Optimizing Uniquely-*Roman* Science in the HLTDS

June 16, 2023

Roman Core Community Survey: High Latitude Time Domain Survey
Scientific Categories: stellar physics and stellar types; stellar populations and the interstellar medium; supermassive black holes and active galaxies; large scale structure of the universe

Submitting Author:
Name: Phillip Macias
Affiliation: UC Santa Cruz
Email: pmacias@ucsc.edu
List of Contributing Authors:
Ryan Foley(UC Santa Cruz, foley@ucsc.edu), Charles Kilpatrick (Northwestern University, ckilpatrick@northwestern.edu), Benjamin Rose (Baylor University, Ben_Rose@baylor.edu), Kaisey Mandel (University of Cambridge, kmandel@ast.cam.ac.uk), Armin Rest (STScI, arest@stsci.edu), V. Ashley Villar (PSU, vav5084@psu.edu)

Abstract: The *Roman* HLTDS will deliver an unprecedented view of the expansion history of the Universe, allowing for a generation-defining measurement of dark energy as well as placing strong constraints on its evolution. Rose et al. [1] present one survey configuration that is able to meet the Dark Energy Task Force Figure of Merit (DETF FoM) requirement of 325 [2] and demonstrate that its gradient in key survey parameters (e.g., cadence, area, tiers) is relatively shallow, allowing for a range of choices that will meet the DETF FoM requirements, but can be adjusted to address other open questions in transient astrophysics only accessible by *Roman*. We advocate for a holistic approach to optimizing multiple transient science cases simultaneously. Since several transient classes have similar observables and rates, we suggest (initally) simplifying the parameter space by looking at representative science cases. For this purpose, we highlight supernovae at the epoch of reionization (slow-evolving, rare), kilonovae (fast-evolving, rare), and $z > 2$ supernova rates (typical evolution, common) . We present steps toward a systematic exploration of this phase space and quantify the effects of allowable trades on non-SN Ia yields and their respective FoMs.

1 Transient Astrophysics Opportunities with the High-Latitude Time-Domain Survey

Current and next-generation ground-based transient surveys have dramatically improved our knowledge of transients, their underlying progenitor systems, and how they interact with their environments. As a result, several new and unexpected questions have emerged that can only be solved with a large-area, NIR, space-based transient survey like the *Roman* High-Latitude Time-Domain Survey (HLTDS).

Simulations of reference surveys for the HLTDS indicate that it will discover $>10^4$ astrophysical transients *other* than Type Ia supernovae (SNe Ia) to $z \gg 3$, increasing the number of transients discovered at $z > 2$ by orders of magnitude and showing the exceptional promise of the HLTDS to make major discoveries in time-domain astrophysics. In this white paper, we emphasize that a holistic approach to transient science is necessary; not all science cases are equal, some science questions can be achieved through different observations, and some topics have distinct thresholds for success while others are a continuum. While a holistic analysis can be complicated, we note that several transient classes have similar properties, allowing for a simplified approach that focuses on representative transient classes.

We highlight a handful of questions that span various classes of transients that have significantly different observational properties and rates, propose metrics for making significant progress toward answering these questions, and demonstrate how these metrics are impacted by survey choices:

1. **Science Case:** Measuring rates of various transient classes at $1 < z < 3$ provides exceptional information about their progenitor systems. The SN Ia rate as a function of redshift is highly dependent on their delay-time distribution, which can be used to differentiate between single- and double-degenerate systems. The highest redshifts, corresponding to the shortest delay times, have the most constraining power. Similarly, the core-collapse rate at $z \gtrsim 2$ directly probes the convolution of the cosmic star-formation history with the initial-mass function. Any divergence between the SN rate and star-formation rate before cosmic noon will indicate an evolving IMF that may be a result of, e.g., changing metallicity. Additionally, the rates of rarer classes have far reaching implications. For instance, the rate of TDEs with redshift will probe the growth and merger of super-massive black holes. **Proposed Metric:** To properly track the evolution of transient rates over cosmic time, we must measure the rate to high precision in multiple redshift bins. We will focus on the SN II rate at $z > 2$ (before cosmic noon) as a proxy for all other rates. While one could design a more sophisticated metric looking at specific models, the sum of the square root of the number of well-observed SNe II with $2 < z < 2.5$ and $2.5 < z < 3$ closely matches the precision on the slope of the SN rate at $z > 2$.
2. **Science Case:** The discovery of a transient, a kilonova (KN), associated

