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1 Science Goals

1.1 Concise List of Main Science Goals

1. Use Type Ia Supernovae (SNe) to precisely measure the expansion history of the universe to redshifts $z > 1$. In particular, to measure the dark energy equation of state parameter $w$ and its time evolution, and to measure the dark matter content $\Omega_M$.

2. Measure the Supernova rate versus redshift for all SN types (Ia,Ib/c,II) to better understand the SN progenitors as a function of redshift and host-galaxy properties such as metallicity. SN rate measurements will also improve our understanding of the chemical enrichment history of the universe.

3. Measure cosmological parameters with core-collapse (Type II-P) SNe up to redshifts $z \sim 0.5$. Although Type II-P SNe are dimmer than Type Ia SNe and have larger scatter in their brightness, Type II SNe are much more common and they may offer useful crosschecks on the results from Type Ia SNe.

1.2 Details of Main Science Goals

The standardized brightness of Type Ia SNe (SNe Ia) has been used for more than a decade to measure properties of the dark energy (DE) that is currently accelerating the expansion of the Universe. The underlying nature of DE is unknown, and it is the only known fundamental interaction whose effects cannot be detected in a terrestrial laboratory. Astronomical observations are the only tools currently available to study DE, and SN observations provide the most precise method. While it may seem presumptuous to assume that today’s interest in DE will persist for the next decade, the guidance from previous examples of exotic new forces suggests that the study of DE will continue well past the LSST era; electromagnetic interactions were studied for more than a millennium, while the weak and strong interactions took a good part of a century to obtain our modern understanding.

With little theoretical guidance beyond the assumption that Einstein’s cosmological constant describes DE, the road to progress is to measure the properties of DE with increasing precision and to explore variations as a function of local environment and cosmic time. The current world sample of SNe Ia consists of nearly 2000 spectroscopically confirmed objects with photometric light curves observed with many different telescopes and cameras. The LSST Deep-Drilling Fields (DDFs) offer an opportunity to increase this sample by more than an order of magnitude, and to significantly increase the light-curve quality in both the signal-to-noise ratio (S/N) and temporal sampling. Finally, the LSST-measured SN Ia light curves will be observed from a single instrument, thereby reducing the complications in cross-calibrating sub-samples from different telescopes.

A correlation between the host-galaxy mass and SN Ia brightness has been reported (Kelly et al. 2009, Sullivan et al. 2010, Lampeitl et al. 2010), but the current data quality allows only for a simple
binary correction based on a high-mass or low-mass host galaxy. The DDFs offer vastly improved photometric accuracy, wavelength coverage, redshift range, and statistics for both the host-galaxy and SN data. The unbiased LSST transient detection will enable probing these correlations over the full range of galaxy properties. These improvements may lead to a better understanding of the underlying cause of this SN-brightness correction, as well as an improved correction.

Type Ia SNe are believed to occur when a white dwarf accreting matter from a binary companion approaches the Chandrasekhar mass limit. Theoretical models indicate that the nature of the companion star determines in part the time delay between the formation of the binary system and the SN. This time delay can be constrained (or measured) by comparing the measured redshift dependence of the SN Ia rate to that of the star formation rate (SFR). The DDFs are ideal to accurately measure this redshift dependence out to redshifts \( z > 1 \), and such measurements may be able to detect a possible turn-over in the rate in which the rate falls with increasing redshift.

The redshift dependence for the rate of core collapse (CC) SNe is believed to follow that of the SFR, \( \text{SFR} \propto (1+z)^{\beta} \) with \( \beta \approx 3.6 \). Our current knowledge of the CC rate extends to \( z \sim 0.4 \) and has a 30% uncertainty in the fitted exponent term \( \beta_{\text{CC}} \).\(^1\) The LSST DDFs will result in vastly improved rate measurements in redshift bins that extend beyond \( z \sim 0.4 \), and thus offer a complimentary measurement of the SFR \( z \)-dependence out to intermediate redshifts. In addition to comparing the redshift dependence, it is also interesting to compare observed and predicted CC/SF rate-ratios. Horiuchi et al. 2011 suggest that the measured CC rate is too small due to many undetected faint CC SNe; the DDFs will offer improved sensitivity to potential faint SNe.

