Using Supernovae to find faint galaxies in the High Latitude Time Domain Survey: An Appeal to "save the pixels" After a Supernova

Roman Core Community Survey Category: *High Latitude Wide Area Survey (Imaging)*

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ABSTRACT

The Nancy Grace Roman Space Telescope (Roman) , scheduled for launch in late 2026, will revolutionize our knowledge of cosmology. In particular, the High Latitude Time Domain Survey (HLTDS) is designed to observe approximately 1500 supernovae per year at redshifts as high as $z = 0.2$. A significant fraction will be in faint galaxies which lie below the knee of the Schechter galaxy luminosity function (LF), providing critical information about the evolution of the most numerous galaxies in the cosmic web. However, because of their low luminosities they are almost impossible to find outside of targeted surveys, and, at present, the shape of the LF is poorly constrained below an absolute magnitude $M_R \approx -17$ at even the very lowest redshifts. Roman offers two unprecedented pathways to detecting these critical galaxies. The most straightforward is via the High Latitude Wide Area Survey (HLWAS), which will reach $m_R > 26$ and detect galaxies at $M_R \approx -17$ (i.e., SMC) at $z = 0.65$ and at $M_R \approx -12$ (i.e., Draco), to $z = 0.2$. However, for galaxies below these detection limits the incredible number of supernovae in HLTDS provide a second avenue for discovery. By following up the $\sim 5-10\%$ of supernovae that are apparently hostless in transient surveys such as PTF and ASSA-SN, we have found a significant number of faint galaxies at this end of the LF. We propose that the HLTDS retain all pixels within 5 arcsec of all supernovae for a period of two years after the event. This will enable a much more sensitive search for faint galaxies. Galaxies at $M_R \approx -17$ will be found at $z = 2$, and galaxies at $M_R \approx -12$ will be found at redshifts as high as $z = 0.5$. This will provide the community with an unprecedented data set of galaxies back to cosmic noon which is sensitive both to star-forming and passive galaxies.

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1. SCIENTIFIC JUSTIFICATION AND IMPACT

Until recently, large-area optical surveys such as the ESO Digitized Sky Survey and early releases of the Sloan Digital Sky Survey have probed large volumes, but only to shallow depths, making it nearly impossible to study the spatial density galaxies fainter than the SMC. The ratio of stellar mass/dark matter mass indicates that there are a large number of small, low-z dwarf galaxies with dark matter masses $< 10^{10} M_\odot$ at a spatial density of at least 10^{-2} Mpc^{-3} (Loveday 1997), forming the overwhelming majority of the constituents of the cosmic web (e.g., (Benítez-Llambay et al. 2013; Bacon et al. 2021), which may be fractal in nature (Einasto et al. 2020). However only a fraction of these faint, largely dwarf, galaxies, $M_V > -14$, have been detected to date, largely in targeted surveys of the environments of more massive galaxies (e.g. SCABS (Taylor et al. 2017) & PISCES (Crnojević et al. 2019)).

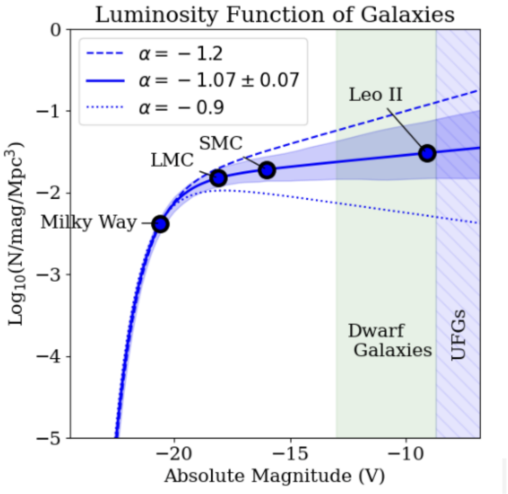

Figure 1. A plot of galaxy number density vs. their absolute magnitude, identifying the cutoffs for dwarf galaxies and ultra-faint galaxies. The poorly constrained value of α leads to an uncertainty in the low luminosity regime by a factor of several magnitudes.

Typical galaxy luminosity functions (LFs) are well represented by the Schechter function – a combination of an exponential at high luminosities and a power law at low luminosities, with the Milky Way sitting very close to the "knee" between the two ends. However, the intrinsic difficulties in the detection of dwarf galaxies limits our ability to constrain the slope of the low-luminosity power law. These difficulties include not only the intrinsic faintness, but their low surface brightnesses as well.

