Summary of Recommendations

We present the Strong Lensing Science Collaboration’s (SLSC) recommended observing targets for the science verification and science validation phases of commissioning. Our recommendations have been developed in collaboration with the Dark Energy Science Collaboration (DESC) Strong Lensing Topical Team. In summary, our key recommendations are as follows:

1. Prioritize fields that span the full range of declination observable from Cerro Pachón during the engineering focused Science Verification phase of commissioning, before concentrating on equatorial fields for the Science Validation surveys.
2. Observe quadruply lensed quasars as the ultimate test of the Active Optics system towards the end of the Science Verification phase of commissioning. These systems are the strongest tests known for delivered image quality (DIQ; Figure 1).
3. Prioritize candidate science validation survey fields (both single deep pointings and wide fields) that have been searched thoroughly by precursor surveys for strong lenses.
4. The optimal wide ($\approx 100$ degree$^2$) science validation field would include the CFHT-LS W4 field, and overlap with the SDSS Stripe 82, DES-SN, KIDS and HSC-SSP fields.
5. The optimal single pointing science validation fields are the XMM-LSS and COSMOS Deep Drilling Fields, the equatorial Hubble Frontier Fields galaxy clusters, and strongly lensed quasars with measured time delays that are well-matched to commissioning timescales.
1 Introduction

This document is the Strong Lensing Science Collaboration’s (SLSC) “Commissioning Note”, and has been prepared in response to the Rubin Project’s call for community input to the on-sky observing strategy during commissioning. Recommendations from the SLSC contained in this Note span both the science verification and science validation phases of commissioning. Our understanding is that the Rubin Project Team define the former as primarily an engineering-focused phase in which opportunistic on-sky observations with ComCam and LSSTCam will be performed. We understand that science verification will be followed by sustained on-sky observing which aims to achieve at least ten-year depth and to enable testing of transient detection via two complementary science validation surveys.

Strong gravitational lensing is broadly accepted as having huge potential for major scientific breakthroughs in the next 10+ years. These breakthroughs are expected to span a diverse range of high impact topics including testing cold dark matter predictions on sub-galaxy scales, measurements of the Hubble parameter independent of the cosmic distance ladder based on time delay cosmography (e.g. Suyu et al. 2013), novel constraints on the dark energy equation of state parameter from multiple source-plane lenses (Jullo et al. 2010; Collett & Auger 2014), discovery of optical counterparts to gravitationally lensed gravitational waves (Smith et al. 2019), and a new window on high redshift galaxy evolution.

Our ability to achieve breakthrough strong lensing science is fundamentally limited by the number of known strong lenses across the dark matter halo mass function, from galaxy-scale lenses through to the most massive cluster-scale lenses. Rubin’s Wide Fast Deep survey therefore has the potential to revolutionize strong lensing science by expanding the number of lenses by three orders of magnitude from hundreds to hundreds of thousands. Realising this expansion relies in turn on the quality of the data products delivered by Rubin, both in low latency as “Prompt Products” (PP) and on longer timescales as “Data Release Products” (DRPs) and the template images used in difference image analysis (DIA).

In this Note we recommend commissioning fields that will enable a step-by-step approach to helping the Rubin Construction Project pass the Operations Readiness Review (ORR), and ensuring that Rubin data will enable strong lensing science promptly once survey operations commence. Each step will be critical, beginning with verifying the performance of the active optics system with quadruply lensed quasars, validating the quality of PPs, DRPs and template images during the science validation phase, and then running the lens discovery pipeline that we are developing jointly with DESC on the second data preview (DP2). Here we describe the selection of the fields themselves, and discuss them in relation to pre-ORR science validation and verification tasks. Our early science plans for DP2 lie beyond the ORR and are therefore outside the scope of this Note.

We organise our recommendations under science verification (Section 2) and science validation (Section 3), list the commissioning fields that we recommend in Table 1, and summarize our preferred science validation survey scenarios by quarter in Table 2.

1https://community.lsst.org/t/community-input-to-the-on-sky-observing-strategy-during-commissioning/4406
2 Recommended fields for Science Verification

Rubin’s delivered image quality (DIQ) is mission critical for many high profile science goals across LSST Science Collaborations. It is therefore essential to evaluate and optimize Rubin’s DIQ prior to the beginning of science operations using well-defined and challenging scientific “use cases”. Strongly lensed point sources (i.e. quasars and explosive transients) in early type galaxies are the strongest use cases that we have identified so far, driven by the challenges of source crowding and the resulting complex background.

