Roman CSS White Paper

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

Core Community Survey Under Discussion: High-Latitude Time Domain Survey (HLTDS)

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

Ori D. Fox
mail: Space Telescope Science Institute, 3700 San Martin Dr, Baltimore, MD 21218
phone: 617-851-6561, **email**: ofox@stsci.edu, **twitter**: @fox_ori

Co-authors :

Christopher Ashall (V Tech; cashall@vt.edu), Eddie Baron (PSI; ebaron405@gmail.com), Ting-Wan Chen (TUM; janet.chen@astro.su.se), James DerKacy (V Tech; jmderkacy@vt.edu), Steven Finkelstein (UT Austin; stevenf@astro.as.utexas.edu), Suvi Gezari (STScI; sgezari@stsci.edu), Sebastian Gomez (STScI; sgomez@stsci.edu), Norman Grogin (STScI; nagrogin@stsci.edu), Peter Hoeflich (FSU; phoeflich77@gmail.com), Rebekah Hounsell (University of Maryland Baltimore County/NASA Goddard; rebekah.a.hounsell@nasa.gov), Isobel Hook (Lancaster University; i.hook@lancaster.ac.uk), Susan Kassin (STScI; kassin@stsci.edu), Rubina Kotak (Turku; rubina.kotak@utu.fi), Anton Koekemoer (STScI; koekemoer@stsci.edu), Seppo Mattila (Univ. of Turku; sepmat@utu.fi), Maryam Modjaz (UVA; mmodjaz@gmail.com), Takashi Moriya (NAOJ; takashi.moriya@nao.ac.jp), Justin Pierel (STScI; jpierel@stsci.edu), Robert Quimby (SDSU; rquimby@sdsu.edu) Eniko Regos (Konkoly; regos@konkoly.hu), Armin Rest (STScI; arest@stsci.edu), David Rubin (UH; drubin@hawaii.edu), Steve Schulze (OKC; steve.schulze@fysik.su.se), Melissa Shahbandeh (STScI; mshahbandeh@stsci.edu), Matt Siebert (STScI; msiebert@stsci.edu), Lou Strolger (STScI; strolger@stsci.edu), Tea Temim (Princeton; temim@astro.princeton.edu), Ashley Villar (PSU; vav5084@psu.edu), Bob Williams (STScI; wms@stsci.edu)

Science Categories: stellar physics and stellar types; galaxies; the intergalactic medium and the circumgalactic medium; large scale structure of the universe.

SCIENCE JUSTIFICATION

Big Picture: Supernovae (SNe) at redshifts $z > 2$ are a relatively unexplored frontier that will make it possible to **(1)** test Initial Mass Function (IMF) evolution scenarios, **(2)** constrain the contribution of massive stars to the reionization of the Universe, and **(3)** discover some of the most rare and extreme explosions in our Universe from the first (Pop III) stars. With its extreme wide field of view and near-IR sensitivity, *modifications in depth* to Roman's baseline Deep High-Latitude Time Domain Survey (HLTDS; Rose et al., 2021) will enable the detection and classification of a statistically significant SN sample to test IMF evolution scenarios between $2 < z < 4$. Furthermore, extending the baseline HLTDS in both time (Years 1 & 2) and wavelength (K-band) is needed to more efficiently color select and classify SNe at $z > 2$ and extend the detection of rare transients out much farther (i.e., $z \gtrsim 6$). An extended TDS (eTDS) can generate an unparalleled transient database in terms of combined supernova (SN) redshift reach, area, and timescale (**Tab. 1**). A strategy of repeated visits will also provide legacy value with exceptionally deep and wide imaging for static-sky science comparable to COSMOS-Webb[1] in depth (F158 ≈ 29.5/F213 ≈ 27.5 mag), but 8× larger in area! An eTDS costs between ~400-1000 hours, depending on final design.

The Relevance of Massive Stars at High-z: The Epoch of Reionization (EoR) is a crucial period in the early universe when the first luminous sources, presumably massive stars in nascent galaxies, began to impact the neutral Hydrogen around them. Understanding the EoR is valuable for a variety of astronomical research including, but not limited to, the chemical enrichment, star formation rate (SFR) history, and galaxy evolution in the early universe (e.g., Behroozi & Silk, 2015; Finkelstein et al., 2015). While the general time-frame for reionization ($z \sim 6$) is agreed upon given current observational constraints (e.g. Fan et al., 2006), a number of questions remain unanswered. For example, recent JWST results have found more galaxies than expected at high-z (e.g., Finkelstein et al., 2022). While more galaxies than expected could be interpreted as a challenge to ΛCDM (e.g. Boylan-Kolchin, 2023), there are several other more likely explanations.

