Science White Paper for LSST Deep-Drilling Field Observations

Ultra-deep ugrizy Imaging to Reduce Main Survey Photo-z Systematics and to Probe Faint Galaxy Clustering, AGN, and Strong Lenses

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Summary: As a highly ambitious photometric survey, LSST will be limited by systematics in the determination of photometric redshifts, most importantly in its study of dark energy. Because of their increased sensitivity, the Deep Drilling Fields (DDFs) will improve our knowledge about the selection function of the main survey, which is critical for accurate cosmological parameter estimation. These observations will also allow us to 1) correct for the apparent clustering signal that results from lensing magnification of objects fainter than the normal survey magnitude limit, 2) measure the clustering properties of faint galaxies, and 3) identify faint populations of AGN.

Concentrating on a few fields enables ultra-deep LSST photometry and the best possible multi-wavelength imaging and spectroscopy, but with fewer than five fields we would be limited by cosmic variance. We therefore advocate imaging five fields as deeply as possible over ten years, spending 1% of LSST survey time on each, with a filter time distribution that favors ugriz in order to optimize photometric redshifts without trying to go deeper than the source confusion limit in gri. We identify a set of fields at high Galactic latitude that offer the best complementary multiwavelength coverage.

We urge the Science Council not to finalize the number of fields, filter time distribution, or cadence for DDFs until detailed studies can be conducted to quantify the requirements for joint optimization of Main Survey and DDF science.

1 Science Goals

1.1 Concise List of Main Science Goals

1. Test and improve photometric redshifts critical for LSST Main Survey science.

2. Determine the flux distribution of galaxy populations dimmer than the Main Survey limit that contribute to clustering signals in the Main Survey due to lensing magnification.

3. Measure clustering for samples of galaxies and Active Galactic Nuclei (AGN) too faint to be detected in the Main Survey.

4. Use an optimized cadence to yield significant improvements in the detection and study of AGN, strong lenses, and transients including supernovae.

1.2 Details of Main Science Goals

1.2.1 Photometric Redshifts

Photometric redshifts will be used to select samples for all four main probes of dark energy, namely baryon acoustic oscillations (BAO), weak gravitational lensing, galaxy clusters, and Type Ia supernovae. Hence the dark energy inference will be limited by the quality of our photo-$z$’s, so we need to understand photo-$z$ systematics and outliers to high accuracy (e.g., Ma et al. 2006, Bernstein &...
Any improvements that can be made to photo-z’s via better calibration of templates and priors will result in direct improvements in Main Survey science.

Although extensive photo-z simulations will be performed on mock galaxy catalogs, cross-correlation methods have the advantage of working with real data and are therefore the primary means envisioned for the final calibration. Spatial cross-correlation with spectroscopic samples can determine the true redshift distribution of a set of galaxies chosen to have photo-z’s in a given range (Newman 2008, Matthews & Newman 2010). Likewise, angular cross-correlation between galaxies in different bins of photo-z can reveal the fraction of interlopers at each redshift in a given bin (Zhan & Knox 2006, Zhan et al. 2009), and this becomes the method of choice when spec-z’s are not available. Measuring the true redshift distribution of galaxies in a bin of photo-z does not immediately reveal the photo-z error distribution on each galaxy; determining that requires a complicated deconvolution. The process is made easier by starting with smaller errors, which allows cross-correlation to work more precisely and leaves less uncertainty in the deconvolution.

Because appropriately complete spectroscopic samples cannot be obtained easily over large fractions of the sky, we must rely on a subset of the LSST area with the highest sky density of spectroscopic redshifts for photo-z calibration. If the photo-z’s of particular types of galaxies across a wide range of redshifts can be calibrated sufficiently well in these regions, photo-z’s of those galaxy types located elsewhere on the sky can be used as secondary calibrators for the rest of the Main Survey. This goal is aided by having the best possible ugrizy and multi-wavelength photometry in the same regions of sky in order to have the best possible photo-z’s, leading to the highest precision calibration via cross-correlation. The photometry can then be degraded by adding noise to simulate the photo-z error distribution expected over the rest of the Main Survey.

