***Roman*/Subaru Synergistic Observations White Paper**

1 Roman/Subaru Synergistic Follow-up of RAPID-discovered transients

2 Proposers:

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3 Required Observation Plans of Subaru Telescope

3.1 Subaru instruments to be used

Prime Focus Spectrograph (PFS).

3.2 Required nominal and minimum (threshold) number of nights (hours)

35 nights (280 hours); 24.5 nights (212 hours; HLTDS+GBTDS only).

3.3 Required condition of nights (moon phase, airmass, seeing)

Dark/grey for HLTDS/HLWAS/GAS; bright/grey for GBTDS/GPS. Airmass ≤ 2. Seeing $\leq 2''$.

3.4 Time criticality (year, season, date, time)

All 5 nominal mission years. Optimum: February (COSMOS), May (ELAIS-N1), June/July (GBTDS/GPS), October (XMM-LSS).

4 Relevance to the Roman Core Community Surveys (CCS) or other Roman programs

This white paper describes a program that will observe a magnitude-limited sample of every transient or variable discovered by RAPID in the High Latitude Time Domain Survey (HLTDS), High Latitude Wide Area Survey (HLWAS), and Galactic Bulge Time Domain Survey (GBTDS), i.e., all three CCS, together with ephemeral sources discovered in any of the General Astrophysics Surveys (GAS) optimized for time domain astronomy (TDA), e.g., the early Galactic Plane Survey (GPS).

5 Scientific Rationale/Justification

5.1 Time Domain with Roman

This decade is witnessing the maturation of TDA. The exploration and systematic study of explosive transients and eruptive variables is one of the three pillars of the Astro2020 Decadal Survey. The launch of the *Nancy Grace Roman Space Telescope* presents a unique opportunity to chart the dynamic infrared (IR) sky (Figure 1). *Roman* is a mission with considerable time-domain potential, though this is not one of the defined mission science objectives (which are cosmology and exoplanet demographics). The IR is uniquely suited to study transients reddened by opacity, dust and/or temperature. Emission from multi-messenger neutron star mergers is longest lived and ubiquitous in the IR as the bound-bound opacity of heavy elements pushes the peak of the emission to redder wavelengths. Emission from massive stars experiencing copious mass-loss is self-obscured and better studied in the IR. Emission from white dwarf merger products show dimming events that are easier to detect in the IR. Emission from a classical nova or a Galactic supernova deep in the disk of the Milky Way is also likely brightest in the IR on account of line-of-sight extinction. Emission from the highest redshift supernovae, the very first stars, is also brightest in the IR.

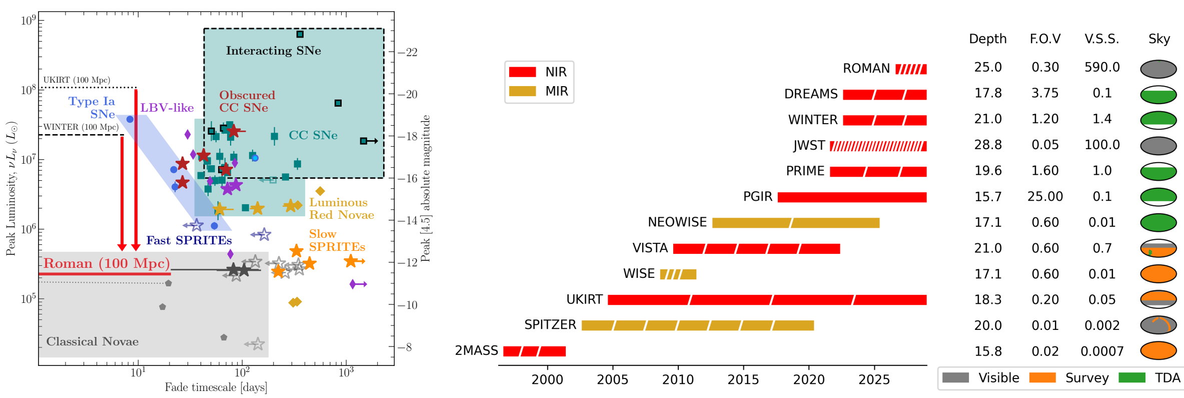

Figure 1: *Left: Luminosity–timescale phase space of IR transients in the Spitzer/IRAC [4.5] band. Objects discovered by the SPIRITS survey are indicated by the star symbols. Right: A timeline of current, future and historical surveys at near-infrared (NIR; red) and mid-infrared (MIR; gold) wavelengths. Surveys operating with multiple filters concurrently are indicated by diagonal white lines. The typical depth (in AB mag) and field of view (in deg^2) for each instrument is listed. The volumetric survey speed is also listed, normalized to the best ground-based NIR facility currently operating (PRime-focus Infrared Microlensing Experiment; PRIME). One hour of Roman time probes an equivalent volume to ∼ten weeks of PRIME observations.*

