LSST DESC Notes

The LSST Dark Energy Science Collaboration Cadence Note

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Introduction

This is the response to the Solicitation for Cadence Notes[1] from the Observing Strategy Working Group of the LSST Dark Energy Science Collaboration (DESC). Our responses are motivated by an extensive analysis of observing strategy simulations, which is detailed in Lochner et al. (2021) (L21 hereafter). While L21 describes over 40 cosmology-related metrics that we use to support our findings, we focus here on seven representative metrics that encompass work across DESC's cosmological probes; these include large scale structure, weak lensing, supernovae, strong lensing, kilonovae, and photometric redshifts, which enable several probes. Sections 1–7 provide succinct answers to the questions in the cadence note call, while the appendices provide supporting material; the metrics are briefly described in Appendix A, illustrative figures are provided in Appendix B and Appendix C discusses proposals for rolling cadence of the WFD and DDF surveys. The majority of our results are based on the FBS v1.5 simulations, but we also consider select v1.6 and v1.7 simulations for some plots, always comparing against the appropriate baseline simulation for that version. This cadence note summarizes our analysis and makes several observing strategy-related recommendations for improving cosmological constraints with LSST that can be tested with additional simulations and, in some cases, verified with commissioning data.

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[1] `https://docushare.lsst.org/docushare/dsweb/Get/Document-36755`

1. Question 1: Footprint

The definition of the footprint has significant impact on cosmological constraints with LSST. Increased area, given fixed observing time, leads to better statistical constraining power for static probes cosmology (Figures 1 and 2). However, the corresponding reduced depth and fewer visits per pointing have a negative impact on systematics as well as on transient probes due to decreased inter-night cadence, as indicated in Figures 1 and 2.

Following Lochner et al. (2018) (L18), we note that 25% of the baseline footprint does not pass the selection cuts (including extinction and depth cuts and coverage in all bands) to be included in cosmological analyses. **We thus recommend a WFD survey footprint that includes 18,000 sq. degrees with low dust extinction ($\mathbf{E(B-V) < 0.2}$ mag) and limits in declination of $-70^\circ <$ Dec. $< +12.5^\circ$**, as identified by L18. This is similar to the v1.5 simulation `footprint_big_sky_dust`, which has the best overall performance for cosmological constraints considered here[2]. Compared to the baseline coverage of $-62^\circ <$ Dec. $< +2^\circ$, two-thirds of the added low-dust area is equatorial; this is the highest priority addition because it increases the overlap with DESI, 4MOST, Euclid and other facilities that will provide critical spectroscopic and multi-wavelength data. To maintain coverage of the Galactic plane, this large extragalactic footprint will likely have fewer visits compared to baseline. The resulting loss of inter-night cadence could be mitigated with rolling cadence (see Section 6) or if necessary, the number of visits in this region could be increased modestly by restoring a Southern declination limit of -62°, since the Southern extension of the footprint is less crucial than the Northern region.

We recognize that having the WFD footprint prioritize extragalactic area (as in `footprint_big_sky_dust`) is beneficial to cosmology but, to ensure other science goals of LSST are met, this creates a need for an additional Galactic plane survey optimized for Milky Way science. **We propose to formalize what has already been explored in current simulations (such as the `footprint` family in v1.7) and separate the extragalactic/WFD and Galactic plane surveys**. We expect that this will be a win-win situation due to differing science requirements enabling optimal cadences and filter time distributions to be utilized in each region. For example, the current filter distribution in WFD is highly beneficial for photometric redshift measurements, but Galactic studies may benefit from a different choice of distribution.

2. Question 2: Additional observing time

We recommend giving additional observing time to the DDFs beyond the nominal 5%, as this will dramatically improve type Ia supernova cosmology (Scolnic et al. 2018). This is particularly important as the current plan for the DDFs yields a redshift range of discovered type Ia supernovae (hereafter referred to as SNe) that is not significantly higher than that expected from the WFD survey, and therefore does not provide the redshift lever arm needed for supernovae to constrain dark energy at the intended level of precision for LSST (The LSST Dark Energy Science Collaboration et al. 2018). **As the current DDF program is insufficient for cosmology, we provide two suggestions for improvements: i) do rolling deep fields and ii) allocate extra LSST time as implied from this question**. Our ideas for simulations of 'rolling' deep fields with details are given in Tables 2 to 4, where either: only 1–2 deep fields are observed each year, or 1–2 deep fields have much greater depths each year than the other fields. A similar idea is proposed in the AGN-DDF Cadence note based on Brandt et al. (2018), and consensus between these groups should be explored. We also advocate for considering filter allocations that differ from the baseline, as presented in Tables 2 to 4. Lastly, we support the LSST DDF coverage of the southern deep fields of the Euclid and Roman surveys, which in Tables 2 to 4 we denote as 'Euclid/Roman'. Euclid has already picked its deep field, which is now in the nominal LSST observing plan and, while Roman has not, there is a high probability that it will be the same as the Euclid field. We strongly recommend that LSST observes these fields contemporaneously with the Euclid (Years 2–3) and Roman (Years 5–6) surveys. The Euclid field will need to be two contiguous DDFs and therefore the visits would be split into two (see Euclid Cadence Note).