A Potentially Evolving IMF: Finkelstein et al. (2022) present several explanations for the observed over-density of galaxies in their JWST data, but are most intrigued by the possibility of an evolving, more "top-heavy" IMF. At higher redshifts, low metallicities likely resulted in stars with inefficient cooling mechanisms and, thereby, very high stellar masses (> 100 $M_\odot$; Vink et al., 2001; Kudritzki, 2002). In fact, a constant IMF is not even expected theoretically, and a more top-heavy IMF has already been invoked as a possible mechanism for addressing the buildup of "too-massive" galaxies at high-redshifts (e.g., Larson, 1998; Ferguson et al., 2002; Lacey et al., 2008; Davé, 2008; Labbé et al., 2023). While no variations have been unequivocally detected in local studies (Kroupa, 2001), there are hints of IMF variations that favor larger proportions of high mass stars in high-z galaxies (Savaglio et al., 2005; Erb et al., 2006a,b,c; Maiolino et al., 2023).

Using Supernovae to Measure the IMF and Defining κ: SNe hold the key for testing IMF evolution models. Massive stars ($M_{\rm ZAMS} \gtrsim 8$ $M_\odot$) end their lives as core-collapse supernovae (CCSNe). CCSN rates trace the most recent star formation. To understand any changes in the IMF, the CCSN

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

rate must be compared relative to the SFR. A useful metric in the field is k, which is defined as the ratio of the volumetric CCSN rate, $R(z)$, to the cosmic star-formation rate, SFR(z) (i.e., R(z) = $\kappa \times$ SFR(z) ; Botticella et al., 2012). An evolving κ may indicate a changing SFR, changing IMF, or a higher fraction of CCSNe due to other causes, such as more/less efficient explosion pathways at high-z. It could also be a combination of effects. Measuring the redshift dependence of κ is a critical first in disentangling the contributing effects.

A New Field of Transient Astronomy with Extreme, Rare, and Bright Explosions: Measuring SN rates at $z > 2$, even with Roman, will be possible only with the brightest CCSNe. If the IMF does indeed become more "top-heavy" as a function of redshift, the most massive of these stars (i.e., >100 $M_{\odot}$) may also be the source of some of the most extreme and elusive explosions in the Universe, including those from the first stars (i.e., Pop III). These paramount explosions include the brightest CCSNe, super-luminous supernovae (SLSNe; Quimby et al. 2011), and pair-instability supernovae (PISNe; Woosley et al. 2007). Such transients are not only necessary for conducting our IMF experiment, but inevitably open an entirely new field of transient astronomy in and of themselves. For example, the currently unknown powering mechanism for SLSNe (i.e., magnetars/interaction) is also likely present in other transients (normal CCSNe, GRBs, kilonovae, etc.), but its dominance in SLSNe makes it easier to study (e.g., Nicholl et al., 2013). Also, while PISNe are mostly theoretical at this point (but see SN 2018ibb, Schulze et al., 2023), the discovery and study of PISNe are essential to understand progenitors, explosion dynamics, compact objects, and most importantly, new physics, from the first generation of stars (e.g., Hummel et al., 2012).

Technical Justification

Big Picture Strategy: To be clear, Roman cannot probe the IMF evolution at $z > 6$. But with several modifications to the baseline Deep HLTDS design summarized in Table 2 of Rose et al. (2021), Roman can produce a significant SN sample out to at least $z \approx 4$, an important anchor for any future high-z studies. These modifications will also allow for the discovery of extreme and rare high-z explosions at $z > 6$. For newly discovered SNe, the redshift will be constrained by a combination of the intrinsic color and, if available, the host galaxy redshift measured from both photo-z's and possibly Prism observations by the HLTDS. The SN will be classified by its color and light-curve obtained by long-term monitoring. JWST spectroscopy will be a useful tool, but not necessary to do the bulk of the science. An eTDS will require a combination of depth, area, filter combination, and cadence, all of which we expand upon below. A significant amount of this work was first outlined by Moriya et al. (2021) and a complementary white paper is also being led by Moriya, who is a Co-I on this team. This White Paper focuses more on the IMF, while Moriya's White Paper focuses more on the explosions themselves.