The main science drivers for this proposed program are the Core Community Surveys (CCS) which will be using the Wide Field Instrument (WFI) and occupy approximately 75% of the observing time, i.e., the High-Latitude Wide-Area Survey (HLWAS), the High-Latitude Time Domain Survey (HLTDS), and the Galactic Bulge Time Domain Survey (GBTDS). The HLTDS will provide similar constraints on Dark Energy via monitoring of thousands of high-redshift Type Ia supernovae (SNe Ia), which can serve as standardizable luminous candles. This survey will be of a more limited area than the HLWAS. However, the in-guide HLTDS will revisit both northern and southern deep and wide fields in multiple photometric bands with nominally an interleaved cadence of effectively every 5 days over nearly a 6-month period in a 2-year interval. The nominal GBTDS is to cycle through 6 Bulge fields and the Galactic Center, totaling ~ 2 deg^2 in area, almost continuously every 14.8 min through six high-cadence "seasons" lasting 68.5 days each when the Bulge is observable. The primary science goal is to collect a census of exoplanets via gravitational microlensing and orbital transits. A nominal HLWAS will consist of a 3-band medium (2415-deg^2) tier, a 1-band wide (2702-deg^2) tier, and two 7-band deep-tier (19.2-deg^2) fields, to depths of 26.2–27.7 AB mag; a slitless spectroscopy component using the G150 grism also will map the distribution of emission-line galaxies. The ultimate science goal of the HLWAS is to place stringent constraints on the various cosmological parameters and Dark Energy through the techniques of weak lensing galaxy shape measurements, baryon acoustic oscillations, and redshift-space distortions.

The remaining 25% or more of *Roman* observing time during the first 5 years will be reserved for General Astrophysics Surveys (GAS), which can consist of an untold myriad of science projects using all elements of the WFI. The sky is the limit on what the astronomical community will propose to execute with this time allocation. This allocation already includes an early-science GPS, which at this writing will be optimized for TDA.

5.2 RAPID: A discovery engine for Roman time domain

All *Roman* data will become publicly available as soon as they are archived. `RAPID` is developing a pipeline to fully realize the time-domain potential, providing prompt time-domain products to the astronomical community from the public data. The `RAPID` pipeline will by design be agile and work on all available data with complex, intertwined cadences and pointings, from both CCS and GAS programs. By promptly delivering a reliable alert stream, `RAPID` will enable the transient and variable communities to undertake timely panchromatic photometric and spectroscopic follow-up of the most interesting *Roman* discoveries. In these alert packets, `RAPID` will also provide all the necessary metadata, thumbnails and a machine-learning-based classification score (based initially on models; e.g, PLAsTiCC Kessler et al. 2019 and ELAsTiCC Narayan & ELAsTiCC Team 2023) in order to correctly identify high-value transients, enabling proper allocation of follow-up resources.

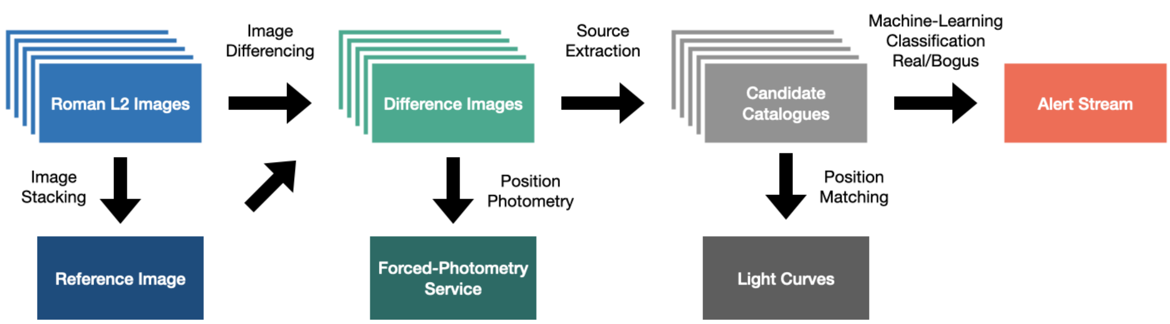

Figure 2: *Schematic overview of the RAPID pipeline. Reference images are made from stacking prior images in the same location & filter. The reference is then subtracted to produce difference images, removing extended underlying structure. Source extraction on the difference image produces a catalog of transient candidates. The catalog is scored and classified using machine learning, producing a rich alert packet per candidate, which are then broadcast. The difference images can also be analyzed to provide a forced-photometry service, and position matching the candidates generates light curves.*

5.3 The Observing Plan

Dedicated spectroscopic follow-up of RAPID-discovered *live* transients and variables is essential. A vivid example of this is the Zwicky Transient Facility (ZTF) Bright Transient Survey[1]. Not only would the follow-up fully reveal the nature of thousands of fascinating objects and events, but it would also provide the ultimate ground truth for any Roman machine-learning-based source classification.