3. Question 3: u-band exposure time

Preliminary analysis suggests that additional u-band exposure time degrades all metrics by a small amount ($\sim 3\%$), except for the number of kilonovae detected (although more analysis is needed to confirm this result). The only cosmology metric for which u-band is important is our photometric redshift metric, given by the "robust standard deviation" defined as (Graham et al. 2018, L21): $\Delta z_{1+z} = (z_{\rm true} - z_{\rm phot})/(1 + z_{\rm phot})$. This metric improves by around 4% for `u_long_ms_50_v1.7_10yrs` compared to the v1.7 baseline (2×15 s exposures). **While further investigation is needed, the choice of 30 s or 50 s u-band exposure time does not appear to be important for cosmological constraints.**

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[2] We note that this simulation is not realistic as it does not include any Galactic plane visits, but it does represent the upper limit on the ideal case for cosmology.

4. Question 4: Filter distribution

Figure 4 shows that while some metrics improve with certain filter choices for the WFD, others degrade. **While we do not see a compelling reason to change the WFD filter distribution from baseline, it would be interesting to have simulations with a significantly lower number of y-band visits to evaluate the impact on the inter-night cadence in other bands.** Previous studies (Graham et al. 2018) have indicated that y-band is less important for photo-z's than other bands and, due to its limited single visit depth, y also does not contribute significantly to WFD SNe analyses. Thus redistributing up to half of the visits in y to other bands has the potential to improve cosmological constraints and this should be explored with new simulations. The exception to this is the DDFs, for which y-band visits can be useful to increase the redshift limit of the SNe sample.

5. Question 5: Visit pairs and triplets

Even though obtaining visit pairs in the same filter increases efficiency, the resulting loss of inter-night cadence is devastating for transients such as supernovae and kilonovae, as can be seen in Figure 6, and **we strongly recommend observing visit pairs in different filters as is done with the current baseline.**

A third observation in a night could help early transient classification by providing additional color information; however, we would expect this to degrade overall inter-night cadence and SNe performance. Preliminary results from the `third_obs` family suggest that *some* strategies with a third observation do not degrade transient metrics significantly, but more research is needed to understand the trade-off between inter-night cadence loss and improved classification. A transient classification metric is critical to answering this question. However, this has proven challenging to develop as expensive simulations would be required to evaluate each simulation and many factors impact classification, making it difficult to create a fast emulator. Work is ongoing in DESC to develop such a metric.

6. Question 6: Rolling cadence, season length and AltSched

Supernovae have long been the drivers of the development of rolling cadence strategies, but these strategies have unfortunately been difficult to simulate. There are many parameters to consider when defining a rolling cadence strategy, including how large an area to roll at a time, how long to roll for and the number of extra visits in the prioritized region. This means that many potential rolling cadence simulations are yet to be explored. The latest rolling cadence simulations yield a number of well-measured SNe that is at best comparable to baseline, rather than significantly higher as we initially anticipated. Rolling cadence and AltSched-like strategies have held promise for improving transient metrics (with the exception of strong lensing which disfavors rolling cadence due to reduced season length) and we recommend continued research into these novel strategies. **To better understand the full potential of rolling cadence, it would be worth producing additional simulations such as a rolling cadence where in one season, a fraction of the sky is observed and a separate fraction of the sky is not observed at all. Similarly, it would be useful to see a simulation that replicates AltSched's deterministic strategy exactly.** These simulations will be useful tests, even if they degrade other science cases, as we have yet to even demonstrate that these strategies in ideal conditions will improve performance of our transient metrics. These requested simulations are further discussed in Appendix C.

Figure 7 shows the impact of season length on selected metrics. The number of well-measured supernovae as well as the number of strongly lensed supernovae both degrade when the season length is shorter than in baseline v1.5 (which has a cumulative season length of 5.47 years)[3]. However, for longer season lengths, other factors such as overall inter-night cadence play a more important role for our transient metrics.

