Rubin Observatory Cadence Note: Maximizing Serendipitous Kilonova and Fast Transient Discovery

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1 Science Case

Binary neutron star (BNS) and neutron star–black hole (NSBH) mergers have long been predicted to be associated with not only short gamma-ray bursts (Blinnikov et al., 1984), but also with optical/IR transients called kilonovae (e.g., Li & Paczyński, 1998). The discovery of a kilonova associated with the first BNS merger discovered in gravitational waves, GW170817, spectacularly confirmed these predictions. This multi-messenger source marked a watershed moment in astrophysics, with prospects to strongly constrain both the neutron star equation of state (e.g., Dietrich et al., 2020) and the Hubble Constant (e.g., Hotokezaka et al., 2018), amongst many other science cases.

Questions about the sources of heavy element production in the Universe and diversity in the kilonova population can only be answered by the study of a large sample of sources. Unveiling such a population is difficult because kilonovae are rare ($< 1\,\%$ of the core collapse supernova rate), fast (fading $\gtrsim 0.5$ mag per day in the optical), and faint transients ($M \gtrsim -16$ at peak). Rates of BNS mergers are still uncertain, with R=80–810 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ (GWTC-2).

The advent of Vera C. Rubin Observatory presents us with a great opportunity to identify a population of kilonovae **independent of any gravitational-wave or γ-ray burst trigger**, thanks to the unprecedented volume that Rubin Observatory will be able to probe (see, for example, Andreoni et al., 2019; Setzer et al., 2019). Due to their fast fading and intrinsically underluminous properties, "detection" is not enough; it is imperative that kilonova candidates found by Rubin Observatory are recognized as such in real time so that follow-up observations can confirm their nature.

Some members of our team are leading a new effort dedicated to fast transient discovery in Zwicky Transient Facility (ZTF) data. This project is called "ZTFReST"[1], which stands for "ZTF Realtime Search and Triggering" (ZTFReST; Andreoni & Coughlin et al., 2021). This pipeline employs i) alert queries ii) forced point-spread-function photometry, and iii) nightly light curve stacking in flux space to discover fast-evolving transients such as kilonovae.

In this work, we a set of new metrics appled to `OpSim` simulations to assess the effectiveness of cadence options for un-triggered, or "serendipitous," kilonova discovery. We employ metrics that both assess Rubin's ability to simply detect the transients, as well as metrics designed to flag a transient as "fast" based on the flux evolution. We argue that the latter are the most appropriate metrics for maximizing the science output from these rare objects.

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[1] `https://github.com/growth-astro/ztfrest`

2 Cadence comparisons and recommendations

To assess kilonova detectability in different cadence simulations, we employed a number of metrics. The main ones considered for this Note are:

- multi_detect: >= 2 detections
- `ztfrest_simple`: metric that reproduces a discovery algorithm similar to ZTFReST
- `ztfrest_simple_red`: same as `ztfrest_simple`, but applied only to *izy* bands
- `ztfrest_simple_blue`: same as `ztfrest_simple`, but applied only to *ugr* bands

The metrics were designed to range from standard transient detection (with >= 2 detections which typically provides only spatial information on the celestial coordinates of a source, to methods more likely to lead to source characterization – in other words, kilonova discovery. Importantly, the conclusions that we draw can be applied to **many classes of fast transients** for which light curve sampling with spacing between one hour and one day is crucial, including GRB afterglows and fast blue optical transients (FBOTS).

There are a variety of methods in the literature to rapidly flag fast-transient candidates (for example using machine rearning; see Muthukrishna et al., 2019; Kessler et al., 2019) A simple but effective strategy to identify transients with rapidly fading (in this note taken to be $0.3\,\mathrm{mag\,day}^{-1}$) or rising light curves is based on magnitude rise and decay rate measurements.

Analysis – We used the new `kneMetrics` to recover kilonova light curves injected in `OpSim` simulations. We improved the existing `TDEsPopMetric` by adding the possibility to inject synthetic transients distributed uniformly in volume. We also modified and expanded the transient recovery metrics.For simplicity, we employed only one kilonova model, which fits the GW170817 kilonova Bulla (2019).

Results – The number of "detected" kilonovae (multi_detect) is much larger than the number of kilonovae for which rapid photometric evolution could be measured (`ztfrest_simple`) at any distance. The rolling cadence outperforms the baseline cadence beyond $\sim 350\,\mathrm{Mpc}$ with the `ztfrest_simple` metric. This means that **a rolling cadence can enable kilonova candidate identification more often than the baseline cadence** at large distances. Fig. 2 and Tab. 1 show that only the new v1.7.1 rolling cadences perform up to $\sim 20\%$ better than the baseline cadence (uncertainties are in the order of 5-10%). This indicates progress in the right direction in the design of rolling cadences. However, the baseline plan may still be preferred over any other cadence family currently available (Fig. 2, right panel) due to a slightly larger efficiency at detecting closer (apparently brighter) fast transients, easier to follow-up with other telescopes.

We found strong evidence that red *izy* bands are preferred for kilonova discovery at distances below 300 Mpc. Finally, we found that **baseline cadences with single 30s exposures shall be greatly preferred over 2×15s consecutive snaps**.