with a gravitational wave source, confirmed that neutron star mergers can produce a significant amount of r-process material [3]. To determine if neutron-star mergers are the *primary* r-process site, we must both determine the range of r-process masses produced in KNe and their rate over cosmic time. Until next-generation gravitational wave detectors (e.g., Cosmic Explorer) are built, sensitive NIR surveys are the *only* way to detect KNe at $z > 0.1$, where we can begin to estimate their rate with cosmic time.
Proposed Metric: *Roman* is uniquely positioned to detect KNe at $z > 0.1$ until next-generation gravitational wave detectors come online. However, discovery is not enough to determine the r-process production. Instead, our metric is the number of KNe at $z > 0.1$ where we can measure the mass of r-process material. To make this measurement, an event must have a well measured peak luminosity, a well-measured decline rate, and well measured colors for at least one week after peak (to separate multiple components). We estimate that a detection within 1 day of peak, a second observation within 3 days of peak, and detections in $\geq$2 bands at $\geq$ 3 days after peak is sufficient for this measurement.

3. **Science Case:** The Universe was reionized at $7 < z < 8$ [4], but the details of the process are still unclear. One key question is the contribution of different ionizing sources: galaxies, quasars, *and* supernovae. Although the SN II rate and luminosity are not high enough to contribute significantly to reionization, super-luminous SNe (SLSNe), SNe that have peak luminosities $>$100× that of typical SNe II and integrated luminosities of $>10^{52}$ erg could be a substantial contributor, at least locally, if their rate is sufficiently high. *Roman* has the ability to detect SLSNe to $z \approx 12$, and thus fully cover the epoch of reionization. Moreover, there is a chance that SLSNe, which are more luminous than galaxies at $z = 10$, could be the highest-redshift objects detected [5].
   Proposed Metric: To test the SLSN contribution to the reionization of the Universe, we need to detect the SNe at $z > 6.5$. A measurement of its ionizing flux requires a measurement of 3 epochs before and 3 epochs after peak luminosity in at least two bands to determine the light-curve shape and a spectral slope.

These science vignettes focus on large numbers of relatively common transients (#1; constraining rates); rare, fast, red transients (#2; KNe); and rare, long-lived transients (#3; SLSNe). Although these science cases are not exhaustive, they illustrate potentially competing trades within the HLTDS (e.g., area for cadence) and potential to supplement the HLTDS (e.g., long-term monitoring of the HLTDS fields outside of the survey duration).

2 Methods and Metric Performance

For a fixed-time survey, trades between cadence, area, depth, and filter (the primary choices for survey design) will always result in roughly the same total signal. Because of this, the DE FoM is relatively insensitive to these survey

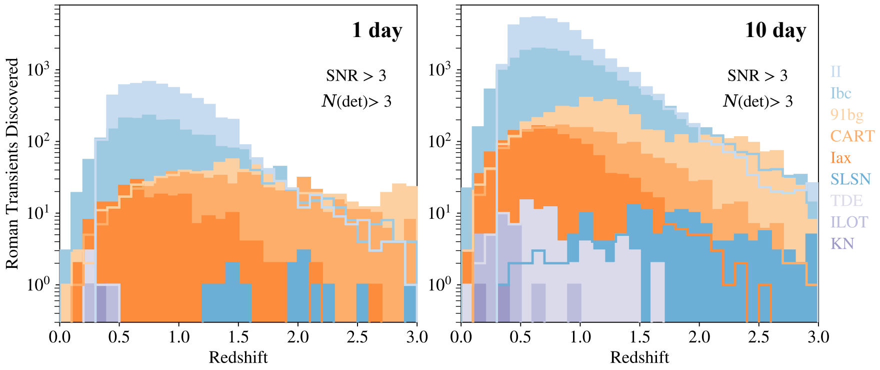

Figure 1: Left: Redshift distribution for non-SN Ia transients expected to be discovered in the reference HLTDS, but for 1 day and 10 day cadences as trades for area. The reference survey was constructed to not simulate any transients with $z > 3$, since this is the SN Ia redshift limit, however, we expect to discover several transients, and especially SLSNe at high z (see Figure 3, Left).

parameters, especially for trades that do not alter the filters used. As we have shown that a nominal 2-year HLTDS survey composed of 6 months of observing time will satisfy mission requirements [1], we are able to more freely study trades that can benefit other science cases.

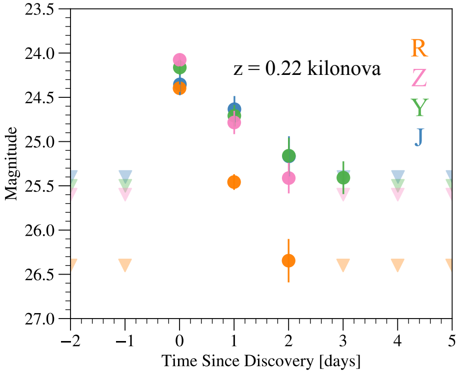

Figure 2: One of the two detected KNe for our 1 day survey. The quality of the *Roman* multiband light curve alone would be sufficient to characterize key physical quantities, however the expected number of events is small.