Survey Size and Depth: The science driver for defining our survey parameters is the number of SNe necessary at each redshift to constrain κ evolution scenarios. While there are many potential scenarios, we consider only two in **Fig 1 (left)**: (1) a constant κ and (2) an evolving κ. The current best-fit to the data is unconstrained and not representative of any physical model, stressing the need to go out to higher-z. We assume that differentiating between models is dominated by counting statistics. In other words, to differentiate at the 10σ level requires a survey that predicts a difference in yields of ∼100 CCSNe. Using our simulations, **Fig 1 (right)** shows the number of SNe at $2 < z < 4$ for both the baseline survey depth of F158 = 27.5 mag per epoch (red) and going deeper to roughly F158 = 28.7 mag per epoch (blue), where we define below an epoch to be stacked observations within ∼1 month. Given our statistical requirements, going deeper (F158 > 27.5 mag per epoch) is necessary for this experiment. Going *as deep* as F158 = 28.7 mag may not be necessary. Tradeoffs should be explored, but **Fig 1** gives a sense of the impact of those variables.

Filters (and Depth Again): The eTDS would benefit from adding F213 to detect higher redshift targets. The color-magnitude space for various transients is shown in **Fig 2** for both our preferred eTDS filter combinations (F158/F213) and the current HLTDS (F158/F184). Although HLTDS goes sufficiently deep to *detect* some high-z transients (particularly SLSNe), the figure underscores that to *color discriminate* these events we must **(1)** use the F213 filter, and **(2)** go deeper in two filters (F158≈28.7 and F213 ≈ 26.6) in a single epoch, which we again define as stacked observations within ∼ 1 month. Tradeoffs should be explored, but **Fig 2** gives a sense of the impact.

Advantage of Slitless Spectroscopy: We also note that deep HLTDS Prism observations of any fraction of the field would be welcome as they provide spectroscopic redshifts for the host galaxies.

Cadence/Timing: PISNe and SLSNe already have long-lasting light-curves (**Fig 3**). At $z > 4$, PISN light curves can already span five years. Monitoring the evolution of these light-curves requires epochs separated roughly 6 months apart. The eTDS proposes to extend the HLTDS to five years and implement a six-month cadence. Such a cadence and time-scale are necessary not just for characterizing these transients, but also filter out low-z fast-evolving SNe. Further cadence designs are possible and encouraged within this framework.

Contiguous: Only the total area matters, but we point out the current HLTDS is already optimal.

Survey Time and Comparison to HLTDS: Our proposed eTDS both complements and stands out from the HLTDS by expanding 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 − 5 years. The survey parameters are driven by the desired sensitivity to and rates of SLSNe and PISNe at high-z. To go deep enough, we will require roughly forty 300-sec exposures in both proposed filters (F158 and F213), adding ~6 extra hours per pointing (totaling 100 hrs for the 15 pointings) every 6 months for 2-4 years, for a total of roughly 800 hours. A trade study is possible to decrease this time, which we think can be done for as little as 400 hrs if we limit our redshift range. A complete swap of the F213 with the F184 filter can keep the overall change in time request at a minimum (we estimate F184 currently costs 540 hrs total). We prefer keeping the F158 filter due to its sensitivity and better color leverage when combined with F213. An even shorter wavelength filter (F106 or F129) is still necessary to filter out low-z transients. 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.

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 $z \gtrsim 2$.