The numerous strongly lensed quasars that have been discovered to date therefore provide a valuable resource from which to select science verification targets. In particular, lensed quasars span a wide range of right ascension, and the brightness of the quasar images are typically well-matched to Rubin’s single-visit depth. Importantly, lensed quasars have for many years been a classic filler/snapshot target list from which an object can be selected quickly when engineering allows on-sky observations.

We have selected eight quadruply lensed quasars that have multiple image separations in the range 0.6 – 1.5 arcseconds, and are thus resolvable in a range of observing conditions (Table 1). The targets span a range of right ascension and declination such that they span the full calendar year and both northern and southern skies as seen from Cerro Pachón. All eight targets are at relatively low airmass for many hours each night; the most northerly system (SDSS J0924+0219) is observable for 2–5 hours per night at airmass<1.5 during November to May. Whilst all targets have been selected for their role in testing the DIQ in commissioning, SDSS J0924 is also ripe for large caustic crossing events for which a 600 ksec target of opportunity programme with Chandra has recently been awarded. This adds considerable scientific interest to these engineering-focused observations.

We emphasize that the visual impression one gets of a lensed quasar is exquisitely sensitive to small variations in image quality. In Figure 1 we show images of the quadruply lensed quasar DES J0405−3308, taken with DECam on the Blanco telescope. Relatively small differences in the DIQ produce dramatic differences in its appearance. Visual inspection of the data at the telescope during science verification observations will therefore give the commissioning team immediate valuable feedback on DIQ variations before the data are analyzed and quantitative measurements are made.

We recommend that each lens is observed through a single filter, ten times during a visit: twice at the center of the field, and once at each the corner of the 3 degree field, and once each at 3, 6, 9 and 12 o’clock. Repeat visits – returning to a quad quasar to repeat this series of ten observations – will also permit assessment of DIQ and feedback on the performance of the active optics system in different seeing conditions and telescope state, and provide invaluable tests of the reproducibility of test results.

In summary, we recommend to test the DIQ performance of the Simonyi Telescope in the most demanding manner possible in the latter stages of science verification. These tests are ideally accomplished through the observations of the targets described here, supported by an individual with strong lensing expertise embedded within Rubin’s SIT-Com team. This individual would interact closely and rapidly with hands-on commissioning colleagues. The core activity would be to analyze Rubin data and measure covariances between observed quantities that depend sensitively on
Figure 1: The impact of small differences in DIQ is very stark and motivates our recommendation to observe quadruplets in the latter stages of science verification (Section 2). Here we show SDSS r-band images of DES J0405−3308 (a quadruply imaged quasar) from the DECam instrument on the Blanco telescope. Each cut-out is from an observation with an exposure time of 90 seconds, and is based on real data, not simulations. The pixel scale is 0.263 arcsec, and thus the full width at half maximum (FWHM) of point sources in each panel is FWHM = 1.37″ (top left), FWHM = 1.18″ (top right), FWHM = 1.16″ (bottom left), and FWHM = 1.08″ (bottom right). All panels are scaled to the same stretch, and the photometric zeropoints are the same within 0.05 magnitudes.

image quality and system / atmospheric quantities including DIMM seeing, airmass, windshake, mirror temperature and residual wavefront error at varying distances from the field center.

3 Recommended fields for science validation surveys

During science validation it is essential to validate that the Rubin Observatory and her Science Pipelines are capable of delivering science-grade data on strong gravitational lenses. We stress that before the ORR, we are interested in validating the robustness of the pixel data and the catalogues derived from those pixels, and not on science. Robust validation tests require commissioning observations of fields that contain a large number of strong lenses that have been discovered and studied by precursor surveys. These considerations, and looking ahead to early science in DP2, both motivate prioritizing equatorial fields for science validation surveys. This is because observing to the North of Cerro Pachón maximizes the overlap with both precursor surveys and observatories that can conduct follow-up observations of new discoveries based on DP2.

We recommend specific wide fields and single pointings that satisfy the over-arching criteria outlined above in Sections 3.1 and 3.2 respectively. In summary the wide fields prioritize equatorial CFHT-LS fields, and the single pointings include carefully selected galaxy- and cluster-scale lenses, in addition to the COSMOS and XMM-LSS Deep Drilling Fields. All recommended science validation fields are listed in Table 1, including the months of the year in which each field is observable for ≥2 hours per night at airmass≤1.5. We also summarise our preferred science
validation fields by quarter in Table 2. This table highlights that there is overlap in our preferred fields with those listed in Table 2 of the DESC Commissioning Note (Amon et al., 2020).

