Roman CCS White Paper

A Sweet Spot for Tidal Disruption Events with the Roman Space Telescope

Roman Core Community Survey: *High Latitude Time Domain Survey*

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A Sweet Spot for Tidal Disruption Events with the Roman Space Telescope

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ABSTRACT

Tidal disruption events (TDEs) are among the few ways to directly probe supermassive black holes in normal, quiescent galaxies, especially in the low-mass black hole regime ($< 10^8\ M_\odot$). At higher redshifts, they are key to understanding the nature ("heavy" or "light") of the primordial seeds from which they grew in the early universe. In this white paper, we simulate TDE observations to show that the Roman High Latitude Time Domain Survey's capabilities are perfect for making the first-ever detections of high-redshift TDEs, and will discover them out to unprecedented redshifts compared to optical surveys. Additionally, we forecast rates of TDE detections in Roman, and find that we expect to detect $\mathcal{O}(10)$ TDEs per year at $2 < z < 5$ and $\mathcal{O}(1)$ TDEs per year at $z > 5$. We expect these high-redshift TDEs to appear hostless, and among the very few transients detectable at these high redshifts. Furthermore, if we co-add the 125 observations of the proposed High Latitude Time Domain Survey, it is possible to detect TDEs up to $z \sim 12$! We advocate for a deep, wide survey in F158 and F184, so that Roman can put constraints on black hole evolution.

1. INTRODUCTION

A tidal disruption event (TDE) occurs when a star passes too close to a supermassive black hole, and is torn apart by tidal forces. Around half of the stellar material is accreted, which produces an extremely luminous flare that lasts around a year (Rees 1988; Evans & Kochanek 1989). Because these transients are so bright ($10^{42.5}$–10^{45} erg s^{-1}), they are visible to cosmological distances, making them invaluable tools for studying otherwise dormant supermassive black holes in distant galaxies. Not only does a TDE provide a transient probe for a supermassive black hole lurking in the center of a galaxy, but it can also characterize the stellar population surrounding it (Gezari 2021). Our current sample of TDEs is still relatively small: to this date, we have spectroscopically confirmed ~ 100 TDEs Hammerstein et al. (2023); Gezari (2021); Gomez et al. (2023).

The origin of supermassive black holes (SMBHs) is relatively unknown; distinguishing between formation mechanisms requires observations of black holes in the early universe, which will be significantly progressed by the Laser Interferometer Space Antenna (LISA) in the next decade (Inayoshi et al. 2020). Observations of TDEs are among the very few ways that we can make direct electromagnetic detections of these early SMBHs to supplement the gravitational wave data. TDEs can indicate both the mass and spin of their central SMBH, so at higher redshifts are critical to understanding the seeds from which SMBHs form. However, to this date, no TDE has been detected at a redshift beyond 1.2 (Andreoni et al. 2022). The Nancy Grace Roman Space Telescope (hereafter Roman) mission will have the capability to change that dramatically. Because TDEs have a blackbody peak around 0.1 micron, at z $\sim$ 2 they become redshifted into the near-infrared, perfectly in the wavelength coverage of the Roman Wide Field Instrument (WFI). Furthermore, the sensitivity of the Roman WFI will allow Roman to probe a previously unparalleled volume, in which high-redshift TDEs can be detected.

The High Latitude Time Domain Survey (HLTDS) is one of the three Roman core community surveys (Rose et al. 2021). It is optimized for supernova cosmology to meet the Roman dark energy figure of merit, however it will be able to push science forward for many kinds of transients, including TDEs. Our primary goal for this white paper is to enable the detection of TDEs up to high redshifts through analyzing the parameters of the HLTDS. For these goals, we aim to maximize the number of TDEs discovered. We expect the HLTDS to operate with a similar strategy as outlined in Rose et al. (2021), with a wide tier, which is shallower but with greater area in the four bluest filters, and a deep tier which is deeper with less area in the four reddest filters.