Detection of these faintest galaxies should be nearly impossible outside of targeted surveys, however, we have an assist from some of the most energetic events in the Universe, supernovae (SNe). While various types of SNe are detectable billions of parsecs out, the galaxies which host the explosions may be too faint for detection by current surveys. It is these "hostless supernovae" which provide the critical assist to observe dwarf galaxies back to Cosmic Noon, serving as a marker for the galaxy that hosted the star which exploded.

Dwarf galaxies have non-negligible star formation rates, on the order of $10^{-4} - 10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$, (Annibali & Tosi 2022) and hence should have a non-negligible SNe rate. Until fairly recently, only a few SNe have been discovered in faint host galaxies as those galaxies have been well below the detection thresholds of their originating surveys. However, as we will discuss in §3, surveys such as PanSTARRS and ASAS-SN are now routinely locating hostless supernovae.

2. THE PROPOSAL: SAVE THE PIXELS

Here we propose a tweak to the design of the High Latitude Time Domain Survey (HLTDS) of the Nancy Grace Roman Space Telescope (Roman). Specifically, that the Roman archive include all pixels within 5″ of any supernova, for two years after the event. This is *not* a change in the design of the HLTDS, merely in how the data are archived. The proof of concept for this proposal is given in §3. Our proposal will help Roman identify the critically important host galaxies of supernovae in dwarf galaxies.

The HLTDS is expected to be sensitive to a depth of $m \approx 26$ (depending on the band) given an exposure of 100-160 seconds, typical of the Wide Tier (Rose et al. 2021). Individual, short exposures will be used to discover supernovae and track their lightcurves. Co-addition of 125 images will give a detection limit of $m \approx 29$ (again, depending on band). Each field is already being observed many times, so as long as provision to save the pixels within $5''$ of any supernova, Roman can seamlessly find these dwarf hosts. Supernovae serve as a marker in otherwise empty regions of space; an indication that something underlying, yet invisible, served as the source of the supernova. We have a unique opportunity with Roman to solve these mysteries, and for the first time gain an appreciation of the structure and prevalence of faint mid-z galaxies.

In addition, our proposal is straightforward for any upcoming transient survey. The Vera Rubin Observatory's LSST will also be able to do such a survey, although it is difficult to accurately estimate the quantity of hostless supernovae Rubin will discover, Rubin would be able to use a similar strategy to discover the dwarf host galaxies for those events. Roman allows a similar project to be done over a smaller area but to much greater depth. The HLTDS will find up to 1500 supernovae per year at $z < 2$, most of which will be at or near the limit of the survey. A significant amount of the host galaxies of these supernovae will only be detectable through stacking of the images taken a year or more after discovery of the event. Our proposal allows both for a high fidelity lightcurve of the supernova as well as stacking of the images from the second year to find the faint, dwarf galaxy hosts.

3. FINDING THE HOSTS OF THE HOSTLESS

Our team began a reconnaissance and recovery campaign to discover the host galaxies of apparently hostless supernovae and determine the supernova rates of the population. Using the ASAS-SN and PanSTARRS databases, we manually selected supernovae that appeared to lack a visible host. Our work was prompted by that of Smith et al. (2012) and Quimby et al. (2012), who attempted to find the supernova rate from dwarf galaxies using surveys that were not very sensitive to dwarfs, and Conroy & Bullock (2015), who built upon that rate as well as up to date estimates of dwarf galaxy number counts to predict that supernovae be used as signposts for dwarf galaxies in the Rubin LSST.

Seventeen supernovae were selected in this way, out of approximately 300 inspected. Our campaign used the RCT 1.3-m and the JKT 1-m for shallow reconnaissance ($m_R < 20$, to greater than 5σ) and in 2015-2018 used the APO 3.5-m and SOAR 4.2m for deeper reconnaissance ($m_R < 23.5$). A few galaxies were selected for deeper imaging with Gemini-N; however, the data gathered were basically unusable due to poor weather and volcanic dust. Our sample of targets have $0.01 \leq z \geq 0.2$, with an average $z \approx 0.05$. This work led to the identification of faint hosts for these objects. An example of this work is shown in Figure 2, which shows the archival, discovery and APO image of PS-15bhh ($z = 0.15$), with the APO image having been acquired more than 1.5 years after the supernova. As can be seen, only when all APO imaging of PS-15bhh is stacked does one see an extremely faint host galaxy, with absolute magnitude $M_R = -16.2$. Our APO and SOAR imaging identified 15 host galaxies for these 17 objects. The hosts range in magnitude between -10.6 and -19, but the majority are between -13 and -16, as shown in Figure 3.

