Presto-Color: An LSST Cadence for Explosive Physics & Fast Transients

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December 1, 2018

Abstract

We propose a cadence for the LSST survey in which three visits are obtained per night: two different filters within a short time window (e.g., g & i or r & z within < 0.5 hours) and a repeat of one of those filters with a longer time window (e.g., > 1.5 hours). We colloquially refer to this as the *Presto-Color* strategy (quick-color). This observing strategy delivers both the color and lightcurve evolution of transients on the same night. This will enable us to identify and characterize fast transients – or fast features of longer timescale transients – such as rapidly-declining supernovae (SNe), kilonovae (KNe), and the signatures of SN ejecta interacting with binary companion stars or circumstellar material. Such extragalactic transients are intrinsically rare, thus LSST could dramatically improve our understanding of their origin and properties. This cadence can be implemented as a Mini-Survey or as part of a Wide-Fast-Deep survey on selected portions of the extragalactic sky.

1 White Paper Information

1. **Science Category:** Exploring the Transient Sky, Dark Energy
2. **Survey Type Category:** We are proposing this cadence as a variation of the "Wide-Fast-Deep" (WFD) Main Survey, but it could also be considered for implementation as a Mini-Survey or a Deep Drilling Field, and done in only a portion of the sky.
3. **Observing Strategy Category:** This is an observing strategy to enable specific time domain science, which is relatively agnostic to where the telescope is pointed.

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2 Scientific Motivation

The advent of wide-field time domain surveys has revolutionized the field of transient astrophysics. Coverage on *short timescales*, in particular, has facilitated rapid strides in our understanding of both supernova (SN) explosions and peculiar transients. Observations of "infant" SN—obtained hours to days after explosion—evolve quickly and provide vital constraints on their explosion mechanisms and progenitor systems. The emission at these epochs contains natal information about the progenitor characteristics [26, 27, 33], potential non-spherical behavior [20, 37], and shock collision with a binary companion [12]. In addition, rapidly-evolving transients (. 10 days) may be associated with a variety of poorly-understood events, including accretion-induced white dwarf collapse [21], underluminous and fallback SN [24], ultra-stripped SN [4, 15, 41], compact-object mergers [13, 23], orphan GRB afterglows [42], and common-envelope ejections [3].

Despite progress, the detection rate for both rapid transients and rapidly-evolving *phases* in SN explosions has remained low—due to a combination of survey efficiency and intrinsic event rates. The volume surveyed by LSST brings the promise of detecting many more intrinsically rare events. However, *using* these events to probe the science questions described herein requires adequate time- and filter-sampling of relatively short-lived events—sampling that will *not* be achieved through the WFD survey alone. Thus, we require a cadence that allows us to effectively *recognize* young and rapidly-evolving transients from within millions of LSST alerts in order to trigger additional follow-up. Such a cadence has two requirements:

1. Observations in **two filters** obtained in quick succession so that **color** can be measured. This is critical to both allow us to distinguish different classes of transients and as a probe of the physics operating during these phases.
2. A **same-filter** revisit separated by hours (before/after the filter pair) so the lightcurve **behaviour/slope** can be analyzed and distinguished from slower-evolving transients.

As we will show, the WFD baseline survey's inter-night revisit rate of once every 10-20 nights (in the same filter) is too sparse, and the intra-night revisit rate of 30 minutes is too rapid, to detect *and recognize* fast transients/phases. The exact form of our proposed cadence is given in Section 3. In order to define our diagnostics we have selected four exemplar types of extragalactic fast transients/features. Representative light curves for each type of transient are shown in Figure 1, and graphical representations of where they separate from normal SN in color and intra-night rate-of-change are shown in Figure 2. Main science cases are discussed below.