Photometric redshift calibration will therefore be optimized in DDFs chosen to have the highest sky density of spectroscopic redshifts, the best multiwavelength coverage, and the deepest possible LSST ugrizy imaging. Better photometry will lead to a reduction in catastrophic errors as well as RMS, and it allows for empirical tests of how photo-z aliasing moves objects into and out of samples. This aliasing occurs in multiple ways; objects dimmer than a “gold sample” limit can enter the sample due to artificially bright fluxes in the selection band, and errors in object colors can shift their photometric redshifts into a different bin due to either small or catastrophic errors in photo-z. We want to use the deepest possible photometry to quantify these effects. Then we can recalculate the photometric redshifts and optimize the choice of survey limits and photo-z bin widths.

We assume that the main survey comprises 90% of LSST time covering 20,000 square degrees with 2000 pointings of 10 square degrees each and that the (extragalactic) DDFs receive 5% of LSST time and have the same ratios of exposure in the 6 filters as the main survey. Then the increase of the limiting magnitude of the DDFs over the main survey is given by \( \Delta m = 1.25 \log(111/N_F) \), where \( N_F \) is the number of DDFs. For our suggested approach of \( N_F = 5 \), this yields combined ten-year images 1.7 magnitudes deeper than the Main Survey in each filter, which we call the “Baseline DDF” in Table 2. Photometric redshifts are limited by the depth in the shallowest bands, especially when those bands are at the endpoints of the wavelength coverage. In order to optimize photometric redshifts, we also suggest a “Near-uniform DDF” scheme in Table 2 which redistributes filter time from gri into uzy. Using 1% of LSST time per DDF with a similar filter distribution scenario was suggested previously in the Science Book, §9.8. Detailed photo-z simulations are underway to quantify the improvements that will result from DDFs with the suggested combinations of total integration time and filter distributions.

### 1.2.2 Properties of Dim Galaxies

One key benefit that the DDFs will provide for large-scale structure studies is eliminating uncertainties in large-scale structure measurements due to magnification from weak lensing. Even if they are
separated on sufficiently large scales that matter correlations are minimal, the observed locations of background galaxies or QSOs will correlate with the presence of objects in the foreground due to magnification from gravitational lensing. This will cause objects that would normally be fainter than the flux limit of a given sample to be brought above that threshold, causing an increase in the density of objects in the background sample near foreground objects. Hence, lensing magnification will cause the observed cross-correlation between two samples of objects to be greater than that expected from real-space correlations (Turner, Ostriker & Gott 1984; Narayan 1989; Bartelmann 1995). This phenomenon has now been observed in data from the Sloan Digital Sky Survey (Scranton et al. 2005).

Cross-correlation measurements will be a key tool for calibrating LSST photometric redshifts (Newman 2008); for this calibration to be accurate, we must constrain the lensing magnification effects well (Bernstein & Huterer 2010). The strength of the observed cross-correlation from magnification is proportional to the product of $\Omega_m$, the matter power spectrum convolved with a lensing kernel depending on the redshifts of foreground and background objects, and $(\alpha(m)-1)$, where $\alpha(m)$ describes the magnitude distribution of the background sample at the sample magnitude limit $m$, $\alpha = 2.5 \log_{10} N(<m)/dm$. An accurate determination of $\alpha$ (or, for more complicated selections, a characterization of the flux distribution of faint objects which may be scattered into the sample) will be key for eliminating lensing magnification as a systematic from cross-correlation measurements, and can only be achieved using deeper-than-normal observations.

Bernstein & Huterer estimate that $\alpha$ must be measured to 2.5% for it not to dominate the redshift uncertainties. Based on the experience of Coil et al. (2004), the slope of number counts can be measured well when we have a $\sim 1$ mag lever arm; hence, we can determine this slope at the sample limit, $m$, using objects with magnitudes from $m-0.5$ to $m+0.5$. Therefore, for this purpose we require DDFs to be at least $\sim 0.5$ mag deeper than the main LSST survey. We expect that cosmic variance will dominate the uncertainty in $\alpha$. Using the cosmic variance code QUICKCV (Newman & Davis 2002), we find that, for a sample of objects with correlation length $r_0 = 4h^{-1}$ Mpc (fairly typical of observed samples at $z = 0-4$), over the redshift range $1.9 < z < 2.1$ (representing a single redshift bin for LSST lensing background galaxies), the number of objects will vary by 3.5% from one LSST field to another. We expect the uncertainty in $\alpha$ from a single LSST field to roughly match the uncertainty in the ratio of the abundance in two redshift bins, which is 4.9%. In that case, we must average measurements from 4 LSST deep drilling fields to achieve the 2.5% accuracy required.

