Roman Early-Definition Astrophysics Survey Opportunity

(1) Submission Title or Survey Name: An Extended Time-Domain Survey (eTDS) to Detect High-z Transients, Trace the First Stars, and Probe the Epoch of Reionization

(2) Contact author (with institutional affiliation and full contact details, including email):

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(4) Do you support the selection of a Roman Early-Definition Astrophysics Survey (as described in the "Request for Information"; yes/no, with supporting motivation, 10 lines max):

Yes. We support the Early-Definition Astrophysics Survey. Since the original Roman Surveys were defined, there have been several significant developments: (1) Roman added the F213 filter, which is a game-changer for time-domain science, (2) wide-field, transient, and infrared science have all undergone significant advancement, and (3) a number of new major observatories are coming online, including JWST and ESO ELT. Taken all together, there are likely new ideas within the community that should be considered in advance of Roman's launch. Advanced planning will ensure these new ideas are successfully integrated into Roman's science strategy.

(5) Describe the science investigations enabled by the survey (as relevant, briefly describe: key science drivers and breadth of science areas engaged; datasets expected upon survey completion; comparison of science enabled, parameter space opened up, or complementarities with respect to ground/space-based state-of-the-art at time of Roman launch; key differences from, and/or complementarities with, Roman core community surveys; one page max):

Big Picture: Roman's extreme wide field of view and near-IR sensitivity provide our only route for probing the Initial Mass Function (IMF) and stellar populations at high z by finding intrinsically rare explosions. The Roman Deep High-Latitude Time Domain Survey (HLTDS) provides a powerful ability to detect explosive transients, but our analysis shows that extending the current HLTDS in both time (Cycles 1 & 2) and wavelength (K band) is needed to color select high-z events (**Figs. 1 & 2**). An extended TDS (eTDS) can generate an unparalleled transient database in terms of combined supernova (SN) redshift reach, area, and timescale (**Tab. 1**). It would make Roman a discovery engine for rare, extreme high-z SNe and, *for the first time*, build a sample of **thousands** of normal high-z core-collapse (CC) SNe (**Tab. 2**). Just as the GOODS observing strategy of repeated visits was designed to serve both time-domain and deep static-sky science, the eTDS will provide exceptionally deep and wide imaging comparable to COSMOS-Webb[1] in depth (F158 $\approx$ 29.5/F213 $\approx$ 27.5 mag), but 8× larger in area! eTDS costs ~360 hours, a small fraction of HLTDS.

Science Driver: The early, high-z (> 6) Universe is the next frontier in transient astronomy. The science driver is *not* just to extend low-z studies. Rather it is probing the first stars (Pop III) and Epoch of Reionization. Only at these redshifts can we begin to detect extreme transients arising from the low-metallicity, massive (> 50 $M_\odot$; Heger & Woosley 2002) Pop III stars, such as the **never-before-seen** pair-instability (PISNe; Regős et al., 2020) and some super-luminous (SLSNe; Abbott et al., 2017) events, which tend to be red and have slowly evolving and long-lasting light curves (**Figs. 1 & 2**). Furthermore, a statistically significant sample of these massive-star explosions (>50 $M_\odot$) uniquely traces the evolution of the high-mass end of the IMF and will resolve open questions to understanding the impact of massive stars on reionization, the buildup of galaxy masses, and other aspects of both stellar/galaxy evolution (**Fig. 3**; e.g., Larson, 1998; Davé, 2008).

Breadth of Science: The eTDS leaves a broader legacy. The expected combination of sensitivity and timescale will allow for monitoring rest-frame long-duration transients (e.g., SN 2005ip; Fox et al. 2020) and extending low-z time-domain science out to high z, where time-dilation effects dominate. This means not only complete coverage of high-z SN light curves, but also other time-domain science such as AGN reverberation mapping to measure black hole masses at $z \approx 6$ (Homayouni et al., 2020). The large SN sample will extend CCSN rate studies beyond anything currently possible (Strolger et al., 2015), and will also include some SNe Ia, likely the highest-z Ia ever discovered (e.g., Rodney et al., 2014). The F213 coverage opens new K-band discovery space with large nearby samples (i.e., non-targeted galaxies) that include dust-obscured and/or nuclear SNe (Kool et al., 2018; Fox et al., 2021) and IR-bright transients (Kasliwal et al., 2017; Mattila et al., 2018). Finally, as noted above, the stacked epochs result in an ultra-deep ~5 deg^2 field.