3.1 Wide fields for science validation

We recommend that wide field science validation surveys observe the equatorial fields from CFHT-LS, namely W1, W2, W4 (Table 1). These are the most thoroughly explored regions of the sky for strong lens discovery, both initially by colleagues using CFHT-LS data, and more recently by colleagues in surveys (KIDS, HSC-SSP) whose footprints expand on the original CFHT-LS fields. In anticipation of ten-year depth observations being limited to $\sim 100–200$ degree$^2$, these CFHT-LS fields offer the perfect criterion on which to select a sub-region of these wider and newer surveys. Should time allow, we recommend to expand these CFHT-LS wide survey footprints into the surrounding KIDS and HSC-SSP equatorial fields.

We strongly disfavor observing a $\sim 100–200$ degree$^2$ region of the DES footprint during science validation because the DES image quality and depth is generally not as good as that of CFHT-LS and HSC-SSP. However, the CFHT-LS W4 field discussed above overlaps with the SDSS Stripe 82, which is included within the DES footprint. Therefore if the observing season allows, a W4/S82-based science validation survey may be optimal (Table 2).

3.2 Single pointings for science validation

Among the LSST Deep Drilling Fields, we strongly prefer XMM-LSS and COSMOS because they match the LSSTCam field of view well, are equatorial, and have been searched previously for strong lenses. Also, the XMM-LSS field is located within the CFHT-LS W1 field discussed above. Equally, we strongly disfavor the ECDFS and ELAIS S1 as science validation fields because they don’t satisfy these criteria.

Turning to pointed observations of known strong lenses, we agree with the galaxy-scale lenses put forward by DESC (Amon et al., 2020), and include them in our Table 1. We prefer clusters that are (1) known as strong lenses, (2) are well studied, (3) are at equatorial declinations, and (4) that have larger Einstein radii. Applying these criteria to the known cluster lenses, we obtain the clusters listed in Table 1. They span the full range of right ascension, and many of them are also listed by Amon et al. (2020). In a nutshell, the optimal cluster-scale lens for science validation observations is one of the Hubble Frontier Fields, due to the wealth of superb data from precursor surveys. Among the Frontier Fields, Abell 370 is our highest priority due to it being equatorial.

Acknowledgments

We thank our colleagues in the Strong Lensing Science Collaboration and Dark Energy Science Collaboration Strong Lensing Topical Team for their support and assistance during the preparation of this note. We thank Keith Bechtol in particular for his patient support, advice, and encouragement. GPS acknowledges support from The Royal Society, Leverhulme Trust, and the Science and Technology Facilities Council.
References