Using similar selection requirements as for SNe Ia, \( \sim 10^4 \) core collapse SNe IIP can be used to construct a Hubble diagram out to \( z \sim 0.5 \). The current method to standardize type II-P SNe requires a spectrum about 50 rest-frame days after explosion, and it is unlikely that such a large spectroscopic sample can be obtained in the DDFs. Therefore, the measurement of cosmological parameters from Type II-P SNe will likely require the development of photometric methods to standardize the brightness.

1.3 Supplementary Science

The large volume of the DDFs allows for probing rare extremes of the SN populations, and these events could provide additional insight into the nature of SNe. Current wide-field surveys are already finding unusual SNe that include very luminous \( (M < -21 \text{ mag}; \text{e.g., Gal-Yam et al. 2009}) \), very faint \( (M > -15 \text{ mag}; \text{e.g., Foley et al. 2009}) \), and very fast \( (\text{e.g., Poznanski et al. 2010}) \) light curves. While these discoveries satisfy our attraction to the bizarre, some of these objects are coming from new progenitor channels that have sometimes been theorized (e.g., Pair Production SNe or ‘Ia’ SNe), but often challenge our understanding of stellar evolution, binary evolution, and mass loss. While it is difficult to predict the frontier for this fast moving field many years in advance, it is clear that the DDFs will enable the exploration of domains unattainable with current resources: in particular, very faint SNe, rapidly evolving SNe (if cadences are of order \( \sim 1 \text{ day} \)), and luminous SNe at high redshift \( (z \sim 2) \).

2 Description of Proposed LSST Observations

Here we refer to simulations described in Appendix A. To evaluate the usefulness of the DDFs we would ideally measure cosmological parameters from a large simulated sample and compare the uncertainties to current measurements. These uncertainties, however, depend on assumptions about intrinsic brightness variations that lead to the anomalous scatter in the Hubble diagram, and they depend on assumptions about systematic uncertainties. Rather than making such assumptions

\(^1\)Our estimate of the uncertainty in \( \beta_{\text{CC}} \) is based on a recent compilation of CC rates in Graur et al. 2011.
here, we instead focus more directly on the measurement capabilities of the LSST and examine three quantitative metrics from these simulations. First is the fitted precision on the \( \text{SALT-II} \) color parameter, \( c \approx E(B - V) \) at the epoch of peak brightness. Specifically we determine the rms scatter (\( \text{RMS}_c \)) on \( c_{\text{fit}} - c_{\text{sim}} \) as a function of redshift. The second metric is the selection efficiency as a function of redshift assuming that all SNe Ia are spectroscopically identified. The last metric is the purity resulting from the photometric identification of SNe Ia using spectroscopic redshifts of the host galaxy.

To set the scale of interest on the fitted color precision, recall that the intrinsic dispersion in the peak brightness after standardization is about \( \sim 0.1 \) mag (Conley et al, 2011). Since the peak-magnitude color correction is about \( 3 \times c \), an uncertainty of \( \text{RMS}_c \approx 0.03 \) mag will contribute an uncertainty in the peak brightness that is comparable to that of the intrinsic dispersion. Therefore, observations with \( \text{RMS}_c \) much larger than a few hundredths will be significantly downweighted in Hubble diagram analyses using SN distances. If future methods are found to reduce the intrinsic scatter further, higher precision on the color determination may be needed.

### 2.1 List of Proposed Fields

We do not have a specific list of fields at this time, but instead provide a list of criteria:

1. Low Galactic extinction.
2. Visible to other telescopes that can use a multi-object spectrograph.
3. Adequate spatial separation to allow year-round observations, and to constrain inhomogeneous models for DE.
4. Overlapping legacy fields is useful if there is a large catalog of spectroscopic galaxy redshifts.

### 2.2 Motivation for Proposed Fields

With the exception of the large Galactic extinction in some of the current OPSIM (v3.61) fields, we find the OPSIM DDF scenario reasonably attractive for SN science. A total of roughly 5–20 fields would benefit the SN science program. Uncertainties in the LSST zeropoints provides an effective limit on the signal-to-noise ratio (\( S/N < 200 \)), and the assumed uncertainty in the Galactic extinction provides a floor on the color precision, \( \text{RMS}_c > 0.01 \) mag. For a fixed observing time, the optimum balance between depth per field and number of fields depends largely on the targeted redshift range. If we decide to push aggressively on redshift out to \( z > 1 \), we would want \( \leq 10 \) fields; this high-redshift strategy will depend on whether we will have adequate spectroscopic resources to acquire a high-redshift training set for photometric identification and redshift determination. We anticipate that Pan-STARRS1, SkyMapper, and the DES will contribute significant experience and knowledge to help optimize and implement the LSST SN program.