I. The Nature of Rapidly-Evolving Luminous Transients: "Rapidly-evolving transients" are defined as extragalactic events that reach SN luminosities but have timescales an order of magnitude faster. To date, only a small number have been identified, but recent systematic studies [5] have shown that they are not *intrinsically* rare—few have been detected simply because surveys were not designed to be efficient at short timescales. They represent a significant channel (5–10% of the core-collapse rate) which we must understand to have a complete picture of stellar death. Known events have rise times spanning 1–3 days and blue colors at maximum [5, 32, 35]. While their true nature is unknown, leading theoretical models range from black hole formation in failed SN to the birth of binary neutron star systems, with recent observations of AT2018cow show evidence for a central engine [14, 19, 31].

II. Kilonovae and the Origin of Heavy Elements: Kilonova (KN) are produced by the radioactive decay of r-process nuclei synthesized in the ejecta of neutron star mergers [18]. Observations of the KN associated with GW170817 revealed thermal emission that rose in $<$1 day and cooled from a temperature of $>$10,000K to 3,000K over 5 days [6]. The initially blue optical light faded at a rate of $>$1 mag/day, and was followed by a longer-lived red transient—consistent with the production of a significant quantity of of r-process elements of *multiple* compositions [6, 16, 38, 40, 43]. Additional examples—with or without associated LIGO triggers—are required to ascertain the "typicalness" of GW170817, with the frequency of early blue emission providing critical constraints on the ratio of light and heavy elements formed, and the total contribution of NS mergers to cosmic nucleosynthesis [22, 28, 36].

III. Progenitors and Pre-explosion Mass Loss of Core-Collapse SN: Early observations of core-collapse SN (CCSN) provide critical constraints on the progenitor radius and envelope structure through the detection of either shock breakout (1 day) or cooling envelope (1-5 day) emission [1, 2, 26]. Indeed, there has been growing evidence that many CCSN either explode in "non-standard" evolutionary states or undergo enhanced pre-SN mass-loss and outbursts in their terminal years [17, 25]. Theoretical studies have pointed to a range of potential explanations to accommodate the observations, such as pulsation-driven superwinds [44], wave heating outbursts [7], and inflated progenitor envelope [8]. However, the nature of this mass loss and the types of SN experiencing it remain uncertain.

IV. Progenitors and Explosion Mechanisms of Thermonuclear SN: Type Ia SN result from the thermonuclear disruption of a CO white dwarf [10]. However, questions remain regarding the nature of their binary companions. Recently, observations of SN2017cbv obtained within 1 day of explosion revealed a rapidly-rising blue "bump", interpreted by some as a collision with a non-degenerate companion [11]. At the same time preliminary population studies reveal an as-yet-unexplained red/blue color dichotomy in the early (<5 days) rapidly-rising light curves of Type Ia SN [39], with implications for outwardly mixed radioactive material predicted by the double detonation explosion model [29, 30]. Further observations are required to ascertain the nature of this early emission, with implications from stellar physics to cosmology.

V. Additional Science Cases: While we have focused on extragalactic fast transients here, a cadence that allows measurement of both color and rate-of-change on the timescale of hours will have general applicability across many areas—from variable stars and microlensing to characterization of solar system objects.

Finally, though we describe here an adaptation to the general WFD cadence to facilitate the timely identification of rapid events, our cadence could alternatively be adopted as a mini-survey over a portion of the sky. If coupled with a shorter intra-night cadence (as part of a mini-survey or within a rolling cadence) LSST observations alone could provide sufficient light curve coverage to probe progenitors and explosion physics of fast transients/features.