7. Question 7: Dithering

Dithering is crucial for cosmology, as non-uniformity in the survey can produce large systematic effects. **The current baseline translational and rotational dithers appear to be sufficient for cosmology, but we would like commissioning data to be used to verify that these dithers are sufficient.**

Random rotational dithers are also important in the DDFs. However, it has arisen that Data Management has also requested translational dithers in the DDFs to remove artifacts. Figure 8 clearly shows the detrimental impact of large dithers on the number of well-measured supernovae in the DDFs. Large dithers should be avoided or compensated for by increasing the number of visits in the DDFs to improve the inter-night cadence and depth.

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[3] We consider here the cumulative season length, which is the sum of all seasons throughout the survey, because this takes into account both the season length and the number of seasons, which could vary for different observing strategies (particularly rolling cadence). This is particularly important for strongly lensed transients.

APPENDIX

A. Brief description of metrics used

We select key representative metrics from L21, including one for each dark energy probe, to focus on for this cadence note. Each metric is transformed such that it can always be interpreted as "bigger is better" and generally correlates with the expected information gain. To enable comparison with other metrics, we always plot the metric minus its value at the relevant baseline simulation for that version, divided by baseline, allowing us to interpret them as a relative improvement/degradation over baseline. See Table 5 in L21 for more details of the metric transformations and L21 Table 6 for details of the simulations used in each plot.

Although all the metrics described in L21 are useful for understanding the impact of observing strategy on cosmological measurements with LSST, some are more closely related to the primary cosmology goals as outlined in the DESC Science Requirements Document (The LSST Dark Energy Science Collaboration et al. 2018) than others. The 3x2pt joint probes analysis (combining large scale structure and weak lensing) and supernovae together have the most constraining power. However, novel probes such as strong lensing and kilonovae can be complementary and offer tests of cosmology that LSST is uniquely suited for. Our recommendations and conclusions are generally guided by the priorities outlined in the DESC SRD, but we attempt to quantify performance of observing strategies in terms of the scientific opportunities offered by more novel probes as well.

Probe	Description	Section in L21
3x2pt joint probes analysis	WL + LSS DETF Figure of Merit (FoM)	4.1.1
Large scale structure	LSS systematics FoM	4.2.2
Weak lensing	WL Average visits	4.1.2
Photometric redshifts	PZ precision (low z)	3.2
Supernovae	Number of SNe Ia with z<zlim(med)	5.1.1
Strong lensing	Number of SNe Ia lensed by galaxies	5.2.1
Kilonovae	kN Population Counts	5.3.1

Table 1: Description of the selected metrics used in this cadence note. The section in which the metric is described in L21 is also indicated. Note: DETF stands for Dark Energy Task Force which proposed the Figure of Merit (FoM), used for the prediction of cosmological constraints (Albrecht et al. 2006).

B. Figures

Our conclusions in this cadence note are supported by figures drawn from L21.

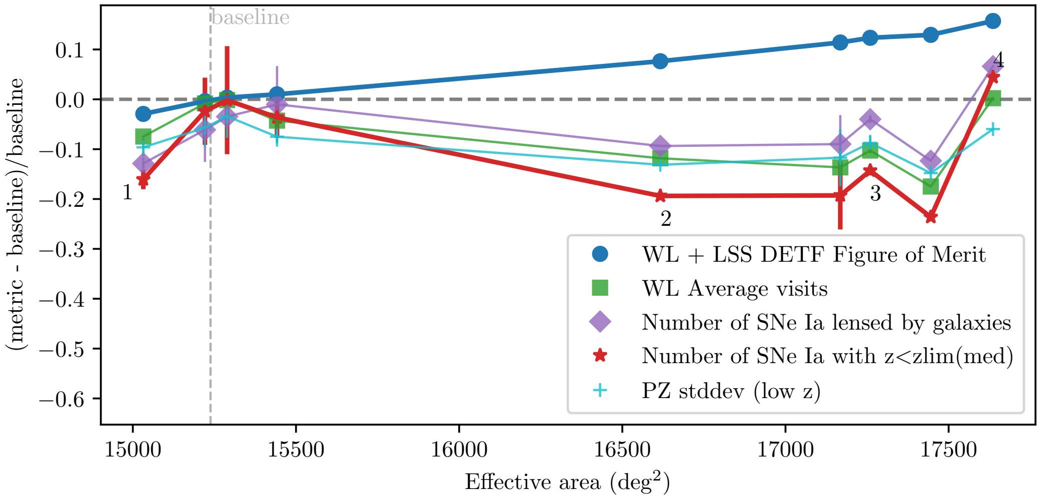

Figure 1: Selected metrics, relative to their values at baseline, as a function of effective area (i.e., the area that meets the cuts described in L21) of different observing strategies. To improve readability, points that are nearby in the x-axis are binned with only the mean and error bar plotted for that bin. It can be seen that the 3x2pt FoM metric simply prefers more area while the situation is more complex for time-dependent metrics. We have highlighted specific simulations with numbered annotations: 1–`footprint_bluer_footprintv1.5_10yrs`, 2–`footprint_newBv1.5_10yrs`, 3–`bulges_bs_v1.5_10yrs`, 4–`footprint_big_sky_dustv1.5_10yrs`.