We have augmented the reference survey simulations presented in [1] to include non-SNe Ia in order to quantify yields of other transients, utilizing the rates presented in the PLASTICC [6] challenge. We include SNe Types II, Ibc, Iax, Ca-rich SNe, 91bg-like SNe, SLSNe, intermediate-luminosity optical transients (ILOTs), tidal-disruption events (TDEs), and KNe. While this list is far from exhaustive, it spans a representative range of expected luminosities, durations, and redshift-distributions.

We have also simulated five possible configurations of the HLTDS: a 1, 3, 5, 10, and 20 day cadence, plus a 5 day cadence book-ended with monthly GO observations of the deep field to extend the baseline. Table 1 shows our detected yields for the various configurations. For our SLSN investigation (Figure 3, Left) we simulate (only) SLSN to $z = 10$.

As seen in Table 1, for $\sim$ days long transients such as KNe, increasing area

Cadence	II	Ibc	91bg	CART	Iax	SLSNe	TDE	ILOT	KNe
1 day	5499	2203	733	575	209	14	5	2	2
3 day	15904	6425	1758	965	487	56	35	15	2
5 day	22879	9366	2446	1199	734	66	34	16	3
10 day	38766	18747	4541	1959	1350	143	88	29	3
20 day	55336	31550	6998	2793	2115	311	124	48	0

Table 1: **Transient yields trading cadence for area** within the reference survey parameters for cadences of 1, 3, 5, 10, and 20 days. Numbers of long-duration transients detected scale with area and therefore linearly with cadence, whereas shorter timescale transients may be undetectable for longer cadences. Note that these numbers only show detected, not classified, transients.

does not allow for a proportional increase in discovery due to the longer cadence lowering the odds of observing near peak. Figure 2 shows a *Roman* light curve of one of two discovered KNe in our 1 day cadence survey. While this cadence is marginally sufficient to characterize e.g. ejecta masses, a cadence of 5 days is likely too sparse for typical r-process masses and compositions, and the expected number of events is low.

Cadence	$\sqrt{N_{\mathrm{II},z=2-2.5}} + \sqrt{N_{\mathrm{II},z=2.5-3}}$	$N_{\mathrm{KNe}}(z > 0.1)$	$N_{\mathrm{SLSNe}}(z > 6.5)$	DETF FoM
1 day	12.1	2	0	251.9
3 day	19.0	2	0	523.8
5 day	22.4	0	1	662.3
10 day	29.4	0	2	642.0
20 day	36.3	0	6	———

Table 2: **Metrics for science cases and transients:** The absolute values are rate and model dependent, but we can examine their gradients along the cadence-area trade axis. The DETF FoM shown is statistical only and will be lower when full systematic uncertainties are applied. We have not calculated the DETF FoM for the 20 day cadence, but this is underway.

Table 2 lists our calculated metrics, along with the DETF FoM for the nominal 5 day survey and its variants. The DETF FoMs are statistical only and will be lower with a proper accounting of systematic uncertainties, but are listed for completeness. Figure 3 (Right) shows the metric performance, normalized to their maxima, for our various science cases as a function of cadence. The general trends are intuitive if not obvious: rare, fast transients are better caught with faster cadence, while rare + slow-evolving, as well as common transients, are better captured with larger area and less sensitive to cadence. One possible solution which we plan to explore is that of a dual-cadence between the wide and deep tier (e.g. 4 and 8 days, respectively) to accommodate the wide range of transient timescales expected.

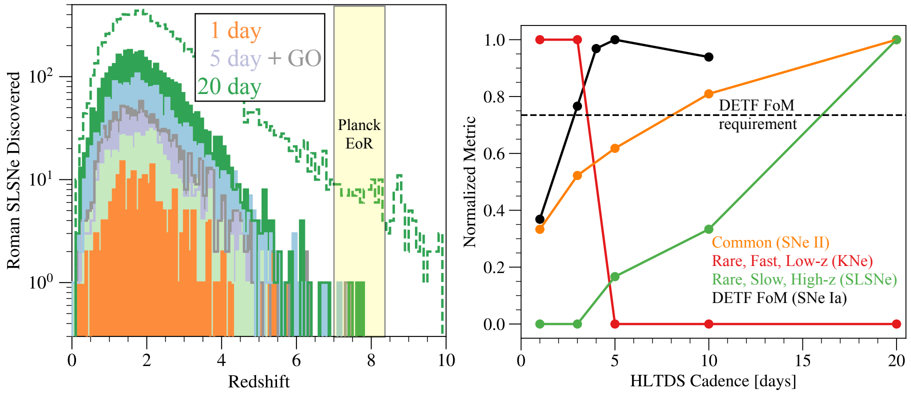

Figure 3: Left: Redshift distributions for detected SLSNe (shown in the solid histograms) simulated out to $z = 10$ for our five survey configurations. The input-distribution for the 20 day cadence is shown in the unfilled green histogram, and CMB constraints on the epoch of reionization are shown in yellow. Right: Metric performance (relative to maxima) for our survey variants. It appears difficult to accommodate all of the expected transients within a single cadence, possibly hinting toward a dual-cadence solution between the two tiers.