### 2.3 Observing Plan, Cadence, Filters, and Expected Depth

We would like the DDF observations to occur in \( griz \) filters, and also in the \( Y \) band if the depth can be increased to be comparable to the other filters; in the current OPSIM DDF scenario, the \( Y \)-band \( S/N \) is \( \times 3 \) smaller compared to the \( z \) band. The usefulness of the \( u \) band is limited because the SN Ia flux is so small in the ultraviolet region. However, \( u \)-band observations would be useful for photometric identification because non-Ia (core collapse) SNe are much brighter in the ultraviolet region.

The relative exposure times should be ideally optimized so that \( \text{RMS}_c \approx 0.02 - 0.03 \) at all redshifts. In practice, however, the uncertainty in the Galactic extinction limits \( \text{RMS}_c \approx 0.01 \) at
low redshifts, and RMS\(_c\) increases with redshift due to larger distances and due to larger sky noise in the redder bands needed to observe more distant SNe Ia. Keeping the total DDF exposure time fixed, increasing the exposure times in the redder bands (while reducing time in the bluer bands) reduces RMS\(_c\) at higher redshifts at the expense of a slight degradation at lower redshifts. In the current OPSIM DDFs, the exposure times are about 5 minutes in the \(g\) band and 10 minutes in the other (rizY) bands.\(^2\) Two crude exposure-time optimization attempts are shown in the left panel of Fig. 1. First we simply remove the \(Y\) band that has the lowest S/N, and double the \(z\) band exposure so that the total exposure time remains constant; the resulting RMS\(_c\) (dotted curve) improves slightly (few mmag) for redshifts \(z > 0.4\). Next we modify the relative exposures times to increase with the central wavelength of the filter; the \(g, r, i\) exposures are reduced to 1,2,6 minutes, respectively, while the \(z\) & \(Y\) exposures are increased to 14 & 22 minutes (dashed curve). For redshifts \(z > 0.7\) RMS\(_c\) decreases more than in the previous case of exchanging \(Y\) band observations for \(z\) band; for \(z < 0.7\) RMS\(_c\) increases slightly. While we are not specifically requesting either of these optimizations, we note that the second optimization (dashed curve) qualitatively illustrates the direction of our strategy; reducing RMS\(_c\) at higher redshifts at the expense of degrading the precision at lower redshifts.

Next we discuss the DDF cadence, which averages 6 days between observations in each filter for the current OPSIM. We have investigated the impact of increasing the average 6-day gap to 12 and 18 days while also increasing the exposure times by factors of 2 and 3, respectively, so that the total exposure time is the same for each cadence. The results for RMS\(_c\) are shown in the right panel of Fig 1. The fitted color precision degrades somewhat when the cadence is dramatically changed, although the sampling requirements reduce the efficiency by 10-20% depending on redshift. Although the SN Ia color precision is relatively insensitive to the cadence, we may want at least some of the DDFs to have a cadence faster than 6 days to improve sensitivity to rare SN types that evolve rapidly.

We have performed a preliminary study on the effect of the cadence on photometric classification, assuming that we have an accurate (spectroscopic) host-galaxy redshift for each SN. The SN Ia purity vs. redshift is shown in Fig. 2 for simulated DDF samples with 6, 12 and 18-day gaps as described above. We find very little difference in the purity as a function of the average separation between observations. A striking feature in Fig. 2 is that the MAIN survey has higher purity for most of the redshift range \((0.25 < z < 0.9)\). This counter-intuitive result is an artifact of using the same selection requirements on all samples. Since the MAIN survey has much lower S/N than the DDFs, the selection requirements are effectively much more strict for the MAIN survey, and these stricter requirements result in a higher classification purity at the expense of much lower efficiency (Fig. 6-right).

### 2.4 Observation-Time Cost

The total observing time will be determined by the LSST management. Clearly we desire as much DDF time as possible, but cannot at this time justify increasing the total time in the current DDF OPSIM cadence. We have also assumed that all of the DDF time will be useful for SN science, and this assumption requires replacing the fields with very high Galactic extinction.