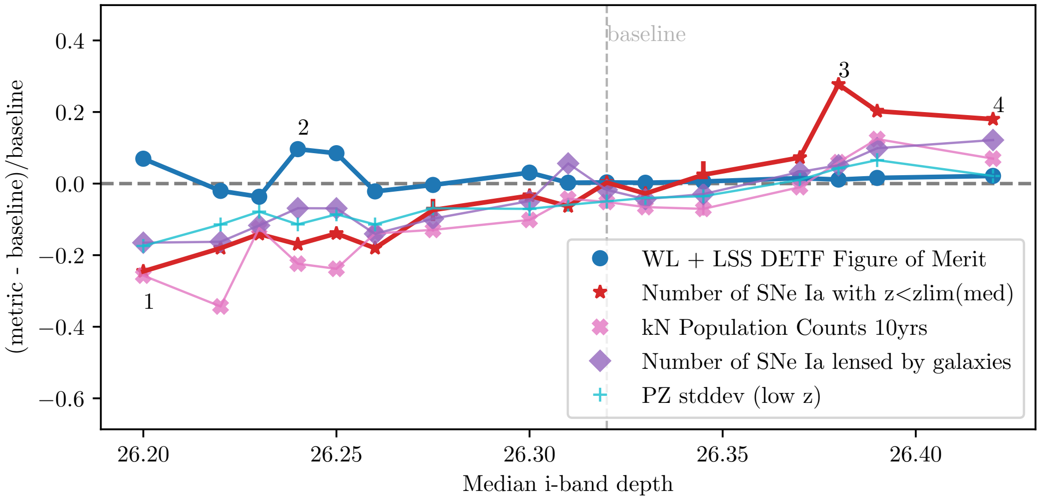

Figure 2: Selected metrics, relative to their values at baseline, as a function of i-band median co-added depth of different observing strategies. To improve readability, points that are nearby in the x-axis are binned with only the mean and error bar plotted for that bin. Here we note that the 3x2pt FoM metric is generally indifferent to depth, implying that larger area is more important (assuming the changes in depth remain small). Photometric redshifts improve with more depth and the transient science probes, particularly supernovae and kilonovae, are strongly affected since generally greater depth corresponds to increased inter-night cadence. We have highlighted specific simulations with numbered annotations: 1–`footprint_newAv1.5_10yrs`, 2–`bulges_cadence_i_heavy_v1.5_10yrs`, 3–`wfd_depth_scale0.99_v1.5_10yrs`, 4–`wfd_depth_scale0.99_noddf_v1.5_10yrs`