Motivated by these results, which form the basis of an in-progress PhD thesis, it is elementary to project that a non-negligible fraction of the supernovae found in any transient survey will have host

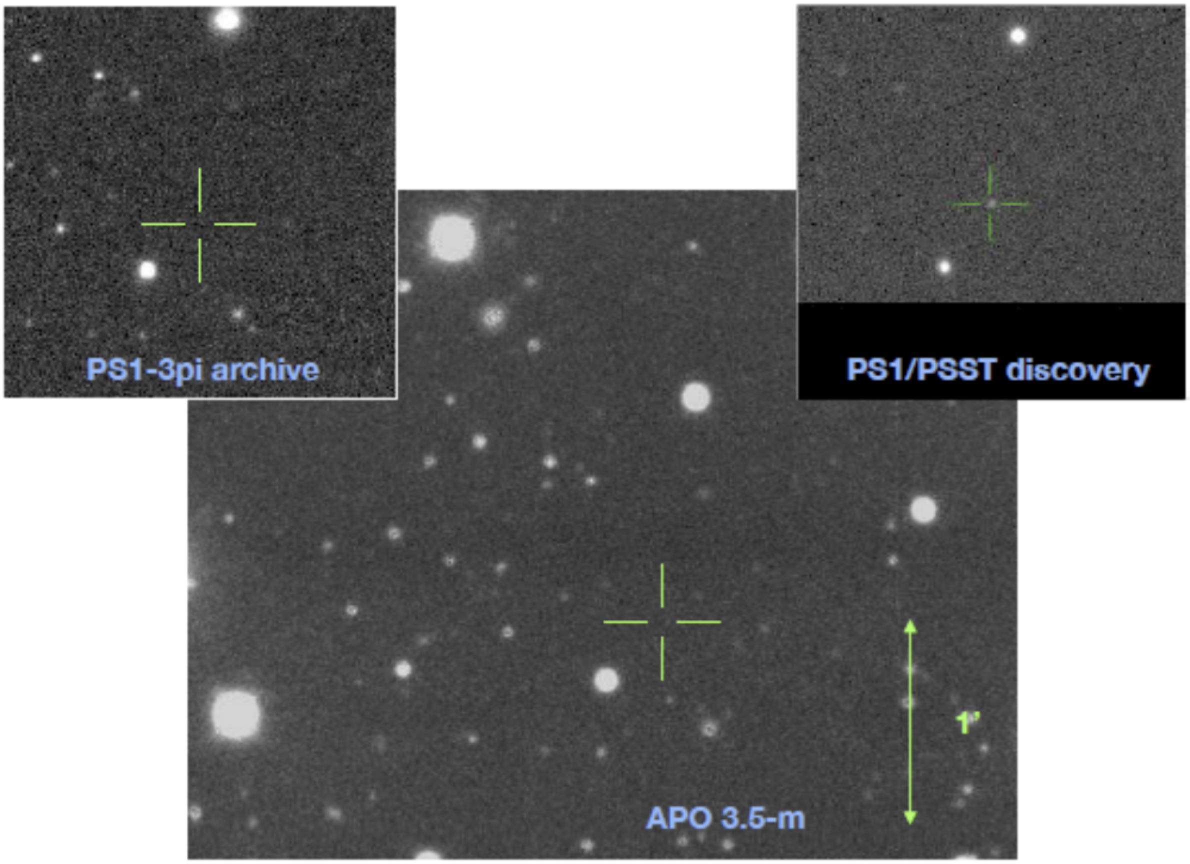

Figure 2. The archival, discovery, and APO stacked observations of PS 15bhh, the most distant supernova selected at z=0.15. Note the faint presence of the host in only the APO stack, yet is otherwise absent in the archival image. The absolute magnitude of the galaxy we find is -16.2.

galaxies that not only were previously unknown but also would have galaxies fainter the survey's detection limit. Projecting forwards, it is elementary to show that the majority of supernovae found in the HLTDS will be found in the faintest magnitude bins. A non-negligible fraction of those will have host galaxies too faint to see in individual HLTDS images. Even in the Deep Tier, individual observations will only include galaxies at $M_R \geq -17$ (comparable to the SMC) at $z = 0.65$, and the faintest galaxies, at $M_R \geq -12$, will only be found out to $z = 0.2$.