Comparison to HLTDS: Based on the white paper (Moriya et al., 2021), an eTDS both complements and stands out from the HLTDS by extending it in three important ways: **(1)** wavelength out to K band, **(2)** SN reach to beyond $z = 6$, and **(3)** the timescale from ~ 2 to ~ 4 years. In addition, an eTDS would work in tandem with Euclid, JWST, and Rubin. Aside from the discovery of SNe, the eTDS has distinct science goals from HLTDS (i.e., IMFs, reionization, CCSNe/extreme SNe), and therefore a unique choice of implementation (e.g., cadence, filter choice). See **(6)** below.

[1]https://www.stsci.edu/jwst/phase2-public/1727.pdf

(6) Provide a possible observational outline of the survey (as relevant/known, touch upon: survey area covered, possible location, and/or (types of) targets observed; optical element (filters/grism/prism) choices; cadence or other timing constraint (if relevant); depth to be achieved; total time needed including estimated overheads; how the survey leverages the unique observational capabilities of Roman; half-a-page max):

Big Picture: The survey parameters are driven by the desired sensitivity to and rates of SLSNe and PISNe at high-z. The eTDS, first outlined by Moriya et al. (2021), would require 18 pointings to cover ∼5 deg^2 per epoch, with ∼4 epochs spaced evenly over ∼2 years (i.e., every ∼6 months). To go deep enough, each epoch would probably require ∼2.5 hours of integration per filter[2], totaling 90 hours/epoch, or 360 hours total (plus relatively small overheads). For each epoch, individual exposures would consist of shorter integrations spaced out over a designated time frame (∼1 month) to optimize sampling of low-z/faster-evolving transients. The choice of field is open-ended, but we strongly recommend overlap with the SN/HLTDS field to optimize monitoring of long-term (i.e., 4-5 year) variability, which is also a strong driver for starting such a survey in Roman's *first year*.

Justification: The color-magnitude space for various transients is shown in **Fig. 1** for both our preferred eTDS filter combinations (F158/F213) and the current HLTDS (F158/F184). We prefer F158 over F184 for eTDS due to its sensitivity. Although HLTDS goes sufficiently deep to *detect* some high-z transients (particularly SLSNe), the figure underscores that to *discriminate* these events we must **(1)** use the F213 filter, and **(2)** go deep (F158 $\approx$ 28.7 and F213 $\approx$ 26.6) in a single epoch, which we define to span $\sim$ 1 month given the evolution timescales (**Fig. 2**).[3] **Tab. 2** justifies our 5 deg^2 FOV by showing the expected SN rates, although we note these numbers are based on extrapolations of low-z observations. Actual numbers will vary based on evolving IMF and metallicities, as well as final survey design. Roman's unique combination of field of view and IR sensitivity make it the only telescope capable of carrying out such a survey.

[2]https://roman.gsfc.nasa.gov/science/RRI/Roman_WFI_Reference_Information_20210125.pdf

[3]Note, the calculation for the deep HLTDS sensitivity assumes, in one month, six 300 s and 900 s exposures in the F158 and F184 filters, respectively. This corresponds to F158 $\approx$ 27.5/F184 $\approx$ 27.7.