In this work, we use a simple model of a TDE spectrum to simulate TDE observations in Roman up to high redshifts. We find that the filters used in the HLTDS are perfectly suited to get multi-band light curves of TDEs at redshifts beyond 2. Additionally, we use the observed TDE luminosity function to forecast rates of TDE detections in Roman, and find that we expect multiple detections of TDEs at $z > 5$ in F158 and F184. We expect these higher-redshift TDEs to appear hostless, as their host galaxies will have no signatures in the HLTDS. Given their high luminosities and restframe ultraviolet peaks, TDEs, superluminous supernovae, and pair-instability supernovae might be the only transients detected past $z = 5$. Furthermore, if we co-add the 125 observations of the HLTDS, it is possible to detect TDEs up to $z \sim 12$! The current HLTDS strategy uses the exact filters we need, and its exposure times provide us adequate depth. To achieve an expected $\mathcal{O}(1)$ TDE observed beyond redshift 10, we would require the HLTDS deep tier to extend its area to at least 10 deg^2.

2. TDE MAGNITUDES

In this analysis, we simulate the spectrum of a TDE at maximum brightess as a 3×10^4 K blackbody, with a luminosity distribution as observed by the Zwicky Transient Facility between $10^{42.5}$ and 10^{45} erg s^{-1} (Yao et al. 2023). We implement

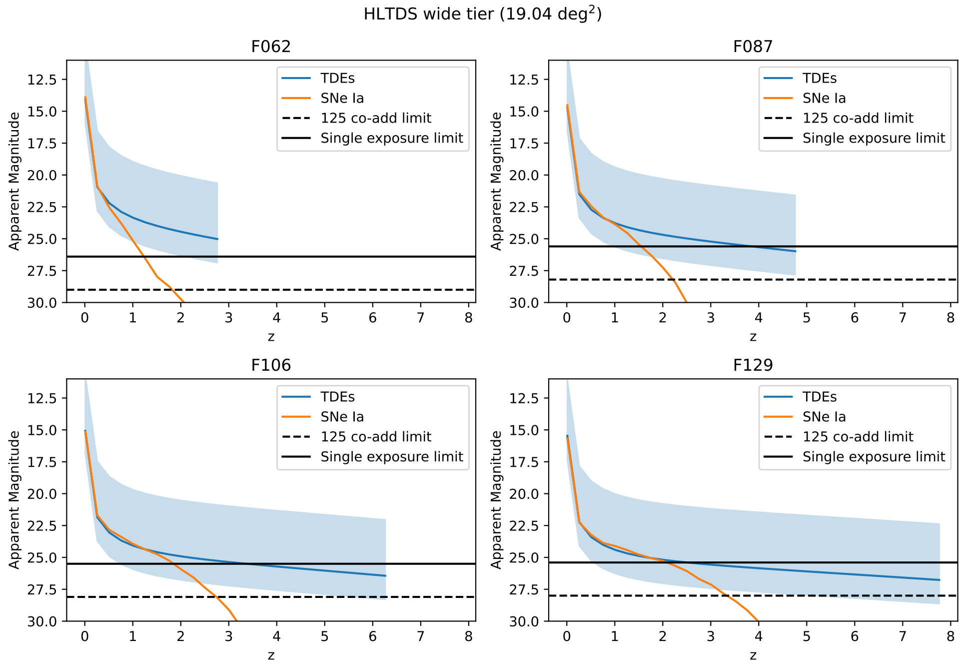

Figure 1. TDE apparent magnitudes as a function of redshift given the HLTDS wide tier filters. Shaded blue regions represent all possible TDE luminosities, while the dark blue line represents a typical $M_g = -19.5$ mag TDE. The lines end when Lyman alpha forest contamination will dominate the flux in that filter. In orange are expected magnitudes for typical Type Ia Supernovae. The black lines represent the HLTDS magnitude limits for single observations (solid line) and for co-added observations (dotted line).

this spectrum as a `Model` in the `SNCosmo` Python package (Barbary et al. 2016). Given this model, we redshift the TDE spectrum and perform synthetic photometry in the Roman band passes.

In Figures 1 and 2, we show the predicted range of TDE magnitudes visible in Roman for a given redshift, as well as the apparent magnitude of a typical TDE. Note that high-luminosity TDEs are significantly rarer than low-luminosity TDEs, so TDEs in the shaded region above the blue line will be uncommon. Therefore, we also include a line for a "typical" luminosity TDE, with $M_g = -19.5$ mag. We separate the magnitude limits into the HLTDS wide tier and deep tier, given their different exposure times. In the wide tier, most bands can observe typical TDEs until $z \sim 3$. F062 is slightly deeper and will be capable of observing the faintest TDEs, but gets cut off by Lyman alpha forest contamination at $z = 2.78$. In the deep tier, typical TDEs are visible until $z \sim 6$, and get fainter very slowly with redshift beyond that. Therefore, to observe the highest redshift TDEs, it is essential to maximize deep tier area.