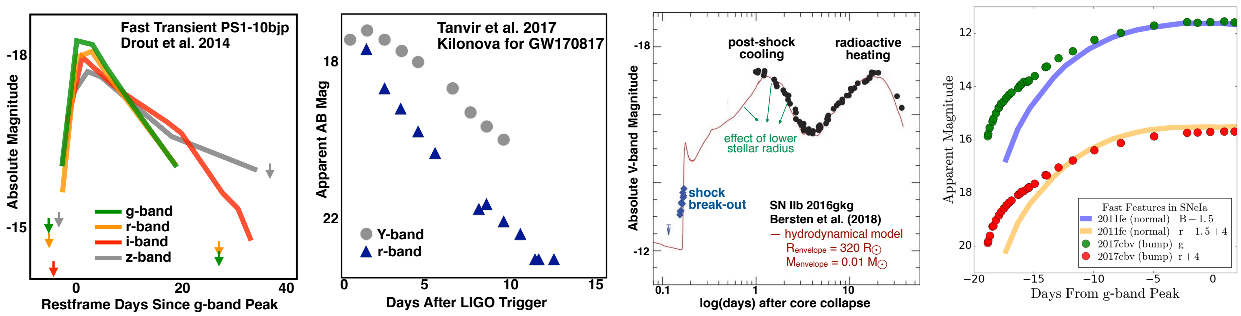

Figure 1: Light curves for our examples of fast transients and fast features. From left to right: fast transient PS1-10bjp [5]; kilonova for GW170817 [40]; the shock breakout model ts for SN IIb 2016gkg's stellar radius [2]; and SN Ia 2017cbv's blue bump compared to SN Ia 2011fe's \normal" lightcurve [9, 11].

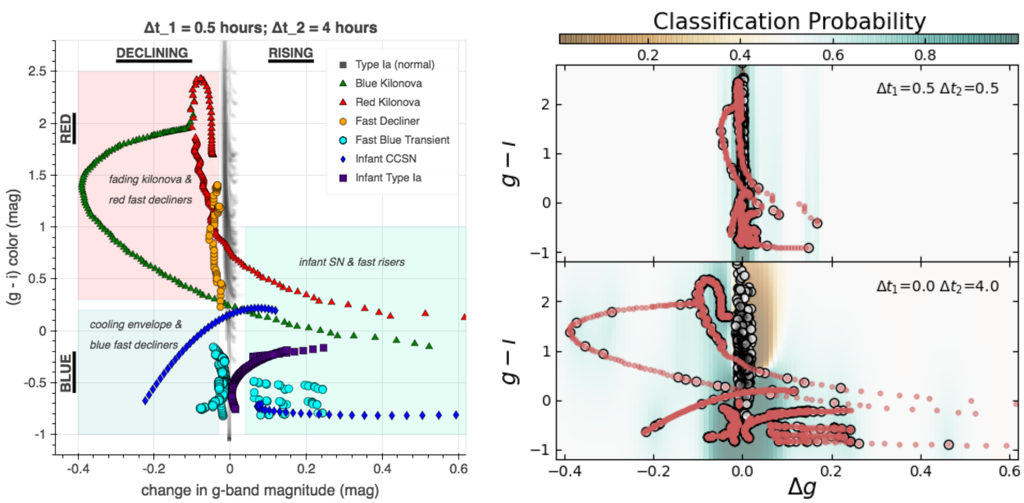

Figure 2: *Left:* Phase space plot showing separation between classes of transients in observed color and intra-night magnitude change. This *fiducial* plot assumes observations are obtained in $g-$ and $i-$band lters within 30 minutes (T_1) and a second $g-$band observation is obtained 4 hours (T_2) later at a range of epochs in each transient's evolution. Rising light curves correspond to positive magnitude changes. Observations of our four exemplar types of fast transients/phases are plotted in color. For kilonovae, we include models of GW170817 both with and without the early blue component. \Infant" SN correspond to observations within the rst 5 days post-explosion. The infant core-collapse SN found in the declining portion of the plot is the rapidly-fading component of the cooling envelope emission observed in SN2016gkg (see Fig 1). We also show a population of normal Type Ia SN between -7 and +20 days of maximum light | at a range of redshifts | representing slower evolving transients from which we wish to *distinguish* our transients of interest. *Right:* A classi er can be trained to recognize fast transients in the color/magnitude change phase space. Here a Gaussian Processes Probabilistic Classi er [34] (with RBF kernel) is trained to disambiguate fast transients from SN Ia in $g+i$ observations at T_1, T_2=0.5,0.5h (*top*), and T_1, T_2=0,4h (*bottom*). The data is the same as in the right panel, red dots are all transients of interest, black are SN Ia, white circles are part of the training set. In both cases we obtain high (&95%) accuracy in cross-validation. However, disambiguation is obviously harder for smaller T_2, and only for small T_1 we can obtain true color information for fast evolving transients.