Since lensing magnification by large-scale structure (i.e. beyond the smallest scales) should only very rarely cause apparent brightness to increase by 60% or more, any deep drilling strategy which goes at least 0.5 mag deeper in all bands should be sufficient for this science goal. Since errors in the DDF galaxy magnitude distribution will be dominated by “cosmic” variance, the uncertainty in $\alpha$ will decrease as $N_{\text{fields}}^{-1/2}$; $\sim 5$ deep drilling fields should be sufficient, while a greater number would provide additional insurance.

1.2.3 Clustering of Faint Galaxies and AGN

The DDFs will enable studies of galaxies and AGNs that are fainter than those in the main sample. Even though the DDFs will produce a much higher number density of objects than the main survey, these objects will not significantly improve the measurement of small scale galaxy clustering properties beyond what the main survey can do. Rather, these objects are interesting to study in their own right, because they are from different populations either with low luminosities or at very high redshifts.

With a conservative value of the faint-end slope of the luminosity function $d \log N_g/dm = 0.4$,
and substituting the formula for $\Delta m$ given in §1.2.1, we get the increase of the galaxy number density

$$\frac{\Delta n_g}{n_g} = 1.15 \log \frac{111}{N_F}.$$  

According to the Science Book (§3.7.2), the main survey will obtain roughly 40 galaxies per sq arcmin, so we expect to find 102 (56) galaxies per sq. arcmin if there are 5 (50) DDFs. Here we have not accounted for other factors such as the confusion limit. The main survey will measure clustering with high precision for galaxies brighter than the “gold sample” limit of $i = 25.3$, so the samples of interest here are the differential set of 62 galaxies per sq. arcmin with $25.3 < i < 27.0$ given 5 DDFs and of 16 galaxies per sq. arcmin with $25.3 < i < 25.7$ given 50 DDFs.

Figure 1: S/N per bin in $\ell$ at which galaxy clustering can be measured. The S/N is calculated for a galaxy bin centered around $z = 1.7$ with a width of 0.12 in photo-z (see, e.g., Fig 13.4 in the Science Book). Lines bracket the possible number of DDFs: 5 (solid) and 50 (dashed). We assume that 5% of the LSST observing time is split evenly between each DDF. Multipole $\ell = 1000$ corresponds to an angular scale of roughly 10 arcmin. While area wins out at large scales, the approach of 5 ultra-deep DDFs proposed here allows us to cover galaxies much dimmer than the Main Survey and measures their clustering with great precision.

Figure 1 shows the S/N obtained from a single bin at $1.64 < z_{\text{phot}} < 1.76$ for clustering of galaxies fainter than the Main Survey limit when splitting 5% of LSST time over 5 or 50 DDFs. On large scales (low $\ell$) the error is dominated by the sample variance, while on small scales it is dominated by the shot noise, i.e., the reciprocal of the galaxy surface density. It is seen that trading depth for area is effective in reducing statistical errors on large scales, but at the same time it will make the faint population inaccessible. Comprehensive studies of the trade-offs are needed to optimize the DDF survey design, but it is clear that pushing the DDFs as deep as possible is required to study galaxies significantly fainter than those found by the Main Survey, and that the available S/N from 5 DDFs is sufficient for this purpose.

Obtaining high S/N clustering measurements on galaxies so faint will provide a constraint on the relationship between galaxies/AGN and their dark matter halos and larger-scale environments.
for samples nearly 2 magnitudes fainter than in the Main Survey. We will also be able to measure number abundances as a function of luminosity and environment for galaxies and AGN too faint to be studied in the Main Survey. At $z = 4$, the standard LSST gold sample goes down to $L^*$, which will provide only very poor/degenerate constraints on $L^*$ and abundance. Our proposed DDFs go 1–1.7 mags deeper to reach the power-law tail, giving much stronger constraints on the luminosity function and its dependence on environment.

1.3 Supplementary Science

By offering the opportunity to probe beyond the Main Survey in the time domain, DDFs enable a wide range of new science. The depth and filter time distribution required to reach the above science goals provide constraints on the total exposure times but not the detailed cadence, leaving sufficient flexibility to pursue the following supplementary science goals:

1. Densely sampling the lightcurves of a range of extragalactic sources, including supernovae and AGN. The DDF lightcurves we propose will provide large samples of these objects, each with comparable S/N per observation to the Main survey but with $\sim 5$ times denser time sampling. If the observations are spread out in this way, we will be able to use them to study
   - AGN variability on the widest possible range of timescales, revealing transient activity of supermassive black holes.
   - The statistical properties of AGN lightcurves, and how they correlate with other AGN attributes.
   - The intrinsic lightcurve shapes of supernovae of all types.