On behalf of the entire Roman TDA community we therefore propose a dedicated, systematic magnitude-limited Prime Focus Spectrograph (PFS) follow-up program of RAPID-discovered transients.

[1] For a graphical representation of this Survey, see https://www.youtube.com/watch?v=IBeEAA_g-gc.

The primary goal would be to obtain single-epoch classification spectra, with multi-epoch spectral evolution for sources a secondary goal. The observing time request will be primarily driven by the HLTDS and the GBTDS, and to a lesser extent by the time-domain-enabling Deep tier component of the HLWAS and any GAS programs which would be optimized for TDA.

For transients discovered at high latitude, these will include SNe Ia, core-collapse supernovae, luminous red novae (LRNe; i.e., stellar mergers, common-envelope ejections), luminous blue variable (LBV)-like massive-star eruptions, tidal disruption events (TDEs), AGN flares, and (to a lesser extent) superluminous SNe (SLSNe of type I and II) and pair-instability supernovae (PISNe) at higher redshift. RAPID will also discover the comparatively few transients and variables in the Galactic halo.

The in-guide HLTDS core component in the north is proposed to consist of both wide (10.68 deg^2) and deep (1.97 deg^2) imaging of ELAIS-N1 in a wedding-cake arrangement. The imaging tiers will be revisited with an interlaced cadence of 10 days, with filter subsets every 5 days, over a total of 157.8 days. The in-guide also consists of a pilot component over 15.4 days and an extended component over 7.1 days; the former is intended primarily to test methods for the HLTDS and build reference images, and the latter is concentrating on detection of fainter, high-redshift transients, so we expect the yield of discoveries for our purposes here to be quite low from these two proposed survey extensions.

We will obtain once a month classification spectra of every possible RAPID-discovered transient complete to $J \lesssim 23$ mag in the northern HLTDS field. This will require multiple PFS footprints. At this depth we will detect[2] SNe of types Ia, Ia-91bg (underluminous Ia), Ib/c, and IIP/IIL out to redshift $z \lesssim 0.4$; AGN to $z \lesssim 0.8$; TDEs to $z \lesssim 0.6$; and SLSNe-I to $z \lesssim 1.8$. We estimate a total number density of these transients (not including the less common LRNe, LBVs, SLSNe-II, and the very high-redshift PISNe) to these redshifts of ~ 16 deg^{-2}, or ~ 20 per PFS science field-of-view (FoV), *per month*[3]. We would require ~ 9 PFS pointings to cover the northern HLTDS field.

From the PFS ETC (for a flat spectrum[4]), at $J \sim 23$ mag we can obtain a $S/N \sim 1$ pixel^{-1} in the Near-IR Arm in 1.5 hr (3×1800-sec exposures). So, 9 pointings times 1.5 hr per pointing times the number of visits (once a month for 6 months during both Year 1 and Year 2 of HLTDS) results in **20 (dark/grey) nights total**[5], or ~ 20 science fibers times 9 FoV times 162 hr or ∼29,160 fiber hours.

The in-guide recommendation for the HLWAS is a 2415 deg^2 3-band (YJH) Medium tier, a 2702 deg^2 single-band (H) Wide tier, a 7-band (YJH+ZFK+Wide) 19.2 deg^2 Deep tier, and a 3-band (YJH) 5 deg^2 Ultra Deep tier (within the Deep tier). The Medium and Wide imaging surveys would entail 2 time-spaced, dithered passes of the fields, whereas the Deep and Ultra Deep fields would be imaged in 5 and 10 additional time-spaced passes, respectively. While it is not practical to cover the Medium and Wide tiers with PFS, the Deep tier, which is comparable in area to the northern HLTDS, represents a viable possibility. The Deep tier includes both the COSMOS and XMM-LSS fields (each 9.6 deg^2). The ideal cadence recommended for the passes of the Deep tier is, acquire 2 passes with a 9–24 hour separation between passes and 4–6 weeks later acquire a second pair of passes, also with a 9–24 hour separation; then, acquire a third pair of passes 4–8 weeks later (with only the Wide filter in the second dithered set)[6].

We propose here to target the Deep fields at some time not long after the second pair of passes and then again not long after the third pair. RAPID will then have discovered new sources from the

[2]Based on Figures 4 and 5 of the HLTDS Definition Committee Report.

