of the 41 collaborators, 19 are at U.S. institutions. In spite of the 13 time zones our team spans, the collaboration is working well. We have been having bi-weekly telecons and we are now planning our second all-hands meeting – to take place sometime at the end of summer. A smaller 1-day team meeting with about half of the collaborators has been scheduled to follow the STScI May Symposium on Dark Matter. On the U.S. side, two post-doctoral fellows have been hired (1 at JHU, 1 at STScI) and are here and working hard. A third postdoctoral fellow will be supported on the CLASH grant starting in April 2011.

**External Collaborations:** The collaboration with the CANDELS supernova search
program has been very smooth. The CLASH/CANDELS supernova team works as a single unit, has weekly telecons, has shared data storage facilities, and a single shared pipeline. Both teams have benefitted from this collaboration. We have also developed a new collaboration with researchers at Caltech to obtain SZE observations of all our clusters using Bolocam at the CSO in Hawaii and with MUSTANG on the GBT in West Bank, VA.

**ACS Failure Contingency:** We were asked to comment on a contingency plan if ACS were to fail. For CLASH, the primary impact of such a failure would be the loss of the supernova search component of the survey. We would clearly not have a parallel observing capability without ACS. The primary dark matter and high-z galaxy science, however, could be preserved completely. We could conduct the ACS passband exposures with the UVIS channel on WFC3. WFC3 has all of the key ACS filters we currently use. There would be noticeable SNR reduction in the redder filters (F775W, F814W, F850LP). If we wanted to exactly match the current depth of our ACS/WFC far-red imaging with WFC3/UVIS, we would have to increase those exposures by about a factor of 2. Doing so would add 4 orbits per cluster to the program (hence, 90 orbits total to the entire MCT over 3 cycles – since 2 of the clusters are now done we would only need to augment the remaining ones). However, because we would not be performing a supernova search in parallel fields, we could abandon the 8-epoch/2-orientation observation strategy, which would actually allow the cluster observations to be completed on a far shorter timeframe. The total area imaged in the 16 filters would also increase slightly because observations could be done at a single orientation. However, the loss of the larger FOV of ACS would mean that some outskirt regions of the cluster would not be surveyed and might reduce overlap with radial coverage provided by our weak lensing measurements from our Subaru Suprime cam data. But we could live with that FOV loss.

**High-Level Science Products:** We are on track to produce a suite of high-level science products that will be made available to the community via MAST. Our plan is to release the initial products within 3 months from the end of each cluster's observing sequence. For Abell 383 and MACS1149, this means the first HLSP will be available in May 2011. The products to be released within 3 months of the end of each cluster’s observing sequence include:

- Co-added images of the clusters in each passband, both in native resolution and on our chosen master global coordinate grids (0.065''/pixel and 0.030''/pixel).
- Master detection images - 2 versions - one summing all filters and one summing just the NIR filters (optimal for high-z galaxy detection).
- Source lists for each cluster (with pixel and celestial coordinates, various photometric parameters).
- Photometric redshift catalogs for each cluster (including the redshift probability function, $\chi^2$, and best-fit SED model type).
• Color jpeg images of the clusters. On timescales of 6 months after a cluster observing sequence is complete we will release much improved photo-z catalogs. As we publish scientific papers, we will release the relevant supporting data (e.g., ground-based images and catalogs, x-ray data, spectroscopic observations, etc.) once each paper appears in print. We will also release software – e.g., improved photo-z estimation tools, better color image makers, lens modeling codes, etc. Indeed, we have already released a preliminary version of our color image software (called trilogy) – see http://www.stsci.edu/~dcoe/trilogy/Intro.html.

STScI Support: To date, the support from the Institute has been very good. STScI enabled a “guard dark” exposure program to help us mitigate IR persistence without having to use allocated science orbits. This was very useful. Our program coordinator did an outstanding job of implementing our phase II program. We have been allocated an RIA to help with some data reduction and python coding tasks as well. Ample disk space was purchased on the central storage system to provide a password-protected area on which the team could store proprietary results and access those data via MAST. MAST will also help set up the public CLASH HLSP website that we will use to distribute our products to the community. Finally, STScI is hosting the CLASH public website on its web server (see http://www.stsci.edu/~postman/CLASH/Home.html).

Lessons Learned: We have learned a couple of key things since the original phase I observing plan was crafted. These are:

1. Our WFC3-UVIS near-UV exposures (F225W, F275W) were originally split across visits and in some cases a single visit included only F225W and F275W. Our program calls for 1.5 orbits of exposure in each of these filters. After A383 and MACS1149 were observed this way, we concluded that aligning the images from these filters was extremely challenging since very few objects could be seen in any single exposure. The pipelines were able to align about 1 orbit’s worth of the F225W and F275W data but had great difficulty getting the full 1.5 orbits worth of exposures to align since that last 0.5 orbit was done on a second visit. To fix this, we have altered our phase II program for all our subsequent clusters (beginning with Abell 2261) to put all the F225W exposures into a single 2-orbit visit and include 2 exposures of F390W with them. Many objects are visible in F390W and that will then provide the alignment reference for the rest of the F225W data. Since we also require F390W data, the use of the F390W exposures does not use any additional orbit allocation. The same strategy is adopted for F275W as well. We just received our first data from Abell 2261 with this revised scheme and the full 1.5 orbit alignment worked fine. It should be noted that the F225W and F275W data are essential for removing degeneracies in photo-z redshift estimates for z < 0.5 galaxies. We have verified this in our improved ability
to determine cluster members in Abell 383 (z=0.189) when we use the UV photometry vs. when the UV data are excluded.

2. Our original phase I proposal did not call for use of the F435W and F625W filters. Subsequent to being awarded time, we did some refinements on our photo-z models and concluded that adding coverage in these two filters would significantly improve our ability to accurately predict redshifts for z < 1 objects. We thus included a 1-orbit exposure in each of these 2 filters for each cluster (sacrificing 1-orbit of F606W and 1-orbit of F814W). Preliminary comparisons with galaxies in A383 and MACS1149 that have spectra suggests we are achieving our goal of photo-z uncertainties that are ~2% x (1 + z) or better.