Active Galaxy Science in the LSST Deep-Drilling Fields: Additional Points on Footprints, Cadence Requirements, and Total-Depth Requirements

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Introduction and Overall Context

This cadence note serves as an update to the earlier cadence white paper titled "Active Galaxy Science in the LSST Deep-Drilling Fields: Footprints, Cadence Requirements, and Total-Depth Requirements" by W.N. Brandt et al. (arXiv:1811.06542v2; hereafter, the "2018 AGN white paper"), and the 2018 AGN white paper and this cadence note should be read together. As per the title, we focus specifically on AGN science issues related to footprints, cadence requirements, and total-depth requirements for the four LSST Deep-Drilling Fields (DDFs) chosen and announced in 2012. Some of our considerations regarding cadence and total depth will also be relevant to other DDFs, such as the Euclid Deep Field-South.

We stress at the outset that *we are not recommending any radical changes relative to the 2018 AGN white paper*. In fact, the goals of the AGN Science Collaboration can still largely be met satisfactorily if the Rubin DDF observations are executed following that white paper, and some of the below is simply buttressing key points from it. The one possible exception is the relatively shallow ultimate depths of the DDFs, and below we provide a possible partial remedy for this in terms of an "accordion cadence" that would not excessively harm AGN time-domain science. We also describe a possible way that the exposures on the DDFs could be reduced in cost and made easier to execute overall, without overly harming AGN science.

Considering the specific questions posed in the 2020 December 8 "LSST Cadence Notes Solicitation", our recommendations below primarily address Question 2 (observing-time allocation) but also have relevance to Questions 4 (band distribution) and 7 (dithering pattern).

Footprint Considerations

A key motivation for announcing four LSST DDFs in 2012 was to stimulate preparatory multiwavelength data gathering in these fields, including with unique space-based facilities with limited lifetimes. Thankfully, this stimulation has largely been successful. For example, at large observational cost, Spitzer (e.g. M. Lacy et al. 2021, MNRAS; M. Annunziatella et al., in preparation) and/or XMM-Newton (e.g. C.-T. Chen et al. 2018, MNRAS; Q. Ni et al., ApJS, submitted) have now gathered superb datasets over 3-10 deg^2 areas in the CDF-S, XMM-LSS, ELAIS-S1, and COSMOS fields. Additional data in these fields are currently being gathered by, e.g., the MeerKAT International GHz Tiered Extragalactic Exploration (MIGHTEE) survey (e.g. J. Delhaize et al. 2021, MNRAS), the Looking at the Distant Universe with the MeerKAT Array

(LADUMA) survey (e.g., S. Blyth et al. 2016, Proc of MeerKAT Science), and the Deep Extragalactic Visible Legacy Survey (DEVILS; e.g. A. Hashemizadeh et al. 2021, MNRAS) – much additional deg^2 data will be coming soon from facilities including MOONS, PFS, 4MOST, and LMT TolTEC. All these data will be *extremely* valuable for AGN selection and characterization in conjunction with the observations from Rubin, as well as for science investigations on many other topics. They are already being actively used for Rubin DDF science preparation, e.g. see the recent derivation of 1.6 million photometric redshifts from forced photometry over 0.36-4.5 microns by F. Zou et al. (2021, RNAAS).

All this data gathering has been substantially motivated by the 2012 announcement of the LSST DDFs, and all four of these fields remain premiere multiwavelength survey fields that will enable superb Rubin science. They will also serve as essential "training sets" for unlocking the potential of the Wide-Fast-Deep main survey for AGN, galaxy, and cosmological science. Thus, our first recommendation regarding footprints is that *all four of these fields should remain as LSST DDFs and should receive substantially elevated exposure with Rubin relative to typical sky areas in the main survey.* Our specific recommended cadence is detailed in the 2018 AGN white paper with some further relevant points below – *this represents a recommended aggressive investment of exposure in the DDFs.*

Moreover, the multiwavelength data gathering described above has necessarily been done in specific carefully chosen footprints, and these prime multiwavelength regions now largely serve to define the scientifically optimal central DDF pointing directions for Rubin, at least for AGN studies.[1] Thus, our second recommendation regarding footprints is that *these four LSST DDFs have their central pointing directions chosen to be those specified in Section 3.2 of the 2018 AGN white paper.* As noted in that Section 3.2, a perturbation may be necessary for the XMM-LSS field owing to its proximity to the star Mira, but this perturbation should be kept as small as possible once practical Rubin observing constraints are fully understood.

