LSST Cadence Note - Alerting transient phenomena in the Galactic Plane in time to coordinate follow-up

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1 Introduction

The Vera C. Rubin Observatory alerts and community brokers will provide triggers enabling science from follow-up observations that would not otherwise be possible. With alert brokers providing photometric classification in real-time, LSST promises to deliver a wealth of discoveries in all categories of transients across the Galactic Plane. Not all of these discoveries will be characterized with data solely obtained as part of LSST. For a typical microlensing event, for instance, short timescale anomalous features need to be observed with very high cadence (every $\approx 30\,\mathrm{min}$) in order to fully characterize and confirm the signature of an exoplanet which may only last hours or days. Thankfully, microlensing events can be prioritized based on their estimated planet-detection probability given the observations which makes follow-up more efficient. Rapid-response robotic observing networks such as the Astronomical Event Observatory Network (AEON)[1] are prepared to shepherd global telescope resources of all aperture- and instrument-classes to meet the challenge of timely follow-up observations [5].

For a wide range of science cases, classifying anomalies and triggering follow-up observations will benefit from a higher observing cadence. Moreover, the most relevant photometric passband depends on the category of the transient event - microlensing benefits mostly from observations in the near-infrared while gamma-ray bursts would be initially triggered in the ultraviolet. *In the context of project-independent development of alert brokers and the simultaneous preparation of cadence notes, we approach the research topics that follow independently of recent progress in the fields of broker development and follow-up planning, but we note that a more complete future evaluation should take their input into account.*

In this cadence note, we use microlensing simulations according to the survey strategy outlined in [4] as a proxy to quantify how a better coverage of the Galactic Plane affects the potential of finding the aforementioned microlensing anomalies. These anomalies can show a diverse morphology and are generated by a number of different astrophysical phenomena: e.g. exoplanets detectable as binary microlensing events, brown dwarf binaries or stellar remnants. Microlensing events in the range of 0 to 500 days can be grouped according to typical event timescales for free-floating planets and brown dwarfs in the Milky Way and Magellanic Clouds (0.1 to 10 d), stellar mass planet hosts (10 - 100 d) and stellar remnants beyond 100 d timescales. Ongoing microlensing events will appear in the general LSST alert stream as transients, with specialized brokers subsequently classifying them as microlensing. We use microlensing simulations to evaluate the relative timeliness and degree of confidence when issuing alerts and propose an approach based on the information-carrying window of microlensing events that could be generalized for other types of transients.

In order to characterize events, we would like to ensure an adequate photometric cadence during the information carrying part of lightcurve. This approach aims to infer the lens mass which is related to the Einstein time t_{E} - the characteristic timescale associated with the brightening of the event. The observing window Δt with the highest information contribution is related to the Einstein time t_{E} and impact parameter

[1] `https://lco.global/aeon/`

of the source track u_0 via $\Delta t = \pm t_{\rm E}\sqrt{-u_0^2 - \sqrt{9u_0^4 + 36u_0^2 + 4} - 2}/2$ which corresponds to a window of $\pm 5\,d$ for a typical microlensing event[2].

The second aspect of selecting a meaningful observing window should encompass the probability of finding a planetary signal in a microlensing lightcurve. The lightcurve initially resembles a symmetric bell-shaped curve, and a planetary companion to the main lens may induce a brief perturbation to the lightcurve - most likely close to the peak of a single-lens event. To estimate the planet detection probability for a given event, we calculate the region of highest planet sensitivity [1, 2] for a mass-ratio $q = 10^{-4}$ planet and a signal-to-noise ratio of 20 as shown in Fig. 1. A timely anomaly trigger should ensure that most of the planet sensitivity is retained for highly magnified events with a magnification > 50. Based on this assumption, we can estimate that the observing window $\Delta t_{\rm planet}$ is approximately $\pm t_{\rm E}/4$. For a typical lensing event that coincides with the aforementioned 5 d window before its peak.