3 Technical Description

3.1 High-level description

The prompt characterization of fast transients, and fast features of transients, enables the triggering of crucial follow up observations. Prompt characterization requires the determination of *both color and lightcurve shape*, which in turn requires observations in two different filters, f_1 and f_2, within a short interval of time ΔT_1, and then to return to the same field with either of those filters at a later time ΔT_2. The constraints to evaluate whether an `OpSim` run meets these requirements are:

1. $\max(\Delta T_1)$, an upper limit on the time between the two visits that provide color
2. $\min(\Delta T_2)$, a lower limit on the time between the two visits that provide shape
3. the filter pair f_1 and f_2

This observing strategy, referred to as *Presto-Color* and illustrated in Figure 3, can be implemented simply by alternating pairs of visits on a field and single visits on *the previous field*. The single visits can alternate between the two filters, reducing the number of filter changes.

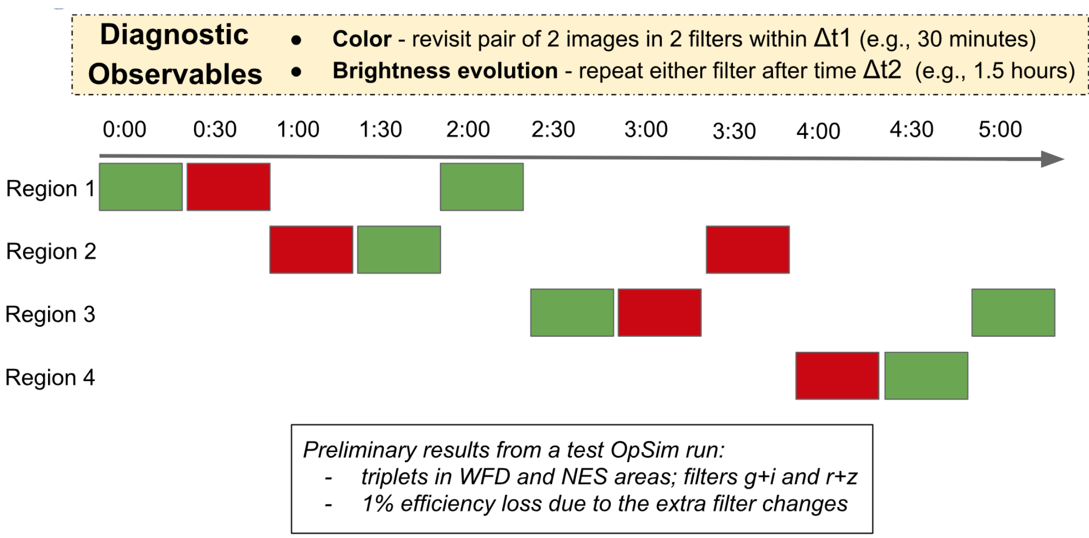

Figure 3: An example *Presto-Color* cadence with two alternating filters cover regions of sky to obtain three observations per region with appropriate time gaps to measure lightcurve color and shape.

3.2 Footprint – pointings, regions and/or constraints

This proposed cadence does not make any additional constraints on the imaging area compared to WFD. The science goals might be reachable if the proposed cadence was implemented over a sub-region of the WFD survey area. As the change of filters in the first pair of observations may limit the detectability of Solar System objects (to the magnitude depth of the shallower filter) this survey strategy could be implemented only in a subset of filters on the extended ecliptic plane (the region of interest for Solar System detections).