[3]Note that the aforementioned figures with the expected number of transients as a function of z in the HLTDS CCS report were based on an assumed 25-deg^2 wide field, whereas the proposed in-guide core component wide field is 10.68 deg^2.

[4]If this concept is selected, we will use spectra of real transients and variables as inputs to the ETC to refine the actual time request.

[5]Assuming ~ 8 usable hrs per night.

[6]https://asd.gsfc.nasa.gov/roman/comm_forum/forum_17/Core_Community_Survey_Reports-rev03-compressed.pdf, pp. 125–126.

differences between pass pairs. We can safely assume that the source density of extragalactic transients in the HLWAS Deep tier is likely comparable to the expectations for the HLTDS, and therefore scaling by the time sampling difference (5–6 weeks, rather than 4), we would expect ~ 25–30 sources per FoV. To cover both Deep tier fields requires 16 FoVs. With the same brightness limit as HLTDS, we require $16 \text{ pointings} \times 1.5 \text{ hr per pointing} \times 2 \text{ visits}$, or **6 (dark/grey) nights total**.

The nominal (in-guide) GBTDS will observe 6 contiguous Bulge fields, plus the Galactic Center, over 6 high-cadence (every 14.8 min) seasons of 68.5 days each, over the 5-year mission. In the GBTDS fields we expect RAPID to discover microlensing events, of course, as well as eruptive young stellar objects (YSOs; i.e., FUors, EXors); "dipping giants;" classical, recurrent, and dwarf novae; other cataclysmic variables (CVs); low- and high-mass X-ray binaries (LMXBs, HMXBs); stellar (GKM dwarf) flares; and pulsating variables (Lucas et al., 2024). We would implement as many science fibers as required to cover every transient with $J \sim 15$–20 mag (i.e., from saturation to the ground-based confusion limit in the Bulge[7]) for the GBTDS fields during all 6 survey seasons. We will observe about once a month, i.e., 2 nights, per season. The 6 contiguous fields together total $0\overset{\circ}{.}8 \times 2\overset{\circ}{.}4$, so 2 PFS FoV would be required; plus, 1 FoV to cover the Galactic Center region.

For the Bulge we expect the most plentiful transients to be the flare stars (with the more exotic transients, e.g., novae and CVs, being significantly less so), and an estimate of the total number in the GBTDS is roughly ∼26,000, depending on the confusion limit[8]. This is ∼2166 per observing run, so we would likely require ∼2200, or nearly all of the available, science fibers per FoV per run. Again, similar $S/N \sim 1$ pixel^{-1} stipulations as above, from the ETC for the Near-IR Arm we would require 1 hr (4×900 sec) per pointing. For the 3 pointings over 2×6 runs, this is 36 hr total, or **4.5 (grey/bright) nights total**, or ∼79,200 fiber hours.

We also include select GAS programs in the north. The GPS has yet to be defined; currently, ∼100–200 of the 700 hours total, could be TDA-optimized, possibly split between early in the mission and then again after ∼2 years. We then tentatively propose to observe the estimated ~ 10 TDA ($0\overset{\circ}{.}8 \times 0\overset{\circ}{.}4$) fields accessible from Subaru once during the first period and once again during the second. Assuming the GBTDS parameters (exposure depth, number of required fibers) also apply, we would require **2.5 grey/bright nights**. We also estimate we would require on order of another **2 dark/grey nights** to cover additional GAS. This is most likely an underestimate, especially if there is a nearby galaxies survey, e.g., a Roman Infrared Nearby Galaxies Survey (RINGS), optimized for TDA.

We are skeptical that a less-unified, less-dedicated global (northern) follow-up program would be as complete or as adequate as the one we propose here. This program could well be designed and executed in collaboration with the SN PIT, RGES PIT, the STRIDE time-domain working group, and the entire Roman TDA community. The program parameters can be better defined after the ROTAC deliberations on the CCS. We are also open to sharing time and fibers with or piggybacking on other proposed PFS programs, including, e.g., HLTDS (Hounsell), SNIa Hosts (Suzuki), SuPR Deep Survey (Newman), AGN Demographics (Onoue), SPLASH (Rhoads), or Oscillating Giants (Huber).

References

Kessler, R., Narayan, G., Avelino, A., et al. 2019, PASP, 131, 094501

Lucas, P. W., Smith, L. C., Guo, Z., et al. 2024, MNRAS, 528, 1789

Narayan, G., & ELAsTiCC Team. 2023, in American Astronomical Society Meeting Abstracts, Vol. 241, American Astronomical Society Meeting Abstracts, 117.01

[7]Private communication, R.M. Rich. A more pertinent estimate should be possible from PRIME.

[8]Private communication, R.F. Wilson & L.T. Mendoza.