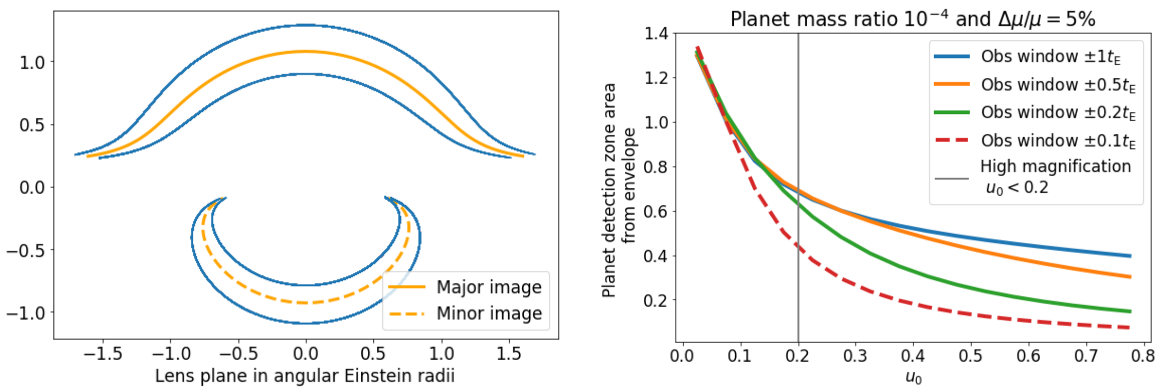

Figure 1: Left: Example of a microlensing event illustrating the planet detection zone for a host star at the origin. Right: Detection zone area for different peak magnifications and respective observing windows.

In order to determine the planet discovery rate for longer events, not only typical observing windows of 5 d but also 10 d have been examined along with the event-dependent maximum information time interval Δt as reference where Δt can be longer or shorter than 10 days from peak and affects the discovery rate depending on the range of $t_{\rm E}$. The resulting discovery rate is shown on Fig. 2 for various operational simulation experiments (OpSims) using the microlensing metric (microlensingMetric[3]). See Microlensing_Cadence_Note_Results.ipynb[4] for the production of this and additional related plots.

2 Survey Footprint

Q1: Are there any science drivers that would strongly argue for, or against, increasing the WFD footprint from 18,000 sq. deg. to 20,000 sq.deg.? Note that the resulting number of visits per pointing would drop by about 10%. If available, please mention specific simulated cadences, and specific metrics, that support your answer.

To assess the impact of the reduced number of visits we consider the discovery rate of the microlensing metric. That also addresses the discovery of outliers on the rising part of the event lightcurve in order to trigger timely follow-up as shown in Fig. 2.

The impact of the expected 10% drop of the number of visits will affect microlensing events with $t_{\rm E} \in [30, 100]$ d. In the worst case this will lead to a 3% reduced discovery rate (*rolling_fpo_6nslice0.9*) but for the footprint with the highest yield, there will be a $< 1\%$ drop (*footprint_6*). Extending the WFD to the whole Galactic Plane and Bulge would increase the discovery rate for $t_{\rm E} \in [30, 100]$ d to 90% (*footprint_gp_smooth*) compared to 60% (*baseline_nexp2*) and 10% (*footprint_big_sky_dust*). For triggering photometric follow-up observations of ongoing microlensing events, extending the WFD footprint to the whole Galactic Plane

[2] $u_0 = 0.2, t_{\rm E} = 20\,d$
[3] `https://github.com/LSST-nonproject/sims_maf_contrib/blob/master/mafContrib/microlensingMetric.py`
[4] `https://github.com/LSST-TVSSC/software_tools/blob/master/Microlensing_Cadence_Note_Results.ipynb`

would be preferred given its higher event rate. That would also apply to transients with similar timescales and detections proportional to star counts.
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 (with an implicit assumption that the main WFD survey meeting SRD requirements will always be the first priority). What is the best scientific use of this time? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

The relative frequency of each type of transient event is a function of their position on the sky. For the most general assessment one would need to normalize detection rates accordingly. In the following, we will reason based on the assumption that transients are behaving like microlensing events but we note that the same approach could be generalized to other phenomena. At zeroth order one has a higher chance of detecting events in crowded fields with a higher number of detectable stars and the star count metric [3] as well as the aforementioned microlensing metric[5]. All OpSims with a higher cadence of the Galactic Plane and the Galactic Bulge will crucially contribute to that, for example (*footprint_gp_smooth*) or (*footprint_6_v1.710yrs*).