We note that the landscape for optimization is complex, but emphasize that these cases should be considered in tandem and in a self-consistent manner to begin to map out, understand, and exploit commonalities between transient types and ultimately maximize the broad transient science capable with the HLTDS.

References

[1] B. M. Rose, C. Baltay, R. Hounsell, P. Macias, D. Rubin, D. Scolnic, G. Aldering, R. Bohlin, M. Dai, S. E. Deustua, R. J. Foley, A. Fruchter, L. Galbany, S. W. Jha, D. O. Jones, B. A. Joshi, P. L. Kelly, R. Kessler, R. P. Kirshner, K. S. Mandel, S. Perlmutter, J. Pierel, H. Qu, D. Rabinowitz, A. Rest, A. G. Riess, S. Rodney, M. Sako, M. R. Siebert, L. Strolger, N. Suzuki, S. Thorp, S. D. Van Dyk, K. Wang, S. M. Ward, and W. M. Wood-Vasey. A Reference Survey for Supernova Cosmology with the Nancy Grace Roman Space Telescope. *arXiv e-prints*, page arXiv:2111.03081, November 2021.

[2] D. Spergel, N. Gehrels, C. Baltay, D. Bennett, J. Breckinridge, M. Donahue, A. Dressler, B. S. Gaudi, T. Greene, O. Guyon, C. Hirata, J. Kalirai, N. J. Kasdin, B. Macintosh, W. Moos, S. Perlmutter, M. Postman, B. Rauscher, J. Rhodes, Y. Wang, D. Weinberg, D. Benford, M. Hudson, W. S. Jeong, Y. Mellier, W. Traub, T. Yamada, P. Capak, J. Colbert, D. Masters, M. Penny, D. Savransky, D. Stern, N. Zimmerman, R. Barry,

L. Bartusek, K. Carpenter, E. Cheng, D. Content, F. Dekens, R. Demers, K. Grady, C. Jackson, G. Kuan, J. Kruk, M. Melton, B. Nemati, B. Parvin, I. Poberezhskiy, C. Peddie, J. Ruffa, J. K. Wallace, A. Whipple, E. Wollack, and F. Zhao. Wide-Field InfrarRed Survey Telescope-Astrophysics Focused Telescope Assets WFIRST-AFTA 2015 Report. *arXiv e-prints*, page arXiv:1503.03757, March 2015.

[3] D. A. Coulter, R. J. Foley, C. D. Kilpatrick, M. R. Drout, A. L. Piro, B. J. Shappee, M. R. Siebert, J. D. Simon, N. Ulloa, D. Kasen, B. F. Madore, A. Murguia-Berthier, Y. C. Pan, J. X. Prochaska, E. Ramirez-Ruiz, A. Rest, and C. Rojas-Bravo. Swope Supernova Survey 2017a (SSS17a), the optical counterpart to a gravitational wave source. *Science*, 358(6370):1556–1558, December 2017.

[4] Brant E. Robertson. Galaxy Formation and Reionization: Key Unknowns and Expected Breakthroughs by the James Webb Space Telescope. , 60:121–158, August 2022.

[5] Masaomi Tanaka, Takashi J. Moriya, and Naoki Yoshida. Detectability of high-redshift superluminous supernovae with upcoming optical and near-infrared surveys - II. Beyond z = 6. , 435(3):2483–2493, November 2013.

[6] R. Kessler, G. Narayan, A. Avelino, E. Bachelet, R. Biswas, P. J. Brown, D. F. Chernoff, A. J. Connolly, M. Dai, S. Daniel, R. Di Stefano, M. R. Drout, L. Galbany, S. González-Gaitán, M. L. Graham, R. Hložek, E. E. O. Ishida, J. Guillochon, S. W. Jha, D. O. Jones, K. S. Mandel, D. Muthukrishna, A. O'Grady, C. M. Peters, J. R. Pierel, K. A. Ponder, A. Prša, S. Rodney, V. A. Villar, LSST Dark Energy Science Collaboration, and Transient and Variable Stars Science Collaboration. Models and Simulations for the Photometric LSST Astronomical Time Series Classification Challenge (PLAsTiCC). , 131(1003):094501, September 2019.