   The results of this program will allow us to construct informative priors for use in detecting and measuring gravitationally lensed (and microlensed) AGN and supernovae in the Main survey.

2. Variability selection of AGN to fainter fluxes. The efficiency of Main Survey variability selection can be determined from these DDFs (Science Book §10.1,10.5).

3. Finding faint AGN, and tracing their evolution. The evolution of the faint end of the hard X-ray luminosity function is still very uncertain. As the DDFs will have deep multi-wavelength coverage, this end of the LF can be constrained. Moreover, the fueling and life-cycle of faint AGN may be different than high luminosity quasars, so studying these faint AGN will probe the physics of galaxy evolution and black hole fueling.

4. Studying Compton thick AGN. These are the most heavily obscured AGN, and a large fraction of them are thought to occur during major mergers and periods of rapid black hole growth. They often appear as ULIRGS in the O/IR, so very deep observations are needed to study them. Deep imaging with Chandra is already available in ECDF-S and COSMOS, and XMM imaging is available over an entire LSST pointing in the XMM/LSS field (see §3.1). NuSTAR plans to undertake deep hard X-ray surveys of the COSMOS field over the same time period as LSST, so we will be able to measure the spectral energy distributions of Compton-thick AGN over a range of redshift and luminosity.

5. Science from strong gravitational lensing will be enhanced by dense sampling of time delays. It will also benefit from improved accuracy of photometric redshifts, which are needed for statistical analysis of the full sample of strong lens time delays (Coe & Moustakas 2009).
2 Description of Proposed LSST Observations

2.1 List of Proposed Fields (see Table 1)

Table 1: Proposed Deep Drilling Fields. E(B-V) values from Schlegel et al. (1998) were determined at 600 points sampling a full LSST FOV centered on the listed coordinates.

<table>
<thead>
<tr>
<th>Field</th>
<th>RA</th>
<th>Dec</th>
<th>(l,b)</th>
<th>Ecliptic lat.</th>
<th>E(B-V) mean (95% range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELAIS S1</td>
<td>00:37:48</td>
<td>−44:00:00</td>
<td>311,−72</td>
<td>−43</td>
<td>0.008 (0.006–0.012)</td>
</tr>
<tr>
<td>XMM-LSS/UDS</td>
<td>02:22:50</td>
<td>−04:45:00</td>
<td>171,−58</td>
<td>−18</td>
<td>0.025 (0.020–0.033)</td>
</tr>
<tr>
<td>ECDF-S</td>
<td>03:32:28</td>
<td>−27:48:26</td>
<td>223,−54</td>
<td>−45</td>
<td>0.010 (0.007–0.016)</td>
</tr>
<tr>
<td>COSMOS</td>
<td>10:00:24</td>
<td>+02:10:55</td>
<td>236,+42</td>
<td>−9</td>
<td>0.025 (0.018–0.045)</td>
</tr>
<tr>
<td>DLS F5</td>
<td>13:55:00</td>
<td>−10:00:00</td>
<td>328,+50</td>
<td>+2</td>
<td>0.047 (0.036–0.062)</td>
</tr>
</tbody>
</table>

2.2 Motivation for Proposed Fields

We advocate placing deep drilling fields at the locations with the strongest present and future multiwavelength imaging and spectroscopy, as listed in Table 1. Multiwavelength photometry will provide a high-quality training set of photometric redshifts we can use to test methods, while spectroscopic data will be key for photo-z calibration. We strongly prefer fields at high galactic latitude, as this will minimize extinction; variable extinction can mimic the effects of galaxy clustering, and will have greatest impact in regions where the average extinction is large. The desire for deep multiwavelength observations drives us to also prefer fields at high ecliptic latitude, both to maximize observability from space and to minimize zodiacal background, which will interfere with our ability to obtain deep infrared data. This is in modest tension with the goal of preferring fields near the equator (and hence observable from the Northern hemisphere).