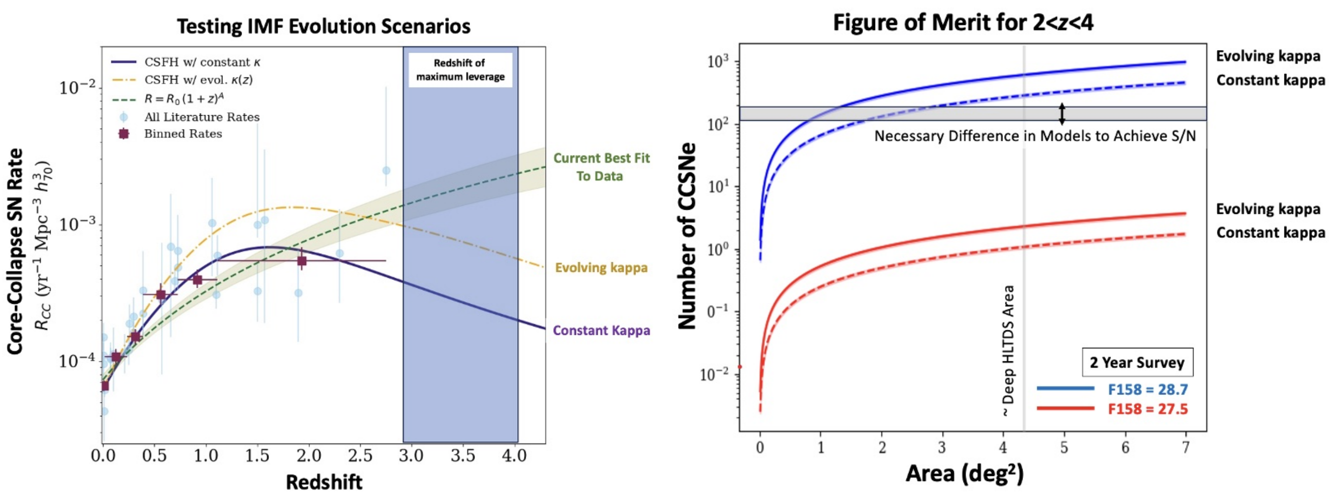

Figure 1: (*left*) Adapted from Strolger et al. (2015), the core-collapse SN (CCSN) rate as a function of redshift. We define k as the ratio of the volumetric CCSN rate, $R(z)$, to the cosmic star-formation rate, SFR(z) (i.e., R(z) = $\kappa \times$ SFR(z)). κ incorporates changes to the IMF due to a variety of different variables, but can be interpreted as a proxy for the degree of top-heaviness in the IMF. Filled circles are individual (blue) and binned (maroon) observations from the literature. Over-plotted are the best-fits for two models: (1) a constant κ (purple) and (2) an evolving κ (gold). The current best-fit to the data (green) is currently unconstrained and not representative of any physical model. To differentiate scenarios, higher-redshift data are needed. (*right*) The Figure of Merit (FOM), which shows the number of SNe at $2 < z < 4$ as a function of area for several illustrative examples. Red lines correspond to the current baseline survey (F158=27.5 mag per epoch), while blue shows the impact of going deeper (F158=28.7 mag per epoch). We define an epoch as stacked observations within ~1 month. Solid lines correspond to an evolving κ, while dotted lines correspond to a constant κ. To differentiate between IMF scenarios, a F158>27.5 mag survey is required.

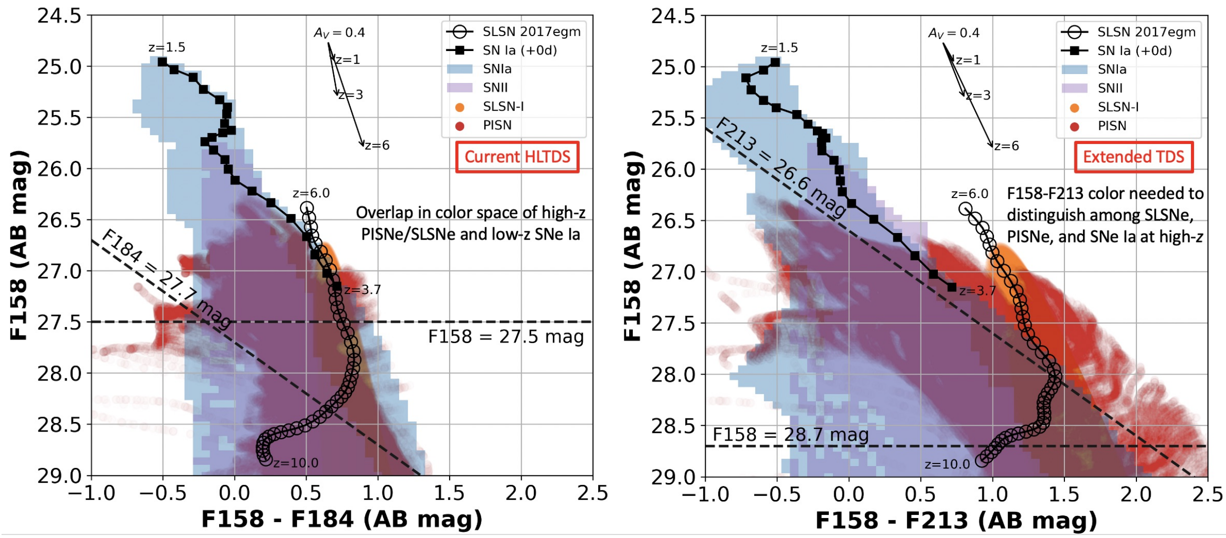

Figure 2: The color-magnitude phase space for (*left*) the current HLTDS (F158W/F184W) and (*right*) our proposed eTDS (F158W/F213W). The F158W-F213W color is critical to distinguish SLSNe and PISNe at $z > 6$ (orange and red) from lower-redshift SNe Ia and CCSNe (in blue and purple). Additional epochs, corresponding light-curves, and potential spectroscopic follow-up will help to further classify the SNe.

