LSST Cadence Note – Enhancing LSST Science with *Euclid* synergy and a mini-survey of the northern sky to Dec $< +30$

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In response to the Solicitation for Cadence Notes we present this technical update on the two Capak et al. 2018 LSST white papers ("Enhancing LSST Science with Euclid Synergy" and "Mini-survey of the northern sky to Dec $< +30$") by the Tri-Agency Survey Coordination Task Force appointed to develop synergies in order to maximally enhance the combined science output of Rubin’s LSST and *Euclid*, as illustrated by the Rubin-*Euclid* Derived Data Products parallel effort. Survey options presented in our two white papers have since been integrated in the LSST simulations. Today, we further endorse the request from the LSST Dark Energy Science Collaboration (DESC) arguing for modifications to the Wide Fast Deep (WFD) towards an extended footprint driven by dust extinction limits since it enhances *Euclid* synergy with up to a 9400 deg$^2$ overlap. We update depth requirements based on the better than expected as-built *Euclid* performance (+0.5 mag) in g, r, i, z for the 20deg$^2$ *Euclid* Deep Field South (EDF-S) now requiring 0.48% of the total number of visits of LSST. We recommend a custom dithering on EDF-South to deliver at least 20 deg$^2$ of contiguous uniform depth as required by *Euclid* versus having two joint but separate DDFs. We update the information so that the LSST DDF cadence can possibly be matched to those of *Euclid* in the two common deep fields, CDFS and EDF-South. We make a case for more LSST science with a mini-survey of the extragalactic area of the northern stripe for Targets of Opportunities (ToOs) by upgrading it from g, r, i to g, r, i, z for a grand total of 0.78% of the total number of visits of LSST. This mini-survey would add an extra 2600 deg$^2$ overlap with *Euclid* outside of the extended WFD. This note focuses on the relevant questions from the solicitation, Q1 and Q2.

**Q1: Are there any science drivers that would strongly argue for, or against, increasing the WFD footprint from 18,000 deg$^2$ to 20,000 deg$^2$?**

**Science:** Extending the WFD to Dec $[+12.5,-70]$ enhances the synergy with *Euclid* while enabling the science cases presented by Capak et al. in favor of the mini-survey of the northern sky: Multi-Messenger Transient Follow-up, Local Group, Nearby Universe, Cosmology, and High-Redshift Universe, all the while boosting the LSST follow-up capabilities with imaging and spectroscopic facilities from the North (e.g. Keck, DESI, PFS, TMT).

**Depth:** *Euclid*’s as-built performance in the near-infrared is better than expected, a noteworthy improvement of 0.5 mag deeper than the initial requirement for the Y, J, H bands, now estimated at 24.5 median across the survey (depth metric is PSF photometry on a point-source at 5-sigma). This shifts equally the matching optical photometry from Rubin, critical for the photometric redshifts, to $g=26.2$, $r=25.6$, $i=25.3$, $z=25.1$, leading to a total of 9, 6, 11, and 28 visits, respectively.

**Sky area:** The *Euclid* region of interest in the sky is defined by dust extinction (E(B-V)<0.09) and Galactic ($|b| > 25$ deg & bulge avoidance) plus ecliptic ($|b| > 10$ deg) latitude thresholds, yielding 17,400 deg$^2$ of sky compatible with the science goals (Figure 1). The 6-year baseline space survey allows only, as required, a 15,000 deg$^2$ survey realization. An extra year of *Euclid* operation could fill the full 17,400 deg$^2$. The proposed WFD extension increases by 1600 deg$^2$ the overlap with the *Euclid* sky. This *Euclid* footprint is now shared with DESC, allowing precise calculation of the overlap area with the DESC extragalactic footprint; Figure
3 shows the overlap area for the v1.7 simulations, and we see that only the footprints that push North and implement a dust-extinction based WFD footprint yield large overlap area, up to 9400 deg².

**Q2: Assuming that current system performance estimates will hold up, we plan to utilize the additional observing time (which may be as much as 10% of the survey observing time) for visits for the mini-surveys and the DDFs. What is the best scientific use of this time?**

**Southern deep fields:** Euclid selected one of its three deep fields to match the DDF on CDFS (EDF-Fornax, 10 deg²). There is an informal agreement with Euclid for the fifth DDF field to overlap the Euclid Deep Field South (EDF-South, 23 deg²) which has been shaped into an elongated area to minimize the Rubin time budget needed to reach a uniform depth across 20 contiguous square degrees required by Euclid’s science. EDF-South has since been integrated in the LSST baseline, although as two individual DDFs rather than one. Interactions between the two projects survey design teams led to the proposed translation dithers illustrated on Figure 2 for which Rubin reaches the Euclid depth goals on 21.6 deg² within the 23 deg² stadium shape area which will be fully covered by Euclid. We favor this dithered approach.