3 Exposure time per visit

Q3: Are there any science drivers that would strongly argue for, or against, the proposal to change the u band exposure from 2x15 sec to 1x50 sec? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

Most photometric time series and microlensing in particular will benefit from near-infrared and red passbands. The reason for that being that more flux is transmitted through regions of high galactic extinction in these passbands. A change of the u band exposure would not affect the science cases considered here.

4 Allocation of observing time per band

Q4: Are there any science drivers that would strongly argue for, or against, further changes in observing time allocation per band (e.g., skewed much more towards the blue or the red side of the spectrum)? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

The authors of [6] have simulated the impact of various bands including the y-band but the quantum efficiency of the detector drops off sharply at these wavelengths, and so it would require significantly longer exposures. Since this filter offers relatively marginal gains compared with the z-band, we recommend prioritizing the g,r,i,z filters.

5 Time sampling and revisit offsets

Q5: Are there any science drivers that would strongly argue for, or against, obtained two visits in a pair in the same (or different) filter? Or the benefits or drawbacks of dedicating a portion of each night to obtaining a third (triplet) visit? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

Specific benefits of the paired filter strategy or a third visit depend on the timescale groups. The longer timescales exceeding 10 d will be much less affected in their ability to trigger follow-up observations. The coverage and capability to trigger alerts is guaranteed by the universal cadence strategy in the immutable SRD. The impact of changing the observing strategy affects the discovery rate and trigger rate for follow-up observations in the range of a few percent as shown in Fig. 2. There are some notable exceptions for shorter event timescales mostly affecting the pertinent *third_obs_pt60* and *third_obs_pt30* OpSims and leading to a drop in the discovery rate by about 20% and 30% respectively for the discovery rate comparing 5 d and 10 d triggers. The overall discovery rate for these events is already low which would indicate that a third visit is mildly disfavoured. We would highlight again that the reliability of the classification of alerts and the respective alert brokers is not within the scope of this cadence note.

[5] `https://github.com/LSST-nonproject/sims_maf_contrib/blob/master/mafContrib/microlensingMetric.py`

Q6: Are there any science drivers that would strongly argue for, or against, the rolling cadence scenario? Or for or against varying the season length? Or for or against the AltSched N/S nightly pattern of visits? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

Answering that question requires defining to what extent we prioritize detections over a better characterization. We are continuing to work on that aspect and envisage to complete that within 3 months time. As part of this, we use the OpSims to determine the density of events as a function of spatial distribution and mass to quantify how many events are providing meaningful constraints on the underlying physical parameter space, i.e. the mass function and galactic distribution of microlensing events and alerts. We can already indicate that longer timescale transients that need to be monitored throughout the year, such as black-hole microlensing events, would be strongly affected.

Q7: Are there any science drivers pushing for or against particular dithering patterns (either rotational dithers or translational dithers?) If available, please mention specific simulated cadences, and specific metrics, that support your answer.

The dithering pattern would not affect the transient detection and alert trigger in this cadence note.

6

References

[1] Horne, K., Snodgrass, C., & Tsapras, Y. 2009, MNRAS, 396, 2087 .

[2] Hundertmark, M., Street, R. A., Tsapras, Y., et al. 2018, A&A, 609, A55.

[3] Poleski, R., 2016, MNRAS, 455, 3656.

[4] Street, R.A. et al., 2018, *arXiv:1812.03137*

[5] Street, R. A., Bowman, M., Saunders, E. S., et al. 2018, *SPIE*, 10707, 1070711.