3.3 Image quality

This proposed cadence does not make any additional constraints on the image quality compared to WFD.

3.4 Individual image depth and/or sky brightness

This proposed cadence does not make any additional constraints on the individual image depth or sky brightness compared to WFD.

3.5 Co-added image depth and/or total number of visits

This proposed cadence does not make any additional constraints on the co-added image depth or total number of visits compared to WFD.

3.6 Number of visits within a night

The proposed cadence requires at least 3 visits per night.

3.7 Distribution of visits over time

We require three total observations in a night in 2 total filters. The 2 observations in different filters are separated by ΔT_1 minutes, and will be used to assess the color of the transient. As the physical processes operating depend on the *intrinsic* color of the—potentially rapidly-evolving—transients, smaller values of ΔT_1 on the order of 30 minutes are preferred. However, ΔT_1 values up to a few hours, while no longer sensitive to the true color of the transient at a given moment, still provide diagnostic power of whether a given transient is red or blue, and will therefore allow us to achieve some of our science goals.

In addition, a second observation should be obtained in *either* one of the two filter separated in time by ΔT_2 minutes. This observation can be obtained either *before or after* the filter pair, and will be used to measure the light curve slope. Longer intra-night separations on the order of 4 5 hours are preferred, as our transients of interest distinguish themselves from longer-lived supernova at higher signal-to-noise over these timescales (Fig 2). Shorter ΔT_2 separations of 1.5 hours will still allow us to achieve some of our science goals, as very young supernovae and rapidly-rising transients evolve at >0.1 mag/hour. However, on these shorter timescales most currently known rapidly-declining transients will evolve by only 0.02 0.03 mag, hindering their identification (Figure 2). We note that a non-detection in the isolated observation or the detection above the saturation limit would still provide constraints on the lightcurve evolution. However, a non-detection would provide some limited constraints on color.

Finally, we note that the science goals which motivate *Presto-Color* – namely, well-characterized light curves for rapid events – have overlap with the science motivations of a rolling cadence. This proposed cadence would benefit from being implemented in regions where rolling cadence is applied (i.e., an intra-night gap $<$ 3 days).

3.8 Filter choice

Filters should be pair. For the fast transients under consideration the preferred filter pairs are g i or r z as non-adjacent pairs provide a larger lever arm for distinguishing a given transient as red or blue. In particular, many infant supernova rapidly-rising transients can be very blue at early times, favoring the inclusion of the g (or r) band. However, we emphasize that some of our science can be be achieved with any filter pair.

3.9 Exposure constraints

This proposed cadence uses the baseline exposure times of 2 15 seconds or 1 30 seconds. 2 15 seconds is a preferred snap strategy, since in case of saturation of these *rapidly evolving transients* constraints a reliable magnitude measurement could be obtained from the individual snaps.

3.10 Other constraints

We propose that *Presto-Color* be implemented on extragalactic fields, but note that it may also be useful in some Galactic Plane fields to detect and characterize microlensing events on short timescales, binary stars, and black holes, for example. Trade-offs and synergies with other proposals are discussed further in Section 3.12, Item 5.

3.11 Estimated time requirement

Since our proposed cadence is a modification of the WFD strategy – a shuffling of the visits, not adding visits – we are not requesting that any additional time be added to the WFD component. However, as mentioned in Section 1, *Presto-Color* could be implemented as a mini-survey instead of as part of WFD. For example, if the majority of g-band visits in the WFD survey are uniformly distributed in time, with paired visits in i-band within a time of ΔT_1, then a mini-survey which adds g- or i-band visits within time ΔT_2 could be implemented to meet our science goals. This option would be within the 1% time requirement for mini-surveys if, for example, it is restricted to areas of 1800 sq. degrees for 10 years, or covers the full 18000 sq degrees for a single year.