(7) Describe specific preparatory activities enabled by early definition (e.g., supporting facility observations, software development work, theoretical/simulation efforts etc.; describe the benefits of conducting these activities early; half-a-page max):

Preparatory Work: Given the immense number of transients expected, it is critical that any high-z time-domain survey be able to filter out low priority events with existing catalogs, deep templates, and real-time follow-up for classification and analysis. In our case, preparatory work will focus primarily on obtaining deep, cadenced pre-imaging to mark known transients (such as AGN) and obtain host-galaxy photo-z's in advance (ground- and/or space-based; i.e., Subaru, LSST, or Euclid). From the theoretical side, we will need to implement a full-scale model at the catalog level with real fluxes and forward-modeling tools to optimize the final survey strategy. We will also need time to propose and coordinate simultaneous time-domain surveys to filter low-z SNe, follow-up photometry to monitor light-curves, and JWST near-IR spectroscopic follow-up to classify high-priority targets. Early definition will provide the time horizon necessary to do all of this work.

Early definition is important because eTDS needs to be a part of Cycle 1. We stress that the *only* way Roman will obtain a full light curve of a high-z PISN and confirm it fades (thereby confirming the transient nature of the source) is to begin this survey in its first year. The eTDS data will then be supplemented by the planned SN HLTDS survey expected to start at >1.5 years. Even without the F213 filter, the planned HLTDS will be sufficient for light-curves once our high-z candidates are confirmed. *Note that given JWST's required minimum lifetime (5 years), there is no guarantee that JWST will be available to support any TDS later in Roman's mission.* Finally, the eTDS will serve as an excellent foundation for the planned HLTDS! The F158 imaging will provide a deep template, while the F213 observations will prove key for measuring photo-z's of the HLTDS candidates' host galaxies. The HLTDS science teams will have real data to work with to prepare for and optimize their surveys and differencing strategies, as well as filter out contaminating transients (such as AGN and variable stars).

[It is allowed to add two additional pages with figures, tables, or references, as needed to support the preceding answers. This can include any past/planned white papers, community building/engagement activities, working groups, workshops, or cross-project/cross-mission planning relevant to the survey; You may use this MS Word template or any other software for editing your responses (12pt font). Once finished, please create, and submit a pdf file.]

Table 1: Characteristics of Various Space Time-Domain Surveys[a]

Name	Near-IR Sensitivity[b,c] (mag)	SN z_{max} (M>-21) (z)	Area (deg^2)	Timescale (yr)
HLTDS	F158=27.5, F184=27.7	5.3	5	2
eTDS	F158=28.7, F213=26.6	8.5	5	> 4
COSMOS-Webb	F444W=27.7, F277W=28.1 F150W=27.6, F115W=27.4 F770W=23.9	5.5	0.6 0.6 0.2	1 1 1
HST-COSMOS[d]	F814W=26.2	–	1.7	2
CANDELS	F160W=25.4, F125W=25.8	2.3	0.25	3
GOODS[d]	F850lp=25.4	–	0.08	4

[a] All numbers are rough approximations since many numbers are case-dependent.
[b] 5σ detection in difference imaging.
[c] In roughly a month of stacked images, which we take to correspond to a single epoch.
[d] These surveys had no sensitivity in the near-IR, but found no transients at $z \gtrsim 2$.