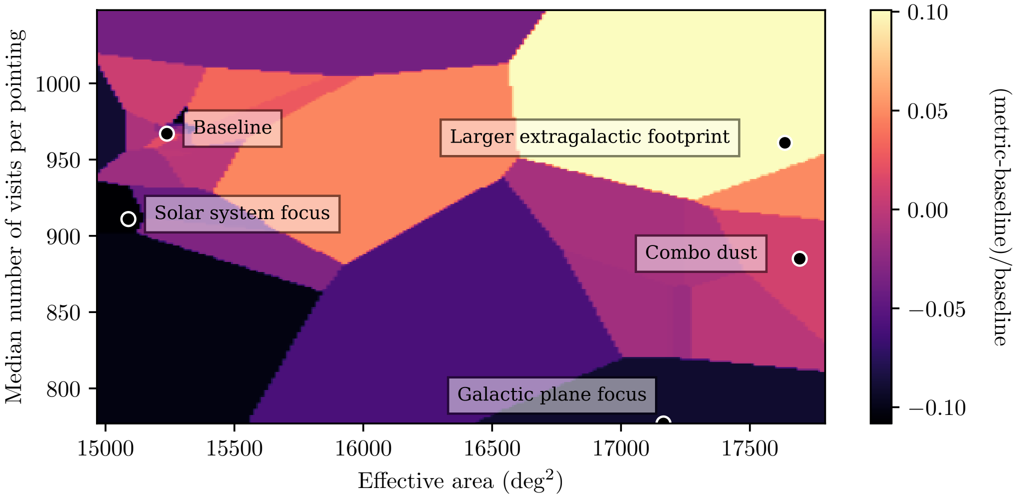

Figure 3: A simple attempt to combine multiple metrics to produce a combined cosmology metric. We show the combined metric, using the usual (metric-baseline)/baseline, as a function of effective area (i.e., the area that meets the cuts defined in L21) and median number of visits (which correlates with depth for most simulations). Although the resulting map is complex, the trade-off between depth and area can be seen. Several specific strategies are highlighted. "Solar system focus" (`ss_heavy_v1.6_10yrs`) and "Galactic plane focus" (`footprint_newAv1.5_10yrs`) both take observations away from WFD to prioritize other science cases. "Combo dust" (`combo_dust_v1.6_10yrs`) is a proposed large area footprint that has more area but less depth than "Baseline" (`baseline_v1.5_10yrs`), thus producing similar performance. "Larger extragalactic footprint" (`footprint_big_sky_dustv1.5_10yrs`) is a larger area footprint that is defined by dust extinction and gives improved cosmological constraints due to the area gained by avoiding extinction. We caution the reader against assuming the performance in this metric would correspond to the exact percentage improvement/degradation in cosmological constraints. Only a full DETF FoM including all probes and systematics can indicate the exact numerical impact of observing strategy choice.

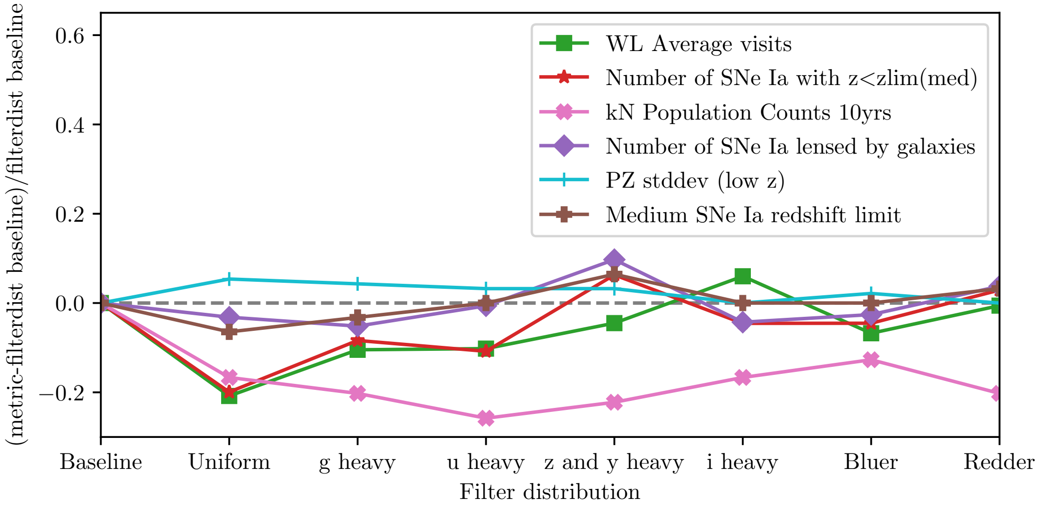

Figure 4: Selected metrics, relative to their values at baseline, as a function of varying choices of filter distributions. Note that these simulations use a different footprint so all metrics are measured against the baseline `filter_dist` simulation, and not the standard baseline. We do not show the 3x2pt FoM or LSS metrics because they do not vary significantly here. We find no compelling reason to vary the baseline filter distribution: different distributions improve different probes but at the cost of others.

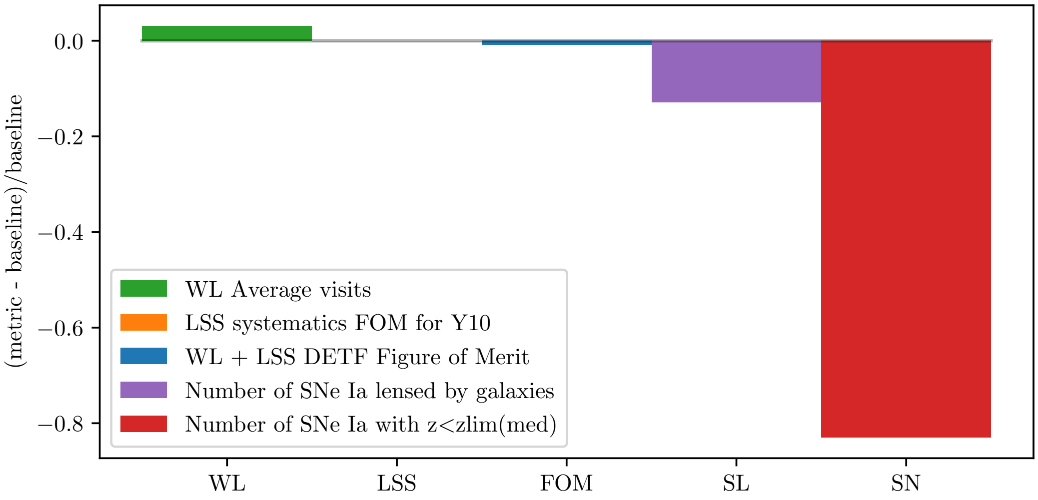

Figure 5: Selected metrics, relative to their values at baseline, for the `baseline_samefilt_v1.5_10yrs` simulation. This clearly shows that while taking visit pairs in the same filter does not impact static science much, it dramatically degrades the transient metrics.