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\(^2\)In these discussions we leave the \(u\) band exposure time fixed since the \(u\) band optimization is related to photometric classification rather than minimizing RMS\(_c\).
Figure 1: Each panel shows RMS$_c$ vs. redshift for the nominal OPSIM v3.61 DDFs (solid black curve) along with variations (dashed and dotted) indicated in the legends. Left panel compares to removing Y band and doubling the z band exposure (dotted), and to increasing the exposure time with central passband wavelength (dashed). Right panel compares to reducing the cadence by factors of 2 and 3 while simultaneously increasing the exposure time by the same factor. Since each simulated sample is based on the same SNe (i.e., same redshift, sky location and SALT2 parameters), the selection requirements (Appendix A are applied only to the nominal DDF sample (solid black curve); therefore the same SNe are analyzed in each variation.

Figure 2: SN Ia classification purity vs. redshift from photometric classification. The simulated samples include SN types Ia, Ib, Ic and II, and use a spectroscopic redshift from the host galaxy.
3 Other Required or Relevant Observations

3.1 Other Required Observations

A spectroscopically classified SN training set will be needed to train photometric classification algorithms, and host-galaxy redshifts will be needed to train photometric redshift determination. We do not yet have an estimate of the resources needed, but these photometric issues are being addressed by Pan-STARRS1 and the Dark Energy Survey (DES), both of which will provide valuable input for the LSST strategy. Also note that the DDFs are ideal for efficiently using a multi-object spectrograph.

3.2 Other Relevant Observations

Beyond simply identifying an object or measuring its redshift, we may want more detailed spectroscopic observations to make additional peak-magnitude corrections. These observations could be related to the SN itself, or the host-galaxy. If we push for a higher redshift strategy, then such observations would be more difficult.

Another interesting possibility is near infrared (NIR) imaging from a space mission, in particular Euclid or WFIRST (see §4.1). This NIR overlap offers extra redshift coverage, improved photometric redshift determination for both the SN and its host galaxy, improved photometric classification, and an important systematic check by using a redder rest-frame wavelength region that is less affected by host-galaxy extinction. Since these space missions are likely to target the ecliptic poles, these regions should be considered for the LSST DDFs.

4 Specific Needs for LSST and for Deep Drilling

4.1 Need for LSST

When the LSST begins, the most competitive instruments for SN observations will likely be the DECam at CTIO (DES: Dark Energy Survey), the Hyper Supreme Cam (HSC) at Subaru, Pan-STARRS4 at Mauna Kea, and possible space missions (WFIRST, Euclid). Each of these surveys is discussed below.

- The DES will have finished its 5-year observing plan when the LSST begins, and we expect a DES sample of approximately 4000 Type Ia SNe, most of which will be photometrically identified. This sample is nearly an order of magnitude fewer than the LSST DDFs will collect with comparable selection criteria. In addition, the Y band filter in the LSST provides additional wavelength (and redshift) coverage compared to the previous surveys.

- The HSC SN program is still under investigation, so we cannot comment at this time.

- Pan-STARRS1 will discover \( \sim 10,000 \) SNe Ia during its 3.5-year mission, with at least several thousand of those being high-quality lightcurves from the Pan-STARRS1 Medium-Deep Fields. These fields are similar to the LSST DDFs, but will be several magnitudes shallower. The resulting SN Ia lightcurves will be similar to those that would be obtained in the LSST DDFs but will only yield high-quality light curves out to a redshift of \( z \sim 0.6 \) and a factor of 10 fewer SNe overall. Pan-STARRS1 is a prototype for a more ambitious proposal (Pan-STARRS4) that would feature 4 telescopes that will scan the sky 4-times as quickly and/or with simultaneous multi-filter observations for time-domain science. This survey could potentially yield up to 10,000 high-quality SNe Ia in a 3–5 year mission.
• There are currently two space missions under consideration with a goal of measuring a few thousand SN Ia light curves at redshifts up to $z \sim 1.5$: Euclid at ESA\textsuperscript{3} and WFIRST at NASA.\textsuperscript{4} Both projects include a near infrared imager up to 1.7 microns, with similar sensitivity as ground-based optical observations. If one or both of these space missions proceed, they would provide SN Ia data that is largely complementary to that of the LSST DDFs: NIR imaging in some of the DDFs, and SNe Ia at higher redshifts. Around $z \sim 1$ there would likely be an overlapping redshift range between the LSST and the space mission, but such a crosscheck would be extremely useful for combining ground-based and space-based SN Ia measurements into a single Hubble diagram.