TDEs are slowly evolving transients, and are time-dilated at high redshifts, so given the current 5-day cadence we expect to observe multi-color light curves for the vast majority of TDEs which meet our brightness criteria. Additionally, over the course of the 2-year HLTDS it will be feasible to co-add the 125 observations for TDE discovery.

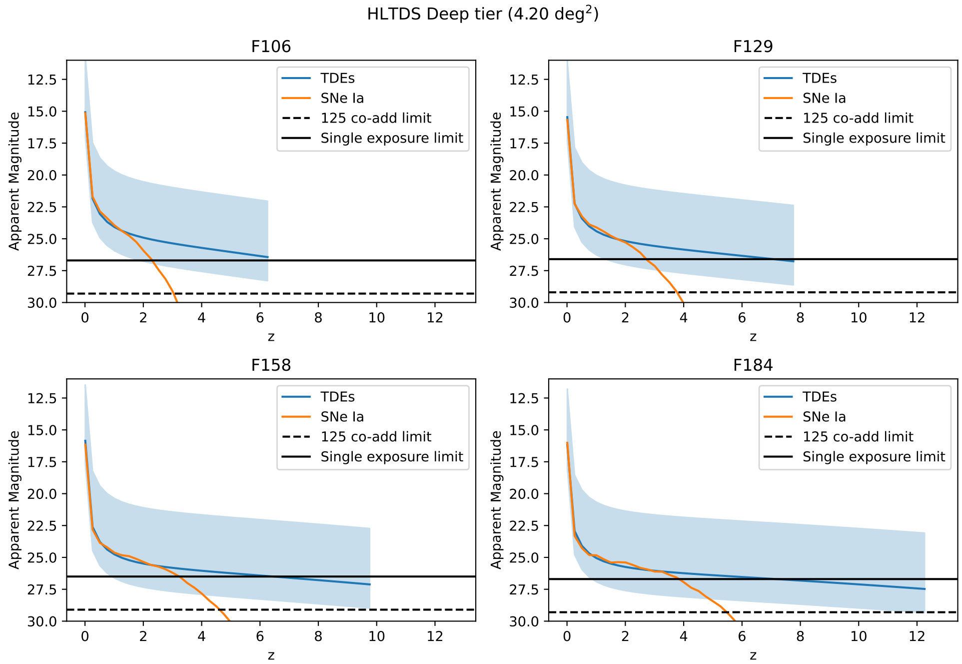

Figure 2. Same as Figure 1 but for the HLTDS deep tier.

In Figures 1 and 2 we also show the co-added magnitude limits. With these limits, Roman is in a unique position in which it could possibly detect TDEs at $z = 12$!

For comparison, we also calculate the apparent magnitude of Type Ia Supernovae (SNe Ia). To simulate these, we use an extended SALT2 spectral model with an absolute magnitude $M_g = -19.5$ mag (Guy et al. 2007; Kessler et al. 2009). Because the extended SALT2 model is only valid at rest-frame wavelengths longer than 1700 Å, we extrapolate to shorter wavelengths using a simple blackbody spectrum with a temperature of 5500 K. We can then see that the supernova is not visible in the Roman filters beyond $z \sim 3$. This indicates that at higher redshifts, TDEs will be some of the only transients visible, alongside superluminous and pair-instability supernovae! Furthermore, the host galaxies of TDEs are predominantly in the green valley, and are primarily post-starburst galaxies (French et al. 2020; Hammerstein et al. 2021). At higher redshifts, these galaxies will also not be visible in any of the Roman photometry, making TDEs appear as hostless transients.

3. TDE RATES

To estimate the rate of TDE observations, we utilize the double power-law TDE luminosity function fit in Yao et al. (2023). Here we assume the local TDE luminosity function at all redshifts; while black hole mass does increase with cosmic time, in optical TDE data there does not appear to be a strong relationship between TDE luminosity and black hole mass. In shells of increasing redshift, we calculate a local TDE rate. In each shell, we integrate over the luminosity function with limits set by the absolute magnitude of the faintest TDE visible at that redshift, and the limits

Table 1. TDE rates given HLTDS limits and area. The maximum redshift represents the redshift at which a typical $M_g = -19.5$ mag TDE will no longer be visible, either due to being too distant or due to Lyman forest contamination.