[Q1] **We recommend to maintain a WFD footprint of 18,000 deg^2 in favor of better sampled light curves.**

[Q2] **We strongly recommend to use the additional time to supplement WFD cadences**, to obtain more highly sampled observations over the large area covered by the main survey. We expect this to bring $\gtrsim 10\%$ improvement over the baseline cadence (see the `ztfrest_simple` metric applied to the filter_dist family in the bottom-left panel of Fig. 2).

[Q3] Observations in u band are not relevant for our science case, so 2×15s exposures, as planned for the baseline cadence, **are preferred over longer u-band exposures** to maximize observing time in other bands. Long u-band exposures perform comparably to (or worse than) the baseline metric with both `ztfrest_simple` and multi_detect metrics (Fig. 2, Tab. 1). In general, **baseline cadences with single 30s exposures are largely preferred over 2×15s consecutive snaps**.

[Q4] **We recommend to increase the number of izy observations, coupled with at least one observation in g (preferred) or r band on the same night**. Kilonovae are expected to appear as red and rapidly-reddening transients due to heavy r-process elements synthesised in neutron-rich ejecta. At redder wavelengths, kilonova light curves are brighter for longer times, especially if the system is viewed from equatorial viewing angles. Very rapid "blue" kilonovae could be found at larger distances (Fig. 1, left panel) due to the greater sensitivity of g and r filters. We injected 5×10^5 kilonovae uniformly distributed in volume out to 300 Mpc and $\sim 68\%$ were found to be fast-fading (`ztfrest_simple_red` metric) in red izy bands and 44% in blue ugr bands (`ztfrest_simple_blue` metric). We also note that only 37% of kilonovae are detected at least 4 times in ugr bands with respect to izy bands. **The combination of transient detection, color information, and possibly association with a catalogued nearby galaxy can lead to the identification of solid kilonova candidates** to be followed up spectroscopically with >8-m class telescopes such as VLT, Gemini, Keck, or with the upcoming NTT/SoXS designed fortransient classification.

[Q5] **Third triplet visit can be extremely valuable** to gauge information about rapid evolution as well as the color of the transient, if multi-band observations are performed in the same night. It is also important that the spacing between paired visits within the night is maximized, especially in the same filter. Although our kilonova metrics do not appear to be particularly sensitive to these changes, their value for fast transient discovery with ML techniques is demonstrated in Bianco et al. (2019) (see also the Note led by E. Bellm).

[Q6] Our team has strongly supported the development rolling cadences, which analytically should outperform baseline cadences (Andreoni et al., 2019) in fast transient discovery. Discovery metrics applied to the newest version v1.7.1 simulations suggest that rolling cadences – as currently designed – indeed perform better than the baseline cadence, especially at larger distances, by only a small amount. Rolling cadences in version v1.5 simulations perform systematically worse than the baseline. **We recommend simulating new rolling cadences further optimizing the algorithms used in v1.7.1**, maximizing the exposure time in each band (barred u-band) rather than using snap pairs.

[Q7] [No response]

Table 1: Performance of the metrics used for cadences v1.7 (v1.1.7 for the rolling_new family). For each family, the best, mean, and worst performing cadences are ranked, according to the `ztfrest_simple` metric, as good (A grade, $>20\%$ better than the best baseline cadence), bad (F grade, at least 20% worse than the best baseline cadence), or average (C grade). The efficiency (ϵ) and name of the best cadence per family are also reported. All the cadence families simulated in version v1.5 lie within a few percent efficiency from the best v1.5 baseline cadence. We caution that uncertainties could be as large as 5-10%, however this does not change our conclusions.

Family	Best	Mean	Worst	`ztfrest_simple` ($\epsilon \times 10^4$)	Best cadence
Baseline	-	C	**F**	4.98	baseline_nexp1
ddf_dither	C	C	**F**	4.36	ddf_dither1.00
euclid_dither	**F**	**F**	**F**	3.92	euclid_dither2
footprint_tune	**F**	**F**	**F**	2.44	footprint_8
pair_times	C	**F**	**F**	4.26	pair_times_55
rolling	**F**	**F**	**F**	2.36	rolling_scale0.2_nslice2
rolling_nm	C	**F**	**F**	4.18	rolling_nm_scale0.4_nslice2
twi_neo	C	**F**	**F**	4.04	twi_neo_pattern2
twi_pairs	**F**	**F**	**F**	3.76	twi_pairs_mixed_repeat
u_long	C	C	**F**	4.3	u_long_ms_30
wfd_cadence_drive	C	**F**	**F**	4.12	cadence_drive_gl30v1.7
rolling_new	A	C	**F**	6.08	six_stripe_scale0.90_nslice6_fpw0.9
v1.5 cadences	C	C	C	-	-