Furthermore, *whatever dithering pattern is ultimately adopted for the DDFs should not compromise obtaining the best-possible Rubin coverage of the prime multiwavelength regions*. In the operations simulation (OpSim) runs `agnddf_v1.5_10yrs.db` and `descddf_v1.5_10yrs.db`, a ≈ 0.4 deg dithering pattern is adopted, which is acceptable in terms of giving good sensitivity over the several deg^2 prime multiwavelength regions nestled in the central parts of the DDFs. Generally, DDF dithers should be kept *as small as reasonably possible*, so that time-domain studies of AGNs will have as many epochs as possible (i.e., large dithers would cause many AGNs to lack coverage in some DDF pointings).

Cadence and Total-Depth Considerations

Most of what was stated in the 2018 AGN white paper regarding cadence recommendations remains applicable, so below we primarily comment upon new issues that have subsequently arisen.

All Rubin DDF observations recommended below should be done in a manner that minimizes nightly lunar sky-brightness effects (e.g., trying to observe the DDFs when the Moon is down on a given night; see E. Neilsen et al. 2021, RTN-014). However, it is essential that a uniform, frequent DDF cadence be consistently maintained during both bright time and dark time.

[1] Useful images of the prime multiwavelength regions can be found in Figures 2-4 of M. Lacy et al. (2021, MNRAS) and in the 2018 AGN white paper. We would be happy to provide the Project with region information to aid coding of relevant metrics.

Consideration of Accordion Cadences to Improve the Ultimate DDF Photometric Depths

Section 3.7 of the 2018 AGN white paper recommended *grizy* observations[2] every other night over the longest observing seasons possible (7-8.5 months), and the OpSim runs indicate such seasons are indeed possible. Qualitatively similar recommendations were made in the Dark Energy Science Collaboration (DESC) DDF white paper by D.M. Scolnic et al. (arXiv:1812.00516), though there were differences in the precise cadence recommended. The OpSim runs performed for the DDFs have shown that this basic "dense monitoring over long seasons" approach has the downside of significantly limiting the ultimate photometric depths achieved in the DDFs. On average, for DDFs in the OpSim run `agnddf_v1.5_10yrs.db`, the coadded depths in the *grizy* bands are ≈ 0.7/0.7/0.6/0.5/0.4 mag shallower than the nominal expectations from Table 2 of Z. Ivezic et al. (2019).

To help improve the ultimate photometric depths of the DDFs while still preserving excellent AGN time-domain science, we recommend consideration of "accordion cadences", named as such because the bellows of an accordion can sometimes be densely packed in the middle and less densely packed near the edges. The idea for Rubin is to have the (generally higher airmass and sky brightness; E. Neilsen et al. 2021, RTN-014) observations at the start and end of each season (still 7-8.5 months in length) be made less densely, while observations in the prime central part of each season should be made nightly (instead of every other night). Such an approach would recover some of the lost photometric depths in the DDFs, if such recovery is deemed to be a critical goal for the DDFs. If suitably implemented, an accordion cadence could conceivably also have some benefits for studies of the generally short reverberation lags in AGN accretion-disk continuum reverberation mapping (e.g. Z. Yu et al. 2020, ApJS) while not compromising the other science goals in the 2018 AGN white paper excessively.

We therefore performed simulations of accretion-disk continuum reverberation mapping to assess what types of accordion cadences would be acceptable (Y. Homayouni et al., in preparation). Encouragingly, some accordion cadences exist that provide similar-quality results for accretion-disk reverberation mapping as the original "every other night" cadence detailed in the 2018 AGN white paper. If an accordion cadence will be implemented to recover some of the lost photometric depth in the DDFs, then based on our simulations we recommend that:

- The *grizy* nightly monitoring part of the accordion cadence be at least 2.5 months in duration.

- The less-dense part of the accordion cadence acquires *grizy* observations at least every four nights.

An illustration of accretion-disk continuum reverberation mapping results for an accordion cadence with 2.5 months of nightly monitoring and otherwise monitoring every four nights is shown in Figure 1. This illustrated choice of accordion cadence obeys our above recommendations, and it has about the same observational cost and provides results comparable to those for the original "every other night" cadence.