The abundance of rare objects (such as galaxy clusters) will vary by 16% from one LSST field to another in a \(\Delta z = 0.1\) wide bin at \(z=2\), or 27% in a bin of the same width at \(z=0.5\). With 5 fields, we can successfully identify which fields are outliers at each redshift; this is considerably easier with 5 fields than 4. Our scientific goals require significantly better sensitivity than the Main Survey and hence prefer the smallest possible number of extragalactic DDFs. We therefore choose 5 DDFs as a compromise between maximizing depth and minimizing cosmic variance.

The first four listed fields are well-known extragalactic deep fields with extensive multiwavelength coverage, as has already been presented to the Science Council. The listed fields are all at reasonable declination and high galactic latitude, but they offer a wide distribution in ecliptic latitude. There are several candidates for a fifth field of roughly equal quality; we show DLS F5 due to its convenient sky location, but we consider its low ecliptic latitude to be a disadvantage for complementary infrared imaging and spectroscopy (including JWST) due to high Zodiakal background. Other fields worthy of consideration as a fifth field include VIDEO-1 at 14:00+0500 and SSA22 at 22:17+0024 (see the Ferguson et al. Galaxies white paper for further discussion of these fields).

2.3 Observing Plan, Cadence, Filters, and Expected Depth

We propose deep drilling to last the entire length of the 10-year Main Survey, with fields constant throughout. The single-visit cadence is the same as the Main Survey, \(2 \times 15s\). We propose to use all regular filters \(ugrizy\) in order to optimize the quality of photometric redshifts. We advocate filter proportions designed to go somewhat deeper in \(gri\) and significantly deeper in \(uzy\) than the Main Survey.
Table 2 shows the filter time distribution and depths for the Main Survey and two DDF scenarios which each use 1% of LSST survey time per field, equal to $22 \times$ more integration time per field. The “Baseline DDF” assumes the same filter time distribution as the Main Survey, and the “Near-uniform DDF” uses a filter time distribution that optimizes photometric redshifts by increasing the depth in the shallower $ugrizy$ filters and avoiding the $AB \sim 29$ confusion limit in $gri$.

Table 2: Filter time distributions and $5\sigma$ point source detection depths.

<table>
<thead>
<tr>
<th>Survey</th>
<th>$u$</th>
<th>$g$</th>
<th>$r$</th>
<th>$i$</th>
<th>$z$</th>
<th>$y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main (AB mags)</td>
<td>7%</td>
<td>10%</td>
<td>22%</td>
<td>22%</td>
<td>19%</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td>26.3</td>
<td>27.5</td>
<td>27.7</td>
<td>27.0</td>
<td>26.2</td>
<td>24.9</td>
</tr>
<tr>
<td>Baseline DDF (AB mags)</td>
<td>7%</td>
<td>10%</td>
<td>22%</td>
<td>22%</td>
<td>19%</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td>28.0</td>
<td>29.2</td>
<td>29.4</td>
<td>28.7</td>
<td>27.9</td>
<td>26.6</td>
</tr>
<tr>
<td>Near-uniform DDF (AB mags)</td>
<td>18%</td>
<td>3%</td>
<td>4%</td>
<td>15%</td>
<td>22%</td>
<td>38%</td>
</tr>
<tr>
<td></td>
<td>28.5</td>
<td>28.5</td>
<td>28.5</td>
<td>28.5</td>
<td>28.0</td>
<td>27.0</td>
</tr>
</tbody>
</table>

2.4 Observation-Time Cost

We propose to spend 5% of LSST survey time on these extragalactic Deep Drilling Fields. This equates to 1% of survey time for each DDF. The expected depths are based upon scaling from the fraction of exposure time devoted to each pointing of the Main Survey, which automatically accounts for LSST overheads including bad weather in the same way that they have been accounted for in the Main Survey.

3 Other Required or Relevant Observations

3.1 Other Required Observations

High-quality photometric redshifts depend on deep optical-through-mid-infrared imaging in $ugrizy$, $JHK$ and the IRAC 3.6$\mu$m and 4.5$\mu$m bands. Calibration of these photometric redshifts requires the availability of spectroscopic redshifts over the full redshift range ($0 < z < 4$), although they can be restricted to brighter objects and still provide calibration through cross-correlation (Newman 2008, Matthews & Newman 2010). Optimal AGN science depends on the ability to measure panchromatic spectral energy distributions via additional imaging in X-rays, ultraviolet, far-IR, and radio. These datasets are already available in significant sub-regions of the proposed fields, as detailed below. References are available upon request.