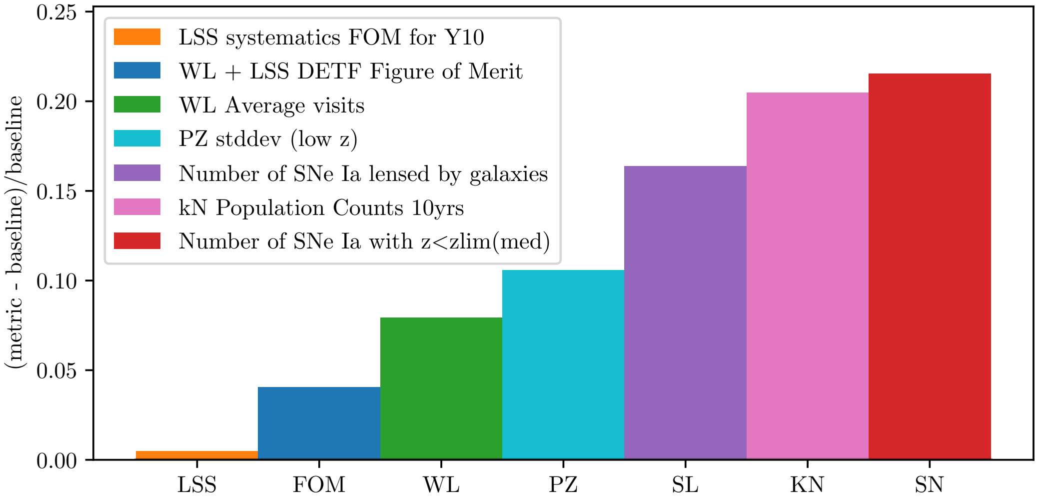

Figure 6: Selected metrics, relative to their values at baseline, for the `baseline_nexp1_v1.7_10yrs` simulation, as compared to the current v1.7 baseline called `baseline_nexp2_v1.7_10yrs`. The only difference between these two simulations is the choice of whether an observation is taken in 2 × 15 s exposures (the current baseline) as opposed to a 1 × 30 s exposure. It is clear that the efficiency gained through a single exposure improves all metrics, some dramatically.

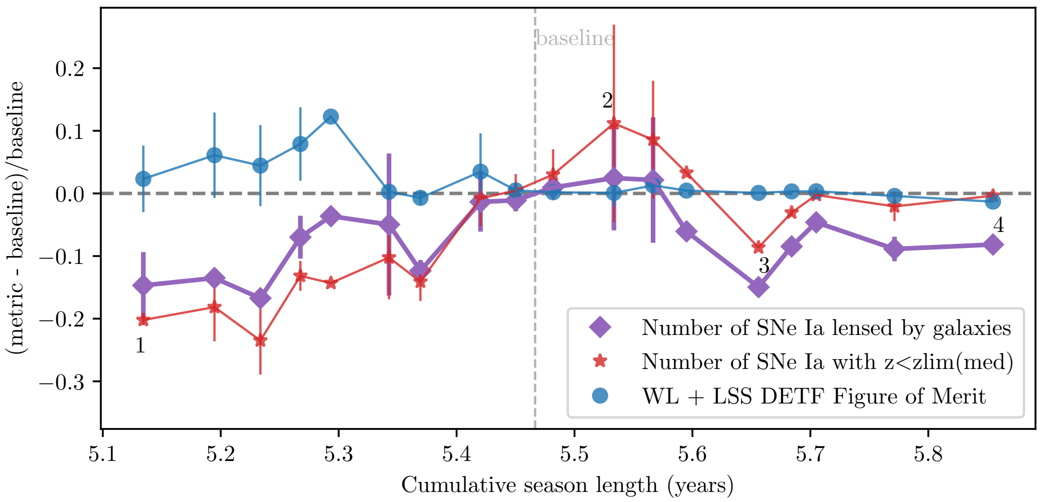

Figure 7: Selected metrics, relative to their values at baseline, as a function of the cumulative season length (the total amount of time a field is observed) of different observing strategies. We use the cumulative season length because it accounts for both the season length each year as well as the total number of seasons, which can vary between simulations (especially for rolling cadence strategies). This is particularly important for strongly lensed supernovae. To improve readability, points that are nearby in the x-axis are binned with only the mean and error bar plotted for that bin. Shorter season lengths degrade strong lensing and supernovae performance but as long as the season length does not fall much below its value at baseline, these metrics do not seem to be strongly affected. We have highlighted specific simulations with numbered annotations: 1–`footprint_newBv1.5_10yrs`, 2–`wfd_depth_scale0.99_v1.5_10yrs`, 3–`short_exp_5ns_5expt_v1.5_10yrs`, 4–`dcr_nham1_ugri_v1.5_10yrs`