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[2] Note, as per the 2018 AGN white paper, that we recommend observations in *all* the *grizy* filters on each night observations are done. We also recommended significant *u*-band observations in the 2018 AGN white paper, though these would necessarily have more limited time-domain coverage than for the other bands. While these *u*-band observations are not discussed in the main text of this cadence note, we still recommend these be executed as defined and justified in the 2018 AGN white paper. The total *u*-band depth of the `agnddf_v1.5_10yrs.db` OpSim run appears suitable; see the Assef et al. cadence note on quasar colors for further discussion.

Further recommendations about the observations, such as relative band depths, are given in the 2018 AGN white paper.

It would be valuable if OpSim runs could be performed for the accordion cadence described above, so that its results could be further assessed quantitatively.[3]

A Possible Reduced Number of Years of Dense Monitoring for Cost Savings and Easier Observing

The 2018 AGN white paper was admittedly aggressive in requesting "dense monitoring over long seasons" for the *full ten years* of Rubin operations, which was implemented in the OpSim run `agnddf_v1.5_10yrs.db`. While this remains ideal for AGN variability science, excellent results could likely be achieved with the following less observationally expensive approach:

- Four of the years for any given DDF could employ dense monitoring, while the other six years for that DDF could have less-dense monitoring every 4-5 nights.

- The long (7-8.5 month) seasons must be retained for the full ten years.

This approach would reduce the total cost of the AGN DDF request substantially, while still providing the dense monitoring needed for accretion-disk continuum reverberation mapping for four of the years - having significantly fewer than four years may lead to unacceptable failures in detection of accretion-disk reverberation lags (e.g. Z. Yu et al. 2020, ApJS; Y. Homayouni and Z. Yu 2021, private communication). It would also allow excellent Rubin AGN time-domain science more generally. As described in the 2018 AGN white paper, obtaining Rubin coverage every year with long seasons is critical for supporting spectroscopic reverberation mapping of the broad line region (where the reverberation lags are much longer than for the accretion-disk continuum reverberation mapping mentioned above), changing-look AGN studies, binary supermassive black hole searches, and general studies of long-term AGN variability. Indeed, opening the hour-angle limits further to lengthen the seasons even more than in the OpSim `agnddf_v1.5_10yrs.db` (say, by an additional month) would likely be beneficial.

Moreover, the DDFs receiving dense monitoring could be strategically "toggled" on an annual basis over the ten years of Rubin operations in order to reduce the instantaneous Rubin observing demands in any given year. This will likely be important for the CDF-S, XMM-LSS, and ELAIS-S1 fields which are clustered in right ascension (along with the Euclid Deep Field-South). We note that the DESC is putting forward a broadly similar suggestion, which they term "rolling deep fields" (D.M. Scolnic 2021, private communication).

It would be valuable if OpSim runs could be performed for this less observationally expensive approach, so that its results could be further assessed quantitatively.

Rubin Coordination with Other Time-Domain AGN Projects

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[3] Clearly, a very wide variety of accordion cadences can be considered, in principle (e.g., an accordion cadence could *gradually* increase and then later *gradually* decrease in observation density). Here, we have just tried to suggest some basic, reasonable criteria that an accordion cadence should follow for successful AGN science. If the Survey Cadence Optimization Committee would like to explore more complex accordion cadences, we would be happy to assess these constructively from an AGN-science perspective.

During the ten years of Rubin operations, other large and important AGN time-domain projects will be conducted in the DDFs. These include the SDSS-V Black-Hole Mapper Reverberation Mapping Project (J. Kollmeier et al. 2017) and the 4MOST TiDES Reverberation Mapping Project (E. Swann et al. 2019, The Messenger). These will be focused on measuring direct black-hole masses via multi-object spectroscopic reverberation mapping of the broad line region for hundreds of AGNs.

Both of these projects will greatly benefit from Rubin photometric observations complementing their spectroscopic observations, and it will be best if the specific years of dense Rubin photometric monitoring coincide in time with the specific years of dense SDSS-V/4MOST spectroscopic monitoring. Thus, to maximize science return, we recommend *coordination between the Rubin Project and these spectroscopic reverberation mapping projects to achieve such temporal alignment*. In particular, given the planned operational period of SDSS-V (2020-2025), it will be valuable if some of the years of Rubin dense monitoring of the CDF-S, XMM-LSS, and COSMOS fields are done relatively early in Rubin operations (say, in 2024).