[6] Sajadian, Sedigheh and Poleski, Radosław, 2020, *The Astrophysical Journal*, 871:205, 17

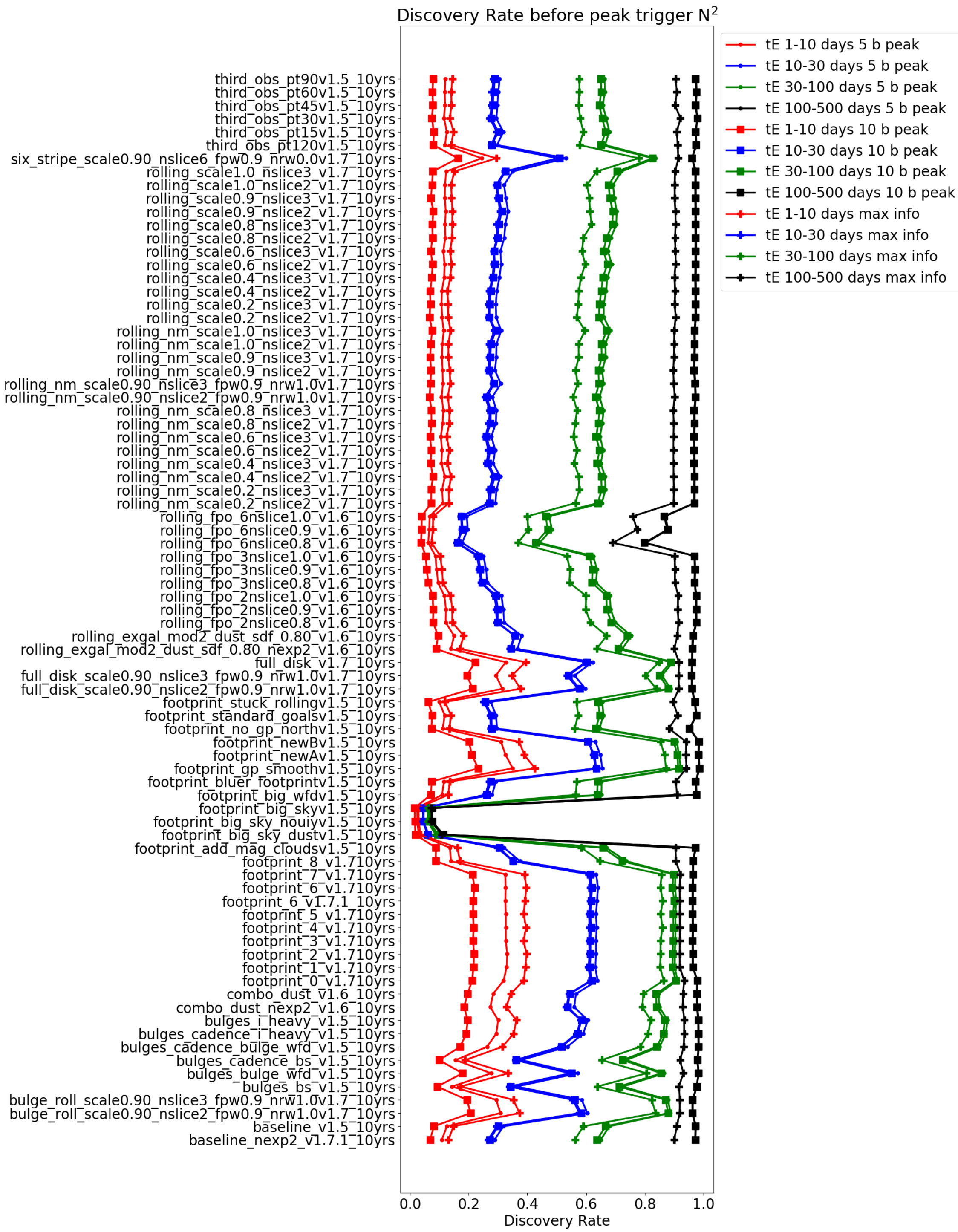

Figure 2: Discovery rate for different OpSims, microlensing event categories and observing windows. Each point was evaluated with 10,000 events with $t_{\rm E}$ drawn between the times in the legend. An event is defined to be triggered if there are two points with a 3σ difference from baseline on the rising portion of the microlensing event before a particular time. Dots refer to the discovery rate of events by 5 days before the peak; squares by 10 days before the peak; and pluses by Δt - the maximum information timescale. The discovery rate is assessed based on the assumptions outlined in the *LSST Cadence Note - Microlensing Discovery and Characterization Efficiency at Different Timescales* by Abrams et al. As expected, the earlier we require that the event must be triggered, the worse the discovery rate is.