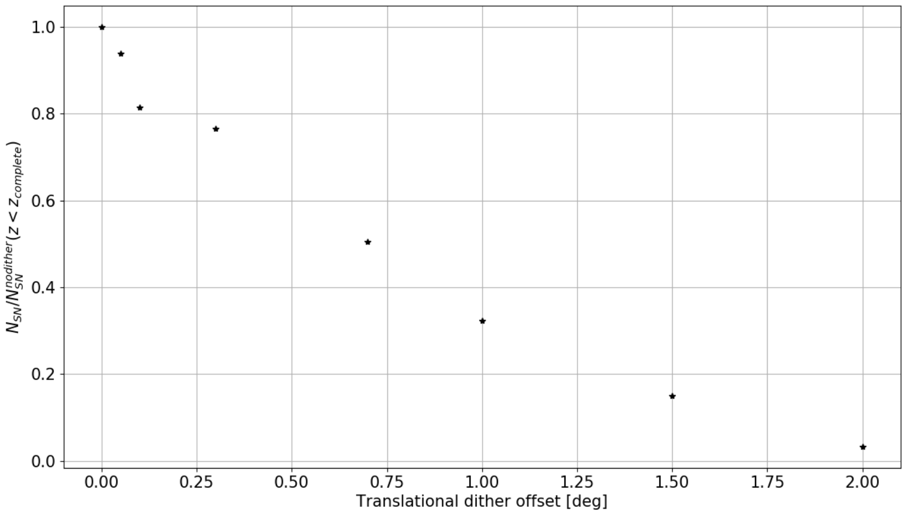

Figure 8: Ratio of the number of well-measured supernovae $N_{SN}/N_{SN}^{nodither}$ as a function of the translational dither offset. Only DDFs are considered in the plot. The quality of the supernovae is mainly driven by the sampling of the light curves, i.e., the inter-night cadence of the observations. Large translational dithers lead to an decrease of the inter-night cadence and to a higher number of supernovae being rejected due to poor quality. Translational dithering effects may be dramatic (more than 80% loss of supernovae for higher dithering), but this could be mitigated by increasing the number of visits in the DDFs and hence, the inter-night cadence.

C. Rolling WFD and DDF mini-surveys

Here we provide new ideas for producing simulations that enable rolling WFD observing strategies and rolling DDF observing strategies.

C.1. Rolling WFD

Rolling cadences may be defined by two parameters: ($f_{\rm rolling}$, $f_{\rm obs}$) where $f_{\rm rolling}$ is the fraction of the sky where a fraction of observations ($f_{\rm obs}$) will be made. It would be worth producing simulations to study such as rolling with the following configurations: $(f_{\rm rolling}, f_{\rm obs}) = (1/3, 1), (1/3, 0.8), (1/3, 0.6)$. Even if these simulations degrade other science cases, it would be interesting to see if they can even theoretically improve performance enough to continue pursuing them.

Replicating AltSched's deterministic scheduling would also be very helpful. It could be done with the current scheduler by observing a well-defined area (at the meridian) per night and allowing observations to be taken in sub-optimal weather and seeing conditions (and rather prioritize slew-time minimization). Additionally, the sky should be split in two strips (North and South), and these areas should be scanned every other night (night 1: N, night2: S, night 3: N, night 4: S, ...). Observing at the meridian and including these other settings would ensure some overlap between observed regions, thus providing a good inter-night cadence.

C.2. Rolling DDF

As discussed in Section 2, the goal of the DDF supernovae program is to collect a large set of well-measured type Ia SNe up to high redshift ($z \sim 1$), which sets strict requirements on the number of visits and inter-night cadence per field. The visit budget would be too large if 5 fields are observed for ten years to the needed depth. Here, we present three rolling DDF scenarios to address this challenge. The first two are "DESC-only" strategies, whereas the third considers optimal observing strategies for both DESC and AGN (see Brandt et al. 2018). Up to five fields are used in our budgets, all of which make up the current baseline LSST strategy: COSMOS, CDFS, XMM-LSS, ELAIS, and a fifth field located at the position of the Euclid/Roman Deep Field near ADFS.