ELAIS-S1:
Spectroscopy: PRIMUS (9367 redshifts over 0.9 deg$^2$)
X-ray: Small amount of Chandra, XMM coverage (archival)
UV: GALEX
Optical: ESIS $BVRI$ to $\sim$25 mag AB
NIR: VISTA VIDEO $ZYJHK$ to 25.7,24.6,24.5,24.0,23.5 mag AB (3.0 deg$^2$)
MIR: Spitzer+IRAC SWIRE (6.8 deg$^2$), SERVS [3.6,4.5] (3.0 deg$^2$)
FIR: Herschel HERMES level 6, Akari, Spitzer+MIPS SWIRE
Sub-mm:
Radio: ATCA ATLAS 1.5 GHz (3 deg$^2$)
**XMM-LSS/UDS:**
Spectroscopy: PRIMUS (43829 redshifts over 2.9 deg$^2$), VVDS (~5000 redshifts), likely Subaru/FMOS target field
X-ray: XMM-LSS (10 deg$^2$), Subaru/XMM Deep Survey (~1deg$^2$)
UV: GALEX
Optical: CFHTLS ugriz wide, deep to ~26 mag AB
NIR: VISTA VIDEO ZYJHK to 25.7,24.6,24.5,24.0,23.5 mag AB (4.5 deg$^2$), UKIDSS UDS (0.8 deg$^2$), HST+WFC3 CANDELS (0.04 deg$^2$)
MIR: Herschel HERMES level 3,4,5, Spitzer+MIPS SWIRE
FIR: Approved SCUBA-2 Cosmology Legacy Survey
Radio: NVSS?

**ECDF-S:**
Spectroscopy: PRIMUS (20760 redshifts over 2.0 deg$^2$), VVDS (1600 objects, 0.1 deg$^2$), about 3000 additional redshifts from various surveys over 0.25 deg$^2$ including FORS-2, ACES, MUSYC, deepest GALEX slitless spectroscopy
X-ray: Chandra 4Ms (0.07 deg$^2$), 250 ks (0.25 deg$^2$), XMM 3Ms (0.25 deg$^2$)
UV: GALEX Deep Imaging Survey
Optical: HST+ACS UDF/GOODS-S BVIZ (0.04 deg$^2$), GEMS (0.25 deg$^2$)
NIR: VISTA VIDEO ZYJHK to 25.7,24.6,24.5,24.0,23.5 mag AB (4.5 deg$^2$), HST+WFC3 CANDELS/ERS (0.04 deg$^2$)
MIR: Spitzer+IRAC SWIRE (7.9 deg$^2$), SERVS [3,6,4,5] (4.5 deg$^2$), SIMPLE deep (0.4 deg$^2$), GOODS ultra-deep (0.04 deg$^2$)
FIR: Herschel HERMES level 2.5, Spitzer+MIPS FIDEL (0.25 deg$^2$)
Sub-mm: LABOCA (LESS, 0.25 deg$^2$), BLAST (shallow over ~10 deg$^2$)
Radio: ATCA ATLAS 1.5 GHz (3 deg$^2$), VLA deep 1.4 GHz (0.25 deg$^2$), approved LADUMA MeerKAT Ultradeep HI Survey (~2 deg$^2$)

**COSMOS:**
Spectroscopy: PRIMUS (17736 redshifts over 1.0 deg$^2$), zCOSMOS (10000 redshifts over 2.0 deg$^2$)
X-ray: Chandra 80-170 ks (0.9 deg$^2$), XMM (2 deg$^2$)
UV: GALEX
Optical: HST+ACS I (2 deg$^2$), Subaru+Suprime-CAM BVRIz to ~27 mag AB, medium-band to ~26 mag AB, CFHT u to ~26 mag AB
NIR: UltraVISTA (deepest ZYJHK, 2 deg$^2$), HST+WFC3 CANDELS (0.04 deg$^2$)
MIR: Spitzer+IRAC S-COSMOS, SEDS
FIR: Herschel HERMES?, Spitzer+MIPS [24]
Sub-mm:
Radio: VLA COSMOS Large Project, LADUMA MeerKAT Deep HI Survey (~1 deg$^2$)

**DLS F5:**
Spectroscopy: PRIMUS (10695 redshifts over 1.0 deg$^2$)
X-ray:
UV: GALEX approved 25ks (equivalent to Deep Imaging Survey depth, ~3 deg$^2$)
Optical: DLS in $BVRz'$ to ~25.5 mag AB (4 deg$^2$)
NIR: Approved NEWFIRM proposal to image in $J,K'$s to ~22 mag AB (2 deg$^2$)
MIR: Pending IRAC warm mission proposal to image in [3.6] to ~23 mag AB (4 deg$^2$)
FIR:
3.2 Other Relevant Observations