Amon A., et al., 2020, arXiv:2010.15318
Collett T., Auger M., 2014, MNRAS, 443, 969
Jullo E., et al., 2010, Science, 329, 924
Smith G. P., et al., 2019, arXiv:1902.05140
Suyu S. H., et al., 2013, ApJ, 766, 70
| Target name | R.A., Dec. [J2000] | Observable | Priority | Comment |
|-------------|--------------------|------------|----------|---------|
| 0029–3814   | 00:29:41 –38:14:26 | May–Dec    | A        |         |
| 0214–2104   | 02:14:16 –21:05:35 | Jun–Jan    | B        |         |
| 0420–4037   | 04:20:47 –40:37:27 | Jul–Mar    | A        |         |
| SDSS J0924+0219 | 09:24:56 +02:19:25 | Nov–May    | A+       | Time delay = 2days; Chandra ToO |
| 1131–4419   | 11:31:00 –44:19:59 | Dec–Jul    | A        |         |
| PS 1606–2333 | 16:06:00 –23:33:22 | Feb–Sep    | A        | Time delays ~10–45days |
| WFI 2026–4536 | 20:26:10 –45:36:27 | Apr–Nov    | A        | Time delay =19days |
| 2100–4452   | 21:00:15 –44:52:07 | Apr–Nov    | B        |         |
| HE 0230–2130 | 02:32:33 –21:17:26 | Jul–Jan    | A        | Time delay = 16days |
| DES 0408–5354 | 04:08:22 –53:54:00 | Jul–Mar    | B        | Compound lens; Time delay > 40days |
| SDSS J0924+0219 | 09:24:56 +02:19:25 | Nov–May    | A+       | See above |
| HSC J142449–005322 | 14:24:49 –00:53:22 | Feb–Aug    | A        | Compound lens |
| PS 1606–2333 | 16:06:00 –23:33:22 | Feb–Sep    | A        | See above |
| WFI 2026–4536 | 20:26:10 –45:36:27 | Apr–Nov    | B        | See above |
| ELAIS S1    | 00:37:48 –44:00:00 | May–Dec    | D        | Not searched for strong lenses |
| XMM-LSS     | 02:22:50 –04:45:00 | Jul–Jan    | A+       | Overlaps CFHT-LS W1 |
| ECDFS       | 03:32:30 –28:06:00 | Jul–Feb    | D        | Not searched for strong lenses |
| COSMOS      | 10:00:24 +02:10:55 | Dec–May    | A        | Overlaps CFHT-LS D2 |
| Abell 2744  | 00:14:21 –30:23:50 | May–Dec    | B        | Hubble Frontier Field |
| MACS J0138.0–2155 | 01:38:04 –21:55:49 | Jun–Jan    | A        |         |
| Abell 370   | 02:39:53 –01:34:37 | Jul–Jan    | A+       | Hubble Frontier Field |
| MACS J0416.1–2403 | 04:16:09 –24:04:29 | Jul–Mar    | A+       | Hubble Frontier Field |
| RXC J0600.1–2007 | 06:00:10 –20:08:09 | Aug–Apr    | A        |         |
| 1E0657–558 | 06:58:38 –55:57:00 | Sep–May    | B        | Bullet cluster |
| Abell 0868  | 09:45:26 –08:39:06 | Nov–Jun    | A        |         |
| MACS J1206.2–0847 | 12:06:12 –08:48:02 | Dec–Jul    | A        |         |
| Abell 1689  | 13:11:34 –01:21:56 | Jan–Jul    | A        |         |
| Abell 1835  | 14:01:02 +02:52:43 | Jan–Jul    | A        |         |
| Abell 2204  | 16:32:47 +05:34:14 | Mar–Aug    | A        |         |
| PLCK G004.5–19.5 | 19:17:05 –33:31:29 | Mar–Oct    | B        |         |
| MACS J2140.2–2339 | 21:40:15.2 –23:39:40 | Apr–Nov    | A        | Bright radial arc |
| Abell S1063 | 22:48:44 –44:31:49 | May–Dec    | B        | Hubble Frontier Field |
| CFHT-LS W1  | 02:18:00 –07:00:00 | Jul–Jan    | A        | Overlaps XMM-LSS |
| CFHT-LS W2  | 08:57:49 –03:19:00 | Nov–May    | A        |         |
| CFHT-LS W4  | 22:13:18 +01:19:00 | May–Nov    | A+       | Overlaps DES, KIDS, HSC, S82 |
Table 2: Strong Lensing Science Collaboration recommended science validation survey scenarios by quarter

| Field type  | Preferred            | Back-up            | Comment                                      |
|-------------|----------------------|--------------------|----------------------------------------------|
|             | **JANUARY–MARCH**    |                    |                                              |
| Wide-field  | CFHT-LS W2           | CFHT-LS W1         |                                              |
| Galaxy lens | SDSS J0924+0219      | DES 0408–5354      |                                              |
| Cluster lens| A0868                | MACS J1206.2–0847  |                                              |
| LSST DDF    | COSMOS               | ECDFS              | Strong preference **against** ECDFS.         |
|             | **APRIL–JUNE**       |                    |                                              |
| Wide-field  | CFHT-LS W2           | CFHT-LS W4         |                                              |
| Galaxy lens | SDSS J0924+0219      | HSC J142449–005322 |                                              |
| Cluster lens| Abell 1689           | Abell 2204         |                                              |
| LSST DDF    | COSMOS               | ELAIS S1           | Strong preference **against** ELAIS S1.      |
|             | **JULY–SEPTEMBER**   |                    |                                              |
| Wide-field  | CFHT-LS W4           | CFHT-LS W1         |                                              |
| Galaxy lens | HE 0230–2130         | PS 1606–2333       |                                              |
| Cluster lens| MACS J2140.2–2339    | Abell 2744         | Abell 2744 is a Hubble Frontier Field.       |
| LSST DDF    | XMM-LSS              | ELAIS S1           | Strong preference **against** ELAIS S1.      |
|             | **OCTOBER–DECEMBER** |                    |                                              |
| Wide-field  | CFHT-LS W4           | CFHT-LS W1         |                                              |
| Galaxy lens | SDSS J0924+0219      | HE 0230–2130       |                                              |
| Cluster lens| MACS J0416.1–2403    | Abell 370          | Both are Hubble Frontier Fields.             |
| LSST DDF    | XMM-LSS              | ECDFS              | Strong preference **against** ECDFS.         |