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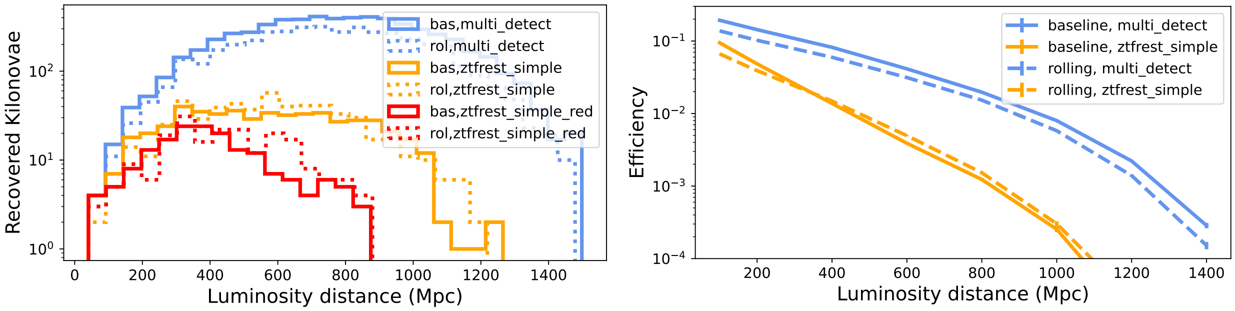

Figure 1: Left: Distribution of recovered kilonovae using a simple multi-detection metric, a ZTFReST-like metric, and a ZTFReST-like metric applied only to red (*izy*) bands. One million sources were injected uniformly distributed in volume between 10 Mpc and 1.5 Gpc. Right: Efficiency as a function of luminosity distance; 5×10^5 sources were injected at intervals of 200 Mpc. For the `ztfrest_simple` metric, the apparently small difference between the rolling and the baseline cadence beyond 400 Mpc is enough to bring an improvement of $\sim 20\%$ in kilonova detection.

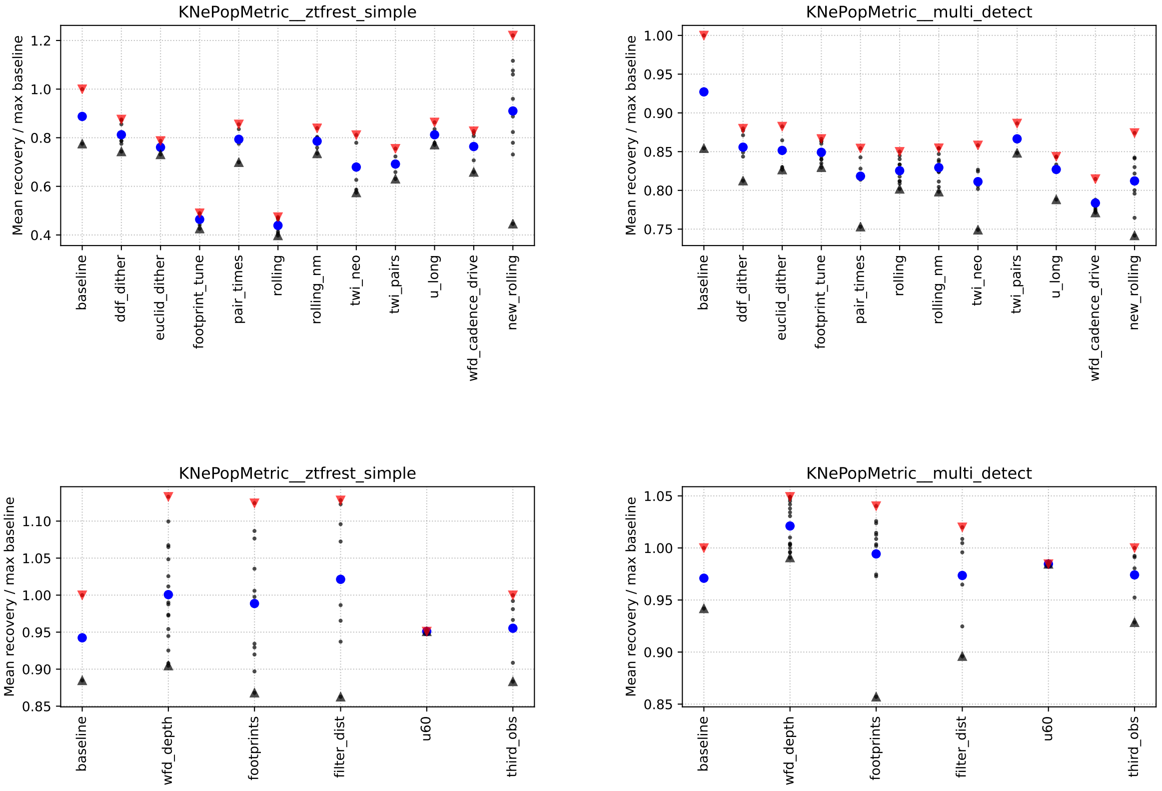

Figure 2: For each cadence family, we report the ratio between the recovery fraction of the individual cadences and the maximum recovery fraction from the baseline cadence. Blue dots indicate the mean of the cadences' recovery fractions, red triangles their maximum, and black triangles their minimum. Simulations part of FBS v1.7 (top) and of FBS v1.5 (bottom) are considered separately.