Properties	Importance
Image quality	3
Sky brightness	3
Individual image depth	3
Co-added image depth	3
Number of exposures in a visit	3
Number of visits (in a night)	1
Total number of visits	3
Time between visits (in a night)	1
Time between visits (between nights)	2
Long-term gaps between visits	3
Other *filter pairs within night*	1

Table 1: **Constraint Rankings:** *Presto-Color* has strict requirements on the filter selection, number of visits per night, and the intra-night revisit time gaps. The science case would benefit from a shorter inter-night gap, because additional observations at a day time scale (in the nights following detection) would help to both refine the follow-up strategy, and collect survey data that could be used in photometric sample studies based on the LSST data alone. Since the transients of interest are predominantly blue, this proposal would prioritize visits in the g-band filter.

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3.12 Technical trades

1. *What is the effect of a trade-off between your requested survey footprint (area) and requested co-added depth or number of visits?*
   As with a rolling cadence, the area in which this *Presto-Color* strategy is applied will lower the visit cadence in other areas, but need not affect the total number of visits per field or the final co-added depths of the WFD survey.

2. *If not requesting a specific timing of visits, what is the effect of a trade-off between the uniformity of observations and the frequency of observations in time? e.g. a 'rolling cadence' increases the frequency of visits during a short time period at the cost of fewer visits the rest of the time, making the overall sampling less uniform.*
   As with a rolling cadence, during the time when a field is not within the area being covered by the *Presto-Color* strategy, it will receive fewer visits.

3. *What is the effect of a trade-off on the exposure time and number of visits (e.g. increasing the individual image depth but decreasing the overall number of visits)?*
   Discovering and characterizing fast transients and fast features does not benefit from increasing in exposure time at the expense of the number of visits. Increasing the number of visits at the expense of exposure time might benefit our program a bit, but

much shorter exposures could increase the uncertainty of slopes and colors measured from two visits.

4. *What is the effect of a trade-off between uniformity in number of visits and co-added depth? Is there any benefit to real-time exposure time optimization to obtain nearly constant single-visit limiting depth?*
   The science goals that motivate the *Presto-Color* strategy do not benefit from increased co-added depth or maintaining a constant single-visit limiting depth.

5. *Are there any other potential trade-offs to consider when attempting to balance this proposal with others which may have similar but slightly different requests?*

   There are a few other cadence proposals similar to the *Presto-Color* strategy. We discuss similarities and trade-offs for each in turn:

   (1) Street et al. "The Diverse Science Return from a Wide-Area Survey of the Galactic Plane", which proposes the "paired-i" strategy: fields in the Galactic plane are imaged every 2-3 days, first in i-band and then 1-4 hours later a revisit in g, r, or z. The basic motivation is the same – to identify rapidly varying transients and characterize them via colors – just for Galactic variables like Young Stellar Objects and Cataclysmic Variables. However, since we propose the *Presto-Color* strategy for the extragalactic WFD there is no tension between these two white papers.

   (2) Bricman et al. "TDEs with LSST", proposes to get same-night color information. The version that we read requested to change the filter between the two 15-second exposures of a visit, which isn't possible, but we surmised that what they actually want is for two visits in a night in two different filters. If so, then this *Presto-Color* proposal would also suite their needs.

   (3) Gezari et al. "An Extreme Rolling Cadence Wide-Fast-Deep Survey", proposes to do the full WFD area in only years 1 and 10, and rotate through 8 equal strips of area in years 2 through 9. While this would often result in 2-3 visits per night, probably in multiple filters, no specific filter pairings or revisit timescales are requested. The trade-off between these proposals is that such an extreme rolling cadence would remove the opportunity for longer-term monitoring of transients with fast features, such as Type IIn SNe, which can last for years.

4 Performance Evaluation

4.1 Diagnostic Metrics

Based on our evaluation of the light curves of fast transients, and the fast features of longer duration transients, we designed 2 diagnostic metrics and submitted them to the *sims_maf_contrib* repository.