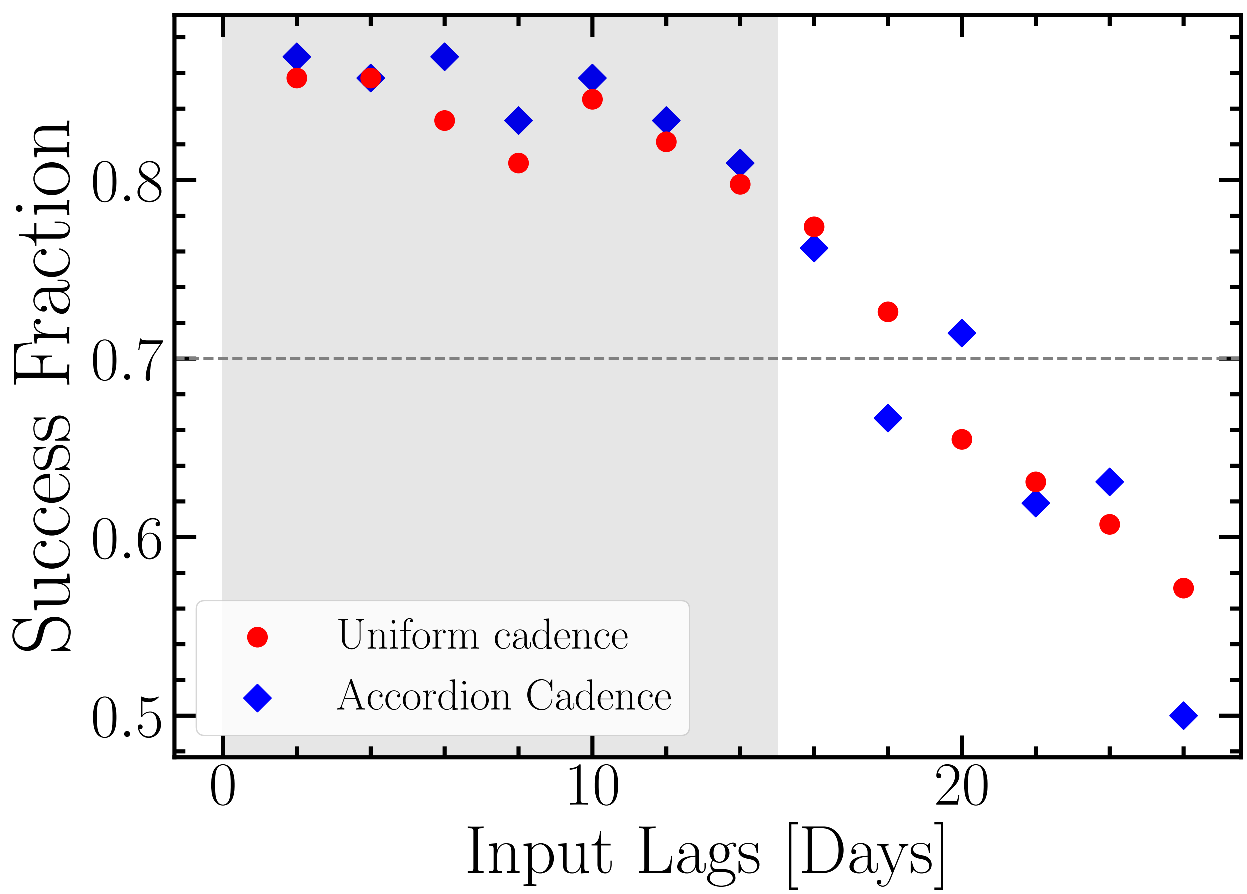

Figure 1: The lag-recovery success fraction for accretion-disk continuum reverberation mapping as a function of input-lag timescale. For lags shorter than ≈ 15 days (gray shaded area), the accordion cadence (blue diamonds) has marginally higher success rate than the uniform cadence from the 2018 AGN white paper (red circles); the simulated accordion cadence is based on the bulleted list in the "Cadence and Total-Depth Considerations" section. For longer lags (> 15 days), the results are mixed. A lag is considered successfully recovered if the fraction of the lag posteriors within the primary peak is > 60% of the primary peak, the maximum cross-correlation coefficient between the optical light curves is > 0.4, and the recovered lag is within +/- 2 days of the input lag. Simulations include 1500 observed quasar light curves drawn from the SDSS Reverberation Mapping Project light curves (Homayouni et al. 2019).