In summary, we expect that the LSST DDFs will contribute a vastly superior SN sample in both statistics and data quality.

4.2 Need for Deep Drilling

The main LSST survey covering 20,000 sq deg is expected to find millions of SNe, a sample that is many orders of magnitude larger than the current SN samples. To make full use of the large statistics in measuring cosmological parameters, systematic uncertainties need to be reduced for calibration, and for using light-curve (and host-galaxy) properties to standardize the SN brightness. However, based on simulations described in Appendix A, the quality of these SN light curves is poorer than existing light curves from the Supernova Legacy Survey (SNLS: Astier et al. 2006). In particular, Table 1 shows that the SNLS is both deeper and has more observations per SN compared to the main LSST survey. For a visual comparison, typical light curves from the SNLS are shown in Fig. 3 and simulated light curves for the LSST DDFs and main survey are shown in Figs. 4-5. To make more reliable comparisons, the simulated light curves are generated at the same redshift, color and stretch as the SNLS light curves. In summary, the main LSST survey will vastly improve the SN sample size, but not the light-curve quality.

The proposed DDFs are ideal for vastly improving the light-curve quality needed to reduce systematic uncertainties, while still delivering excellent statistical power. The superior DDF light curve quality is visually apparent in Figs. 3-5. A quantitative comparison is shown in Fig. 6 which compares RMS\textsubscript{c} and the efficiency for different surveys as a function of redshift. Fig. 6-left shows that for the current DDFs RMS\textsubscript{c} < 0.03 mag for redshifts $z < 0.7$, and increases to RMS\textsubscript{c} $\sim$ 0.07 mag at $z = 1.2$. At low redshifts the color-precision floor of RMS\textsubscript{c} $\sim$ 0.01 is set by the assumed 0.01 mag uncertainty in the Galactic extinction. The color precision for the main survey is also shown in Fig. 6-left for comparison; the precision is several times worse compared to the DDFs, and it is even worse than the current SNLS. The useful redshift range ($z < 0.8$) for the main LSST survey is considerably smaller as well. Finally, we also show results for LSST-DDF/4 corresponding to 1/4 of the OPSIM exposure time and $\times 4$ more area covered. The color precision should naively degrade by a factor of 2, but the simulated precision degrades only slightly. The reason for the reduced RMS\textsubscript{c} sensitivity is that the same selection requirements are applied in each case; therefore the additional lower-quality light curves in the LSST-DDF/4 sample are rejected by the $S/N$ requirement and not used to determine RMS\textsubscript{c}.

The efficiency versus redshift for each survey is shown in Fig. 6-right. While the LSST-DDF/4 scenario results in only a slight degradation in the color precision, the efficiency is much smaller; for example, at $z = 1$ the LSST-DDF/4 efficiency is $\times 3$ smaller than for the nominal LSST-DDF scenario.

\textsuperscript{3}http://sci.esa.int/euclid

\textsuperscript{4}http://wfirst.gsfc.nasa.gov
Figure 3: Typical light curves (flux vs. day) observed by the SNLS (Astier et al. 2006) at redshifts $z = 0.29$, $z = 0.62$ and $z = 0.93$. The passband (griz) is indicated in each panel.

Figure 4: Simulated DDF light curves at the same redshift, color and stretch as the SNLS light curves shown in Fig. 3.
Figure 5: Simulated light curves for the main LSST survey at the same redshift, color and stretch as the SNLS light curves shown in Fig. 3.

Figure 6: Based on simulations (Appendix A), left panel shows RMS$_c$ vs. redshift, and the right panel shows the efficiency vs. redshift. The efficiency is the fraction of all SNe Ia that are detected and satisfy the selection requirements. The legend indicates the samples. The selection requirements are applied to each sample.
5 Feasibility

5.1 General Feasibility

The airmass should be less than 2. Based on previous experience with the SDSS-II, the sky brightness and seeing for some epochs can be somewhat worse than in photometric conditions.