We will attempt to broaden the spectroscopic and multi-wavelength coverage to cover the entire LSST FOV over all five fields as uniformly as possible. Our emphasis will be on obtaining some coverage in each field, and on increasing the redshift range over which spectroscopic redshifts are well-sampled. The enormity of this effort and difficulty of getting the astronomical community to devote valuable resources to fields that do not yet have multi-wavelength coverage is a strong motivation for concentrating on the smallest possible number of DDFs.

4 Specific Needs for LSST and for Deep Drilling

4.1 Need for LSST

LSST is the best telescope to achieve our proposed science goals for reasons of consistency and etendue. As we will probe statistical and systematic errors in the Main Survey photometric redshifts, it is critical to utilize the identical filter set and telescope system. Because we need to cover areas large enough to be robust to “cosmic variance” to significantly greater depths than the Main Survey, we need the large etendue. The roughly square-degree existing deep fields will generate useful supporting multiwavelength data, but their ugriz or UBVRIz images will not cover a large enough area, nor will they go deeper than the LSST Main Survey except in very small regions such as GOODS (∼0.1 deg²).

4.2 Need for Deep Drilling

Our proposed deep drilling observations are designed to probe systematic errors in the Main Survey by observing the distant universe to significantly greater depth. We also propose to extend the scientific reach of LSST to analyze the large-scale structure of galaxy and AGN populations too faint to be detected in the Main Survey.

5 Feasibility

5.1 General Feasibility

Our proposed deep drilling observations do not impose new technical requirements because they utilize the basic 2×15s cadence of the main LSST survey. Although DDFs will be observed more frequently, the fraction of time devoted to each is only 1% of total survey time, making it feasible to perform these observations when DDFs are at relatively low airmass (the equatorial fields reach a minimum airmass of 1.15 and spend 5 hours per night at X < 1.5). We expect sky brightness and seeing conditions to match those of the Main Survey. Only 25% of exposure time is spent in the ugr filters, and half of all observing time is dark, so this is not an obstacle. The y-band observations are best done under favorable atmospheric conditions and are slated for 38% of observing time; we will assess the consequences of sub-optimal observing conditions for the final depth achieved in this filter once the final y-band design has been chosen.
5.2 Bright Objects and Extinction

We do not expect serious complications from objects bright enough to cause bleed trails or scattered light. This is primarily because our individual exposures are not longer than those of the main LSST survey. Nonetheless, most of these fields were not originally chosen at the 10 square degree size, so we have confirmed that none contain stars too bright for high-quality observations \( i.e., r \lesssim 5 \) within 2 degrees of the central pointing. The XMM-LSS/UDS pointing can be moved sufficiently far away from the 3rd magnitude star Mira (and its wake) and still overlap the excellent multiwavelength coverage of this field. ELAIS-S1, ECDF-S, and DLS F5 all have \( r \sim 6 \) stars within an LSST FOV which motivate consideration of repositioning the field center.

Table 1 shows the average and variation of foreground dust extinction across our proposed fields, which is quite low for the first four fields and tolerable for DLS F5.

5.3 Unresolved Feasibility Issues

Several critical issues discussed here are in need of further study. They are as follows:

- Assess the likely confusion limits in \( gri \), which we will do jointly with the Galaxies science collaboration.
- Given these confusion limits, conduct simulations of photometric redshift errors (both RMS and catastrophic error rates) that will result from the observing schemes proposed here and shallower versions of them.
- Use the photo-z simulation results and final \( y \)-band filter design to optimize the distribution of filter exposure times.
- Determine which field beyond the first four shown in Table 1 is the best choice as a fifth field given observability and current/planned multi-wavelength coverage based upon results of currently-pending Spitzer Warm Mission proposals.

6 Other Issues

6.1 Relevance to LSST Commissioning

Our deep drilling observations are designed to ensure the success of the main LSST survey. We strongly support completing a Deep Drilling Field during commissioning and/or the first year of the Main Survey, as this would provide the greatest depth contrast with the first public data release and would generate significant interest and follow-up activity from the astronomical community.

6.2 Other Relevant Information

7 References Cited