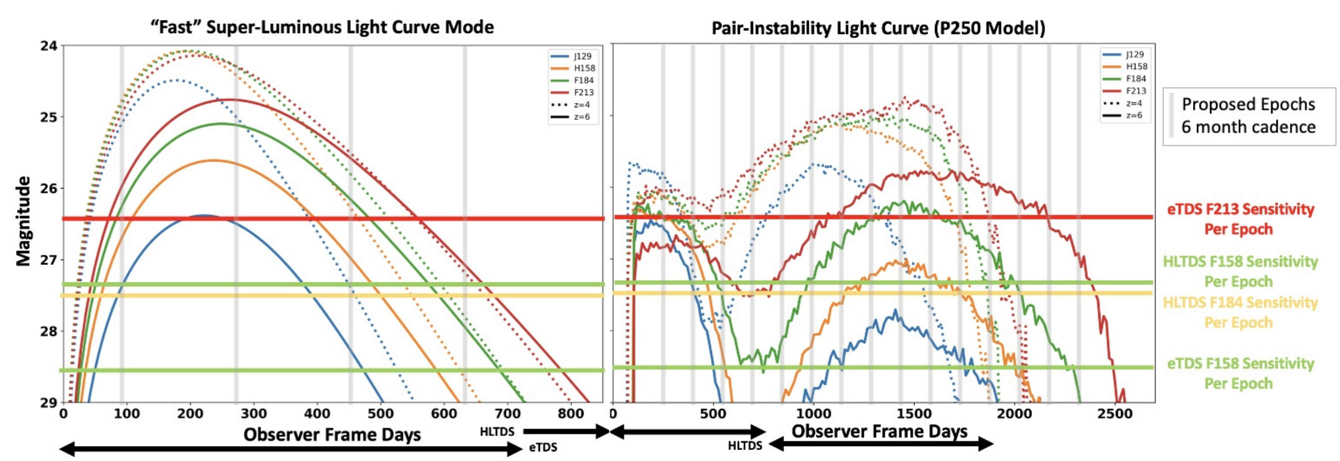

Figure 3: Theoretical observer-frame light curve models of SLSNe (**left**) and PISNe (**right**) at $z = 4$ (*dotted*) and $z = 6$ (*solid*). These light-curves tend to slowly evolve and **last for >2 years**. Horizontal black arrows at the bottom mark the corresponding time-scales of both the HLTDS 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.

References

Behroozi P. S., Silk J., 2015, ApJ, 799, 32

Botticella M. T., Smartt S. J., Kennicutt R. C., Cappellaro E., Sereno M., Lee J. C., 2012, A&A, 537, A132

Boylan-Kolchin M., 2023, Nature Astronomy,

Davé R., 2008, MNRAS, 385, 147

Erb D. K., Shapley A. E., Pettini M., Steidel C. C., Reddy N. A., Adelberger K. L., 2006a, ApJ, 644, 813

Erb D. K., Steidel C. C., Shapley A. E., Pettini M., Reddy N. A., Adelberger K. L., 2006b, ApJ, 646, 107

Erb D. K., Steidel C. C., Shapley A. E., Pettini M., Reddy N. A., Adelberger K. L., 2006c, ApJ, 647, 128

Fan X., et al., 2006, AJ, 132, 117

Ferguson H. C., Dickinson M., Papovich C., 2002, ApJ, 569, L65

Finkelstein S. L., et al., 2015, ApJ, 810, 71

Finkelstein S. L., et al., 2022, ApJ, 940, L55

Hummel J. A., Pawlik A. H., Milosavljević M., Bromm V., 2012, ApJ, 755, 72

Kroupa P., 2001, MNRAS, 322, 231

Kudritzki R. P., 2002, ApJ, 577, 389

Labbé I., et al., 2023, Nature, 616, 266

Lacey C. G., Baugh C. M., Frenk C. S., Silva L., Granato G. L., Bressan A., 2008, MNRAS, 385, 1155

Larson R. B., 1998, MNRAS, 301, 569

Maiolino R., et al., 2023, arXiv e-prints, p. arXiv:2306.00953

Moriya T. J., Quimby R. M., Robertson B. E., 2021, arXiv e-prints, p. arXiv:2108.01801

Nicholl M., et al., 2013, Nature, 502, 346

Quimby R. M., et al., 2011, Nature, 474, 487

Rose B. M., et al., 2021, arXiv e-prints, p. arXiv:2111.03081

Savaglio S., et al., 2005, ApJ, 635, 260

Schulze S., et al., 2023, arXiv e-prints, p. arXiv:2305.05796

Strolger L.-G., et al., 2015, ApJ, 813, 93

Vink J. S., de Koter A., Lamers H. J. G. L. M., 2001, A&A, 369, 574

Woosley S. E., Blinnikov S., Heger A., 2007, Nature, 450, 390