5.2 Bright Objects and Extinction

There is no limit on the SN brightness, but given the expected search area of $\sim 10^2$ square degrees we don’t expect to find more than a few dozen SNe brighter than about $m_r \sim 17$, which will be many fewer objects than the existing bright stars in these regions. We also don’t expect problems in the other passbands. Finally, since we desire fields with low Galactic extinction, the extinction variation across the field should also be small.

5.3 Unresolved Feasibility Issues

It is critical to avoid large temporal observing gaps for SN observations. For the DES observing plan, SN fields have top priority after a 7-day gap in any filter, and we would like a similar priority for the LSST DDFs. In addition, special care is needed to avoid large observing gaps around the full moon and telescope maintenance/repairs.

6 Other Issues

6.1 Relevance to LSST Commissioning

Discovering SNe with a reasonably well-known rate will be very valuable during commissioning. The transient-search pipeline is sensitive to problems in the data and the photometric pipelines. Also, because of the rapid processing required to use spectroscopic resources on SNe while they are bright, the SN science needs will provide a strong incentive during the commissioning phase.

6.2 Other Relevant Information

None.

7 References Cited

Foley, R., et al., 2009, AJ 138, 376
Poznanski, D., et al., 2010, Science 327, 58
A Description of Simulations

The simulations for the LSST DDF and main surveys are based on the OPSIM v3.61 cadence\textsuperscript{5} and the SNANA package (Kessler et al. 2009). The average cadence properties are shown in Table 1 where they are compared to the DES and SNLS. The DDF co-added exposure times are about 5 minutes in the g band and 10 minutes in the other (rizY) bands.

The simulations account for observing conditions, telescope properties, intrinsic SN brightness variations, and Galactic extinction (MWEBV ≡ E(B − V)) from Schlegel et al. 1998. The uncertainty on MWEBV, which affects the fitted color precision, is assumed to be 0.16 × MWEBV, except for the DDFs which have a fixed MWEBV uncertainty of 0.01 mag. For the DDFs we have also removed the two fields with exceptionally large Galactic extinctions (MWEBV ~ 0.3 mag), and assumed that these fields will be changed to locations with much lower extinctions.

SNe Ia were simulated using the salt-II model, and the intrinsic dispersion for each SN was randomly selected from a Gaussian distribution with $\sigma = 0.12$ mag. This random magnitude variation was applied coherently to each passband and epoch; intrinsic color variations were not used in order to better assess the quality of the color measurements from the LSST instrument and from uncertainties in the Galactic extinction. The contamination from non-Ia SNe is based on templates constructed from 42 well-observed type Ib, Ic and II SNe light curves; the simulation is the same as that used in the “Photometric Classification Challenge” (Kessler et al. 2010), and the classification is based on an upgraded version of the software used in the SDSS-II survey (Sako et al. 2008).

The following selection requirements have been applied:

- at least three filters have an observation that satisfies S/N > 10.
- at least one observation with $T^*_{\text{rest}} < 0$.
- at least one observation with $T^*_{\text{rest}} > 15$.
- at least 7 measurements with $-20 < T^*_{\text{rest}} < +60$.
- largest $T^*_{\text{rest}}$ gap is < 30 rest-frame days.

$T^*_{\text{rest}}$ refers to an observation in any filter without a S/N requirement so that a flux consistent with zero will satisfy a $T^*_{\text{rest}}$-defined requirement just as well as a high-S/N observation. These requirements are significantly more strict than in current analyses. In particular, we require three passbands with $S/N > 10$ while analyses on current data typically require a single observation with $S/N > 5$.

The 10-year SN samples sizes after selection requirements is estimated to be $2 \times 10^4$ for the nominal OPSIM DDF scenario, $5 \times 10^4$ for the LSST-DDF/4, and $1 \times 10^6$ for the LSST-MAIN. To compare statistics with current surveys using current analysis cuts, the 3-year SNLS sample has 242 SNe Ia and there are about 1000 spectroscopically confirmed SNe Ia in all of the existing samples. Using the more restrictive cuts above would reduce the current sample by about a third.

\textsuperscript{5}http://opsimcvs.tuc.noao.edu/index.html
Table 1: Average survey properties for the LSST-DDFs (OPSIM v3.61), LSST-MAIN, and SNLS.

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