**Deep fields cadence:** Once Euclid is launched we will know when those two southern deep fields will be visited over the 6-year period. EDF-Fornax and EDF-South will start getting observed regularly on the second year of the space survey, each visit lasting a fixed 5 to 6 days, every 6 months. To optimize transient science the LSST and Euclid cadence should be optimized as much as possible, a topic currently discussed in the context of the Rubin-Euclid Derived Data Products that will help such coordination.

**Deep fields depth:** The revised depth for the Euclid wide survey due to increased performance also applies to the deep fields which will be two magnitudes deeper than the wide (×40 visits). This brings the total number of required visits on EDF-South in g, r, i, z to 360, 240, 440, 1120 for each of the two pointings, a grand total of 4320 visits. Adopting an equivalent FOV of 8 deg² for tiling, this leads to 4320×20/8/2224095 = 0.48% of the total number of visits of LSST. EDF-South could grow as a regular half-speed DDF (single DDF time budget spread across the EDF-South area) until the required depths are reached in each band. Since Euclid will reach its final depth on this field around 2028, there is flexibility in scheduling the EDF-South visits over the years. We note that photometric redshifts would benefit from the u-band visits resulting from the standard DDF plan.

**Beyond the WFD in the North:** The mini-survey of the northern sky proposed in 2018 suggested to push the Rubin northern sky coverage from Dec +2 to Dec +30. We presented science cases through three components (Ecliptic Optimal, Galactic Optimal, and Space Optimal) for ToOs templates, Local Group, Galactic RR Lyrae, Nearby Universe, Euclid and DESI synergies, DESI-2, and High-z. This has since materialized in the LSST simulations in the form of a northern stripe mini-survey for ToOs along the Northern Ecliptic Survey, although only in the g, r, i bands. We endorse this approach of a mini-survey of the northern sky but point the key addition of the z-band in the Space Optimal area which would then enable more LSST science as outlined in the white paper while adding an extra 2600 deg² overlap with Euclid outside of the extended WFD. Considering our revised depths with 9, 6, 11, 28 visits total in g, r, i, z, and an equivalent FOV of 8 deg² for tiling, the total time budget of this Space Optimal component of the northern stripe ToOs mini-survey amounts to (9 + 6 + 11 + 28) × 2600/8/2224095 = 0.78% of the total number of visits of LSST. Euclid does not plan to observe this part of the sky before 2025 (Figure 1).

**Beyond the WFD in the South:** Our paper also endorsed the mini-survey reaching all the way down to the South Celestial Pole as is covers high quality (dark) Euclid sky that will be observed, by mission design, within the first two years (2023/2024). The total Rubin overlap with the Euclid sky through the extended WFD plus the two mini-surveys could reach 12,500 deg², 72% of the Euclid compatible sky.

**Synergy with Roman:** The Nancy Grace Roman Space Telescope will launch in the mid-2020’s, and as part of the mission expects to survey areas comparable to the Rubin field of view with depths of ∼>28-29 AB. Since these fields will be used to identify and follow-up supernovae, the overall science return of both Rubin and Roman would be enhanced by flexibility in the location of future deep fields and by enabling concurrent Rubin+Roman observations. We recommend that the Rubin/LSST Survey Cadence Optimization Committee consider these issues when considering future Rubin/LSST observations.
Figure 1 - *Euclid* has identified 17,400 deg$^2$ of sky compatible with its science requirements (red outline = region of interest) but the 6-year baseline survey allows only, as required, a 15,000 deg$^2$ survey realization, shown here as colored areas in pastel colors. This simulation gave an equal priority through the years to the northern and southern celestial hemispheres but this can be modulated. The *Euclid* deep fields which will be 2 magnitudes deeper than the wide survey are marked in bright green. The six calibration fields are marked with red diamonds. The top signal-to-noise ratio areas of the *Euclid* survey, shown in white and black dashed contours (1300 and 2600 deg$^2$ in each hemisphere), will be observed within the first two years (2023/24).

Figure 2 - The stadium shape of EDF-South was chosen to minimize the time budget needed to cover a contiguous area of at least 20 deg$^2$, as required by *Euclid*’s science goals. Two independent Rubin DDF positions (left) over EDF-South results in high depth outside the desired footprint. A custom extended Rubin dithering pattern (translation dithers, center) brings better footprint coverage, reaching 21.6 deg$^2$, out of the stadium’s 23 deg$^2$ footprint, at the required depths (right).
Figure 3 - Area overlap between the LSST extragalactic footprint (defined by an extinction and depth cut alongside requiring coverage in all six bands) and Euclid’s region of interest. We see that only the footprints that push North yield large increases in overlap, with a maximum overlap (for v1.7 simulations) from footprint_8 which implements an extinction-limited WFD footprint, yielding ∼10% more overlap area than baseline after the first year of LSST survey (Y1), and ∼14% more overlap area than baseline after 3, 6, 10 years of LSST survey (Y3, Y6, Y10, respectively), up to 9400 deg².