C.2.1. Rolling DDF 1: 5 fields, same depth

Field	COSMOS	XMM-LSS	CDFS	ELAIS	Euclid/Roman
cadence	1				
season length [days]	180				
Nseasons	2				
Years	1,3	3,4,5	8,9	6,7,8	2,3,5,6
Nvisits	89 2/2/28/39/18 in $g/r/i/z/y$				

Table 2: Simulation parameters of a proposed rolling DD mini-survey. The depth is similar for all the fields ($z_{\rm complete}$ ∼0.8). The estimated budget is ∼8%. The timely sequence of the survey is tuned to observe one (maximum two) fields per night and to ensure contemporaneous observations with the Euclid/Roman surveys (Figure 9).

C.2.2. Rolling DDF 2: 5 fields, ultra-deep and deep fields

Field	COSMOS	XMM-LSS	CDFS	ELAIS	Euclid/Roman
cadence	1				
season length [days]	147	162	180		
Nseasons	2				
Years	1,3	3,4,5	8,9	6,7,8	2,3,5,6
Nvisits	232 2/2/89/121/18 $g/r/i/z/y$		88 2/2/4/11/18 $g/r/i/z/y$		

Table 3: Simulation parameters of a proposed rolling DD mini-survey. There are two sets of fields in this strategy: ultra-deep fields (COSMOS, XMM-LSS) with a depth of $z_{\rm complete}$ ∼0.9, and deep fields (CDFS,ELAIS, Euclid/Roman) with a depth of $z_{\rm complete}$ ∼0.7. The estimated budget is ∼8%.

C.2.3. Rolling DDF 3: 5 fields plus AGN

Scenario	Field	COSMOS	XMM-LSS	CDFS	ELAIS	Euclid/Roman
DESC	cadence	1				
	season length [days]	147	162	180		
	Nseasons	2				
	Years	1,3	3,4,5	8,9	6,7,8	2,3,5,6
	Nvisits	232 2/2/89/121/18 $g/r/i/z/y$		88 2/2/4/11/18 $g/r/i/z/y$		
AGN	cadence/season length [days]	1/180				-
	Nseasons	10				-
	Nvisits	18 (4/1/1/3/5/4 in $u/g/r/i/z/y$)				-

Table 4: Simulation parameters of a proposed rolling DD mini-survey. This strategy is a combination of the DDF 2 scenario (Table 3) and of a DD program for AGN (Brandt et al. (2018)). The estimated budget is ∼ 10.7% (AGN: 2.7%, DESC: 8%).

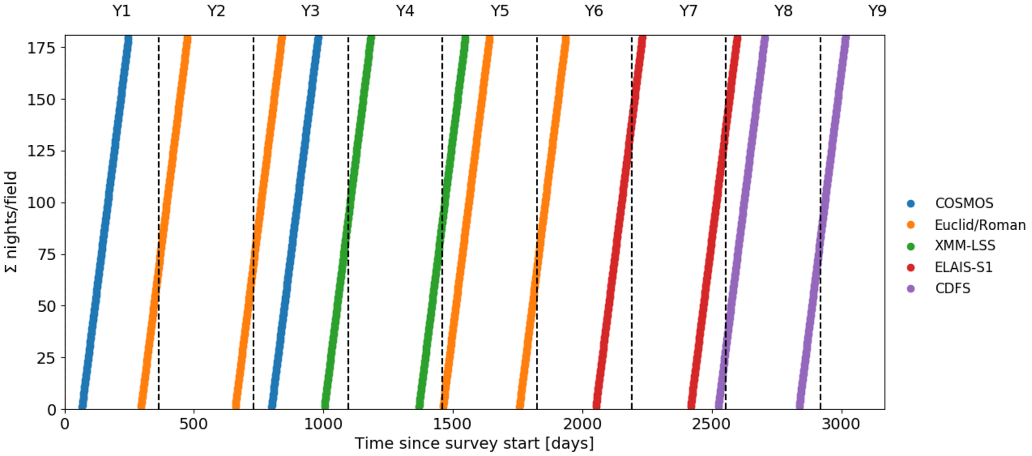

Figure 9: Cumulative sum of the number of nights (per field and per season) as a function of the time since survey start (assumed to be late 2023). The following sequence of observations is considered: COSMOS, Euclid/Roman(x2), COSMOS, XMM-LSS(x2), ELAIS(x2), CDFS(x2), with a maximum season length of 180 days, a cadence of one day, and ensuring only one field is observed per night. The fields are required to be observable (airmass ≤ 1.5 and 20° ≤ altitude ≤86.5°) for at least one hour. There is some overlap in years 3 (between XMM-LSS and COSMOS), 5 (between XMM-LSS and Euclid/Roman) and 8 (between ELAIS-S1 and CDFS) to maximize season lengths.

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