Filter	Magnitude Limit (mag)	Area deg^2	Rate (yr^{-1})	Rate ($z > 5$) (yr^{-1})	Maximum Redshift
F062 (wide)	26.4	19.04	40.5	0.0	2.78
F087 (wide)	25.6	19.04	30.0	0.0	5.00
F106 (wide)	25.5	19.04	23.3	0.18	6.32
F129 (wide)	25.4	19.04	16.4	0.18	7.96
F106 (deep)	26.7	4.20	11.7	0.41	6.32
F129 (deep)	26.6	4.20	10.0	0.48	7.96
F158 (deep)	26.5	4.20	7.8	0.39	9.94
F184 (deep)	26.7	4.20	7.6	0.50	12.32

of observed TDE luminosities. The results of this calculation is shown in Figure 3. We then sum over these shells to determine the total yearly rate of TDEs in Roman, which is displayed in Figure 4, and is quantified in Table 1. These rates roughly agree with the estimates made in Gomez et al. (2023).

In the wide tier, it can be seen in Figure 3 that the vast majority of TDE detections will be between $z \sim 1$ and $z \sim 3$. The F062 band sees significantly more detections than any other band in this tier because it can detect the faintest TDEs, but they drop off steeply at $z = 2.7$ due to Lyman alpha absorption. In the deep tier, we see much longer tails in Figure 4 from detections at higher redshift, however fewer overall TDEs due to the much smaller area being observed.

In Table 1, we also summarize the rate of TDEs at redshifts beyond $z = 5$. Given the current parameters of the HLTDS, we expect ~ 0.5 TDEs per year at these high redshifts. As seen in the bottom panel of Figure 4, we may be able to detect more high-redshift TDEs using total survey co-adds. To maximize our chances of observing at least $\mathcal{O}(1)$ high-redshift TDE in the HLTDS, we suggest doubling the area of the deep tier to 10 deg^2 or greater. Additionally, this would allow us to maximize our chances of observing a $z > 10$ TDE by co-adding.

We experiment with adding the F213 band, and give it the same 300 sec exposure time as the F184 band. TDEs at higher redshifts should be brightest in F213, because it is at the closest wavelength to their redshifted blackbody peak. However, we find that it is significantly shallower than the other bands, with a magnitude limit of 25.4 mag, and would need a significantly longer exposure time to detect deeper TDEs that F184 can.