1. **threeVisitsWColorMetric**: a *diagnostic* metric that checks if a field was observed 3 times in a night with 2 filters, given input constraints on ΔT_1 (an upper limit) and ΔT_2 (a lower limit). The specific filter pair of f_1 and f_2 is also an input to the metric. This metric was run on year 1 of `baseline2018a` and year 1 of our test `OpSim` run `pontus_2591`. Results are shown and discussed in Figure 4.
2. **FastTransientMetric**: a *diagnostic* metric based on the `Transient Metric` that injects continuous saw-tooth shaped transients with a rising slope (input parameter) and a vertical decline, with input peak brightness which can be input independently for each filter (thus enabling the injection of different color transients). The metric calculates the fraction of transients with three detections that are consistent with an input ΔT_1 (upper limit) and ΔT_2 (lower limit) and a specific filter-pair.

4.2 Figure of Merit Metric

Our Figure of Merit (FoM) metric is the fraction of events for which the color and rise-time are constrained (within some accuracy). Different science cases will have different input lightcurves and different gap constraints. We plan on injecting samples of the transients of interest, as well as "normal" transients, by leveraging the Monte Carlo MAF framework and the `transientLC` metric, recovering the lightcurve (`PassMetric`) and measuring color and slope, which will be evaluated in the context of machine learning partitioning of the Color-Slope phase space (Figure 2) to isolate transients for follow-up. Further analysis will assess our ability to distinguish between fast transients with the LSST data alone.

4.3 Create OpSim

`OpSim` runs using the new feature based scheduler are being created. The *Presto-Color* survey strategy is accomplished with a combination of the *Greedy Algorithm* (GA Survey), *Pairs in different filters* (PDF Survey) and *Pairs in the same filters* (PSF Survey) Surveys. To combine observations in filters f_1 and f_2, the Surveys are configured such that when the *GA Survey* in f_1 or f_2 gets an observation, the *PDF Survey* schedules an observation of the same field with the other filter 30 5 min later, and the *PSF Survey* scheduler an observation of the same field with the same filter 60 5 min later. A test simulation combining gi and rz was produced to evaluate the impact in performance and test the metrics. Non-adjacent filters are used to get a better leverage on the Spectral Energy Distribution (SED) color. Overall we noticed that this kind of strategy has a similar throughput (in efficiency and total number of observations) as a strategy to take pairs of observations in different filters.