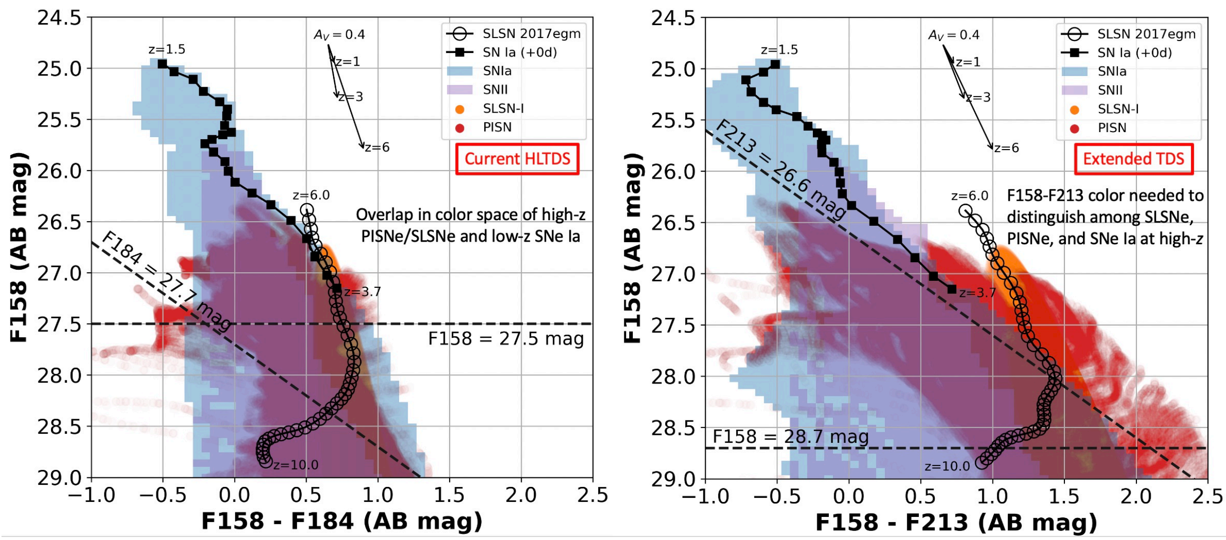

Figure 1: The color-magnitude phase space for (*left*) the current HLTDS (F158W/F184W) and (*right*) our proposed eTDS (F158W/F213W). The F158W-F213W color is critical to distinguish SLSNe and PISNe at $z > 6$ (orange and red) from lower-redshift SNe Ia and CCSNe (in blue and purple). Additional epochs, corresponding light-curves, and potential spectroscopic follow-up will help to further classify the SNe.

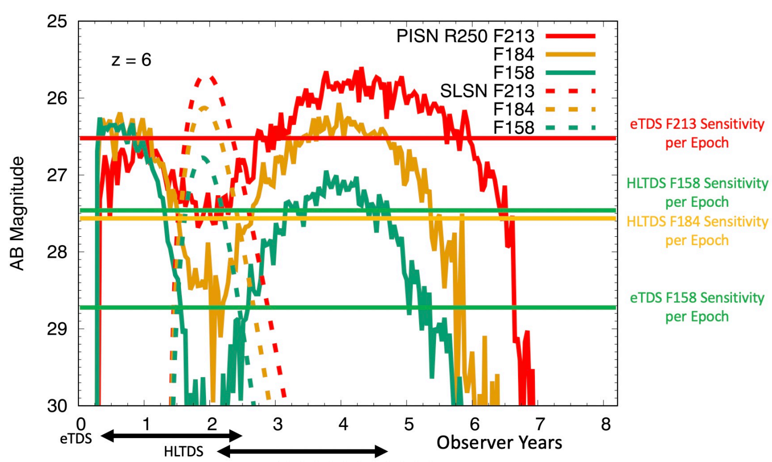

Figure 2: Theoretical observer-frame light curve models of a PISN (solid) and an SLSN (dashed) at $z = 6$. These light-curves tend to slowly evolve and **last for >2 years**. Horizontal black arrows at the bottom mark the corresponding time-scales of both the HLTDS and eTDS, while horizontal colored lines identify the sensitivity per epoch, where the calculation for the deep HLTDS sensitivity assumes, in one month, six 300 s and 900 s exposures in the F158 and F184 filters, respectively.

Table 2: Simulated Number of Transients for eTDS[a]

model	z					
	(<6)	(6-7)	(7-8)	(8-9)	(9-10)	(>10)
CCSN	316355[b]	6766	3713	2075	1299	–
PISN	–[c]	11.2	7.0	3.1	2.0	3.0
SLSN	14.3	2.26	1.15	0.55	0.033	0.003

[a] (F158, F213) = (28.7, 26.6), 5 deg^2, 0.5 yr cadence for 2 years

[b] These rates are based on extrapolations of low-z observations. Actual numbers will vary based on evolving IMF and metallicities, as well as on final survey design.