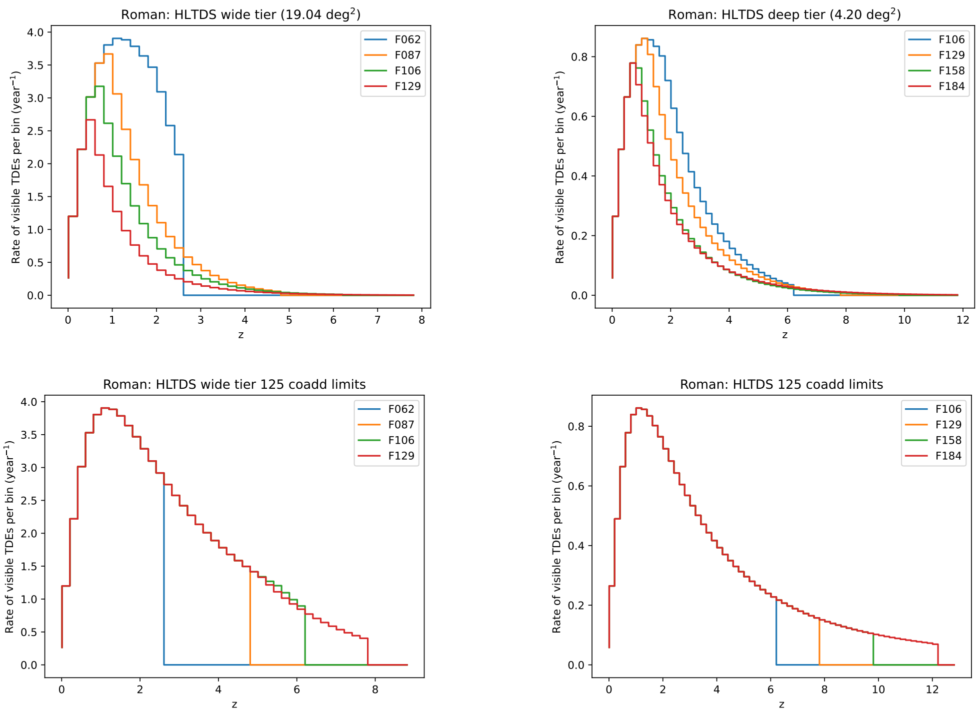

Figure 3. Distribution of TDE observations per year, binned in redshift shells of 0.25. Wide-tier observations in 19.04 deg^2 are on the left, and deep-tier observations in 4.20 deg^2 are on the right. The top row assumes single-detection magnitude limits, and the bottom row assumed co-added magnitude limits.

4. CONCLUSIONS

The Roman time-domain community survey has the opportunity to use TDEs make a primary constraint on the distribution of black hole masses over cosmic time. In order to do this, Roman could detect multi-band light curves of TDEs at unprecedented redshifts. These would complement the binary black hole mergers that will be detected by LISA in the next decade, providing electromagnetic measurements of black holes in the same redshift range: $2 < z < 7$ (Mangiagli et al. 2022).

The figure of merit in our science case is the number of TDEs detected in Roman. In order to get at least $\mathcal{O}(1)$ light curve for a TDE at $z > 5$ per year, Roman should expand the HLTDS deep tier to at least 10 deg^2. This will also allow us to co-add observations to detect at least one very slowly-evolving TDE at $z > 10$. The rate of TDEs observed per year scales linearly with survey area. The rate will increase in the reddest bands, F184 and F213, with survey depth but not significantly. However, it will decrease dramatically if survey depth is reduced. With our suggested requirements, even a non-detection of a very high-redshsift TDE will be revealing about the high-redshift universe.

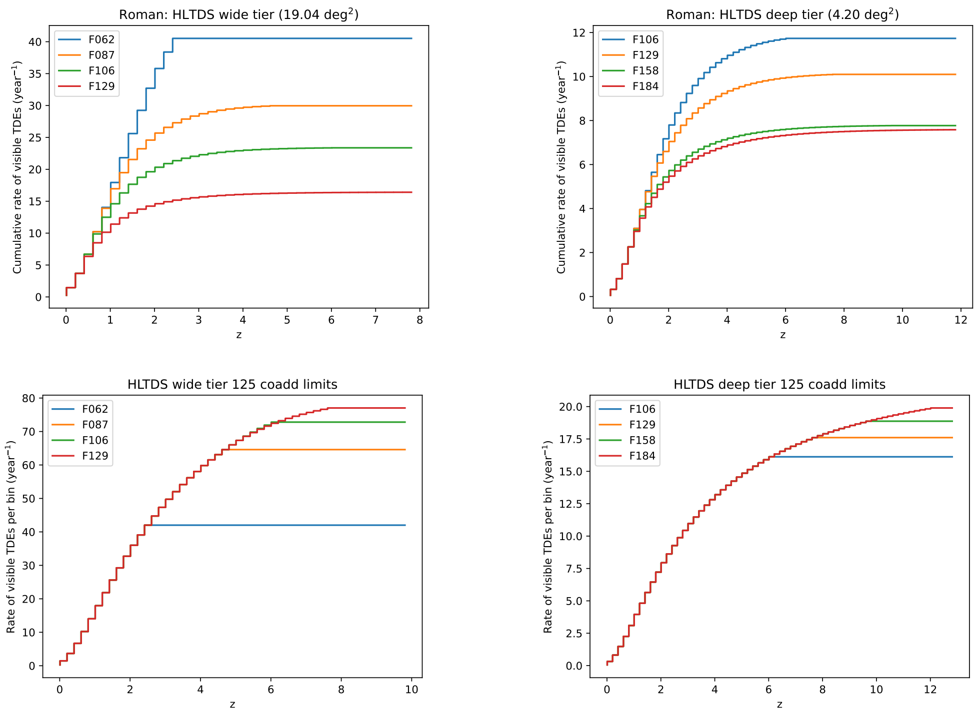

Figure 4. Total rate TDE observations per year. Wide-tier observations in 19.04 deg^2 are on the left, and deep-tier observations in 4.20 deg^2 are on the right. The top row assumes single-detection magnitude limits, and the bottom row assumed co-added magnitude limits.

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