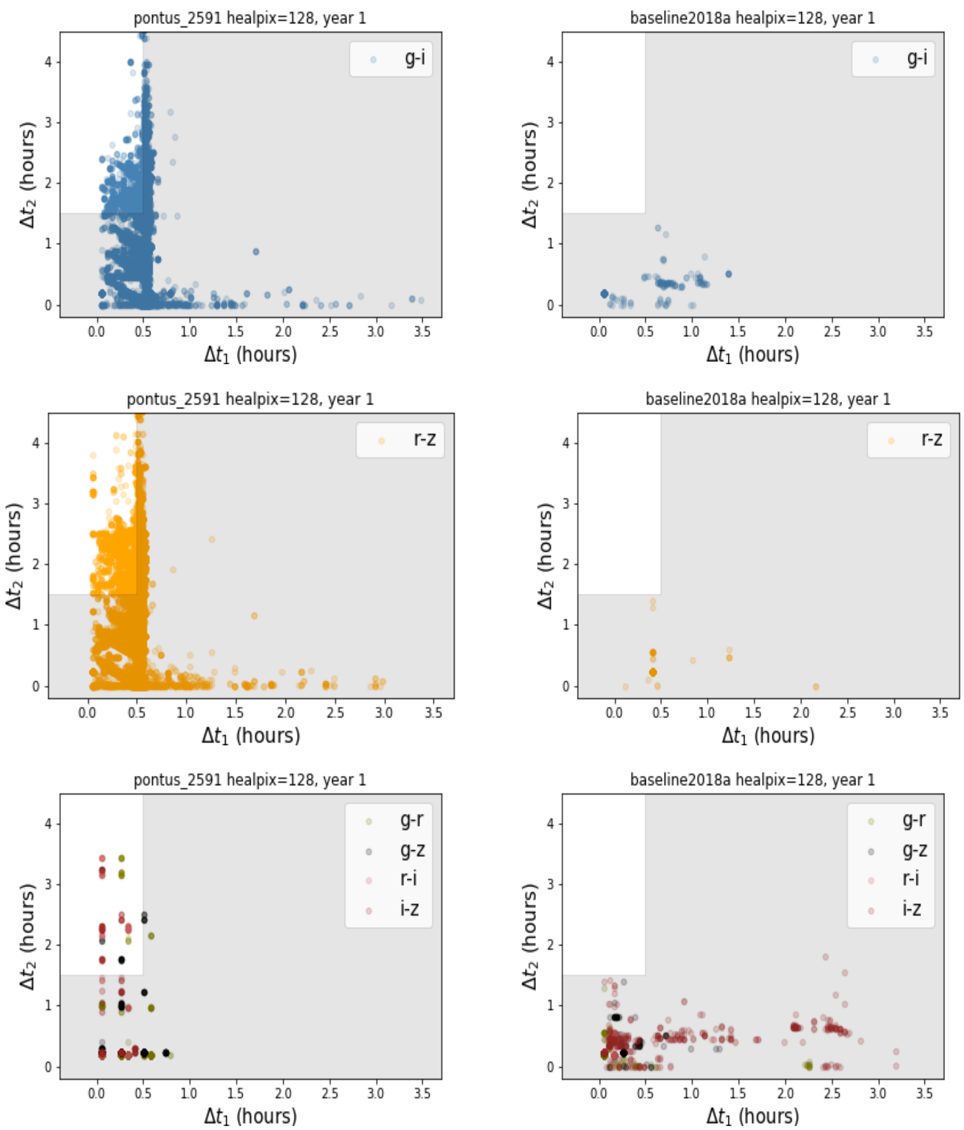

Figure 4: The results of our *diagnostic* metric, `threeVisitsWColorMetric`, that checks for fields that were observed 3 times in a night with 2 filters (as labeled) satisfying the constraints on ΔT_1 and ΔT_2. We show results for 1-year of `pontus_2591` (our *Presto-Color* test run; left), and `baseline2018a` LSST observations (right). All `HEALpix` "fields" that met the conditions of our metric are shown as points, colored by the filter pair f_1-f_2. The x axis is the time between visits in the two different filters (which provide color; ΔT_1), and the y axis is the time between visits in the same filter (which provides slope; ΔT_2). The target area for our science is the white region, where $\Delta T_1 < 0.5$ and $\Delta T_2 > 1.5$ hours, such that both color and brightness evolution can be measured, although there is no hard cutoff at 30 minutes in ΔT_1, so observations just to the left of our target region are valuable, and observations at a larger ΔT_2 within the same night are preferred. In `pontus_2591` 20 thousand observations in year 1 satisfy our constraints strictly ($\Delta T_1 < 0.5$ and $\Delta T_2 > 1.5$) in g i and over 40 thousand in r z. Very few `HEALpix` fields in the `baseline2018a` `OpSim` have observations in triplets in 2 filters and none that satisfy our constraints.

5 Special Data Processing

The science goals that motivate the proposed *Presto-Color* cadence will not require any special data processing; the planned Prompt and Data Release pipelines and their data products will be sufficient for our science goals.

6 Acknowledgments

This work was developed within the Transients and Variable Stars Science Collaboration (TVS) and the author acknowledges the support of TVS in the preparation of this paper. The authors acknowledge support by the Flatiron Institute and Heising-Simons Foundation for the development of this paper.

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