[c] Although the extrapolated rates would seem to suggest a large number of PISNe at $z < 6$, we know this not to be true from current observations. These numbers do not account for metallicity, which limits the likelihood of any PISNe at low z. We therefore do not include any number here.

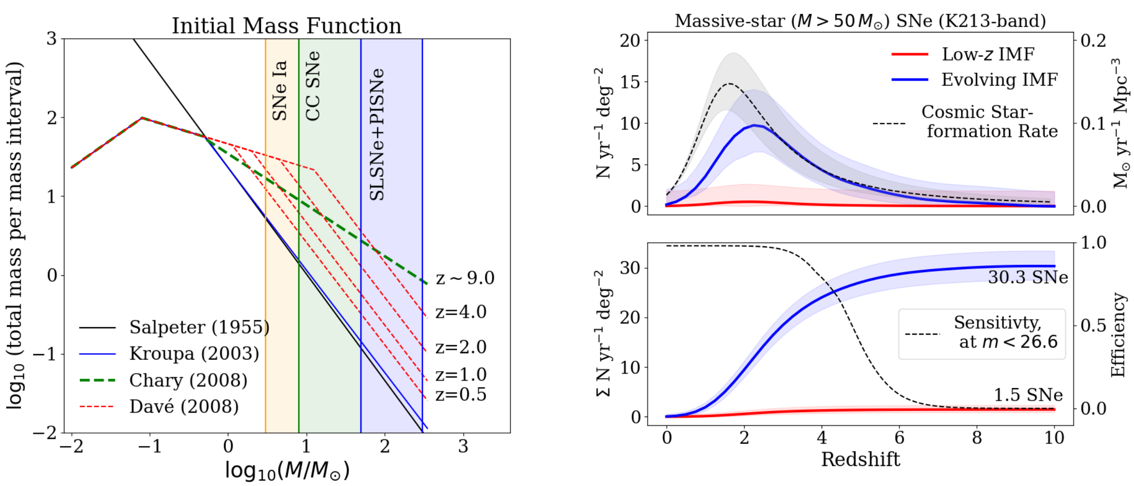

Figure 3: Science drivers for detecting SNe at $z > 6$. Beyond discovering rare high-z transients, the eTDS will, *for the first time*, produce a statistically significant sample (**Tab. 2**) of massive star explosion (>50 $M_\odot$), typically considered to be associated with SLSNe and PISNe (Heger & Woosley, 2002). (*left*) The SLSNe and PISNe uniquely trace the evolution of the high-mass end of the IMF, which is expected to grow increasingly top-heavy with redshift following the prescription shown by Davé (2008). (*right*) Using the eTDS survey parameters, the simulated number of massive star SNe per deg^2 per year for two different IMF scenarios, which can only be differentiated at the 10σ level with a sample size that can be obtained with Roman's extreme wide field of view (**Tab. 2**).

White Papers: Moriya, T. et al. 2021, arXiv:2108.01801

References Abbott, T. et al. 2017, PASA, 34, 12 • Dave, R. 2008, MNRAS, 385, 147 • Fox, O. et al. 2020, MNRAS, 498, 517 • Fox, O. et al. 2021, MNRAS, 506, 4199 • Heger, A. et al. 2002, ApJ, 567, 532 • Homayouni, Y. et al. 2020, ApJ, 901, 55 • Kasliwal, M. et al. 2017, ApJ, 839, 88 • Kool, e> et al. 2018, MNRAS, 473, 5641 • Larson, R. et al. 1998, MNRAS< 301, 569 • Mattila, S. et al. 2018, Sci, 361, 482 • Moriya, T. et al. 2021, arXiv:2108.01801 • Regos, E. et al. 2020, ApJ, 894, 94R • Rodney, S. et al. 2014, AJ, 148, 13 • Strolger, L. et al. 2015, ApJ, 813, 93