The host galaxies of these supernovae will only be revealed when one combines images taken after the supernova has faded. The HLTDS design study (Rose et al. 2021) quotes a typical depth of $m_R \approx 29$ for stacking 125 images, but it is not yet clear exactly how many observations will be done in 2 years. However, if we make the assumption of an image every 2 days, and assume that the supernova is visible for several months, we can roughly estimate that with this proposal there will be ~ 200 such images to stack, thus resulting in a likely detection limit of $m \approx 30$ for the galaxies. Figure 4 shows the galaxies that one would find and their respective redshifts, assuming that the galaxies uniformly fill space according to the Schechter function with $\alpha = -1.1$ and fall above the magnitude limit of $m_R = 29.4$ for 125 stacked images in the Wide Tier, and also assuming that the galaxies would have supernova rates according to their SNe. [1]

Using supernovae as lighthouses to detect this important dwarf galaxy population will allow for significant additional information over and above what the HLWAS will give for three reasons: first, the vast majority of dwarf galaxies known now are in clusters or rich groups, whereas the sample of galaxies that host supernovae will be unbiased towards cluster environment. Moreover, as Roman will find both core-collapse and white dwarf supernovae, different stellar populations will be probed. The HLWAS will be fairly insensitive to whether a dwarf galaxy is star forming, as Roman is an infrared telescope. However, core-collapse supernovae require star forming galaxies, and white dwarf supernovae favor galaxies where star formation happened at most 1 Gyr previous. And finally, the population of dwarf galaxies where supernovae are produced includes objects of all morphological types (Sedgwick et al. 2021) so that information will be difficult to extract from the HLWAS.

A circle of 5" (~ 40 kpc at $z \sim 1$) around each supernova is important, as many supernovae occur far from the center of their host galaxy. Moreover, one of the large uncertainties in the detection and characterization of dwarf galaxies has always been the low surface brightness (LSB) population, which form the large majority of dwarf galaxies (e.g., Jackson et al. (2021)) and could be a major component of the missing galactic satellite population (Bovill & Ricotti 2009). Supernovae in LSB galaxies are already being found with some regularity – examples are SN1964H in NGC 7292, SN 2009Z (Zinn et al. 2012) and SN2016ije (Li et al. 2023), and it is very possible that a significant fraction of the supernovae found by the HLTDS will be in LSB dwarf galaxies. For example, (Sedgwick et al. 2019) matched 2400 supernovae from the SDSS-II Supernova Survey to host galaxies using legacy co-added imaging of the Stripe 82 field. Using a subsample of 900 core-collapse supernovae, they found that the star-forming galaxy number counts required a faint-end LF slope of $\alpha = -1.41$, and about 150 (1/6 of their sample) were previously unidentified LSB galaxies. This result is very different from more typically adopted values around $\alpha = -1.1$, underlining the importance of having multiple approaches to finding dwarf galaxies.

We forsee significant additional impact as well. Dwarf galaxies form the majority of the nodes of the cosmic web, which demarcates the mass distribution in the universe and is predicted by structure formation models (Genel et al. 2014; Somerville & Davé 2015; Primack 2015; Hernández-Aguayo et al. 2022). Additionally, the evolution of the galaxy LF in various environments as a function of redshift is extremely topical (e.g., (Capozzi et al. 2017)), yet the LF's evolution in the dwarf regime is almost completely unknown (Simon 2019). Finally, this will allow the first real progress to be made on this question, which could help reveal how dwarf galaxies evolve and quench, not just near massive host galaxies, but in the field as well. Dwarf galaxies will also be the majority population of star forming galaxies at cosmic noon (Förster Schreiber & Wuyts 2020), and so uncovering them at those redshifts will give us important new tools to learn about the evolution of star formation and galaxy properties as a function of cosmic time.

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[1] Note that the projected redshift distributions for supernovae from the Wide and Deep Tiers (Rose et al. 2021) are significantly different because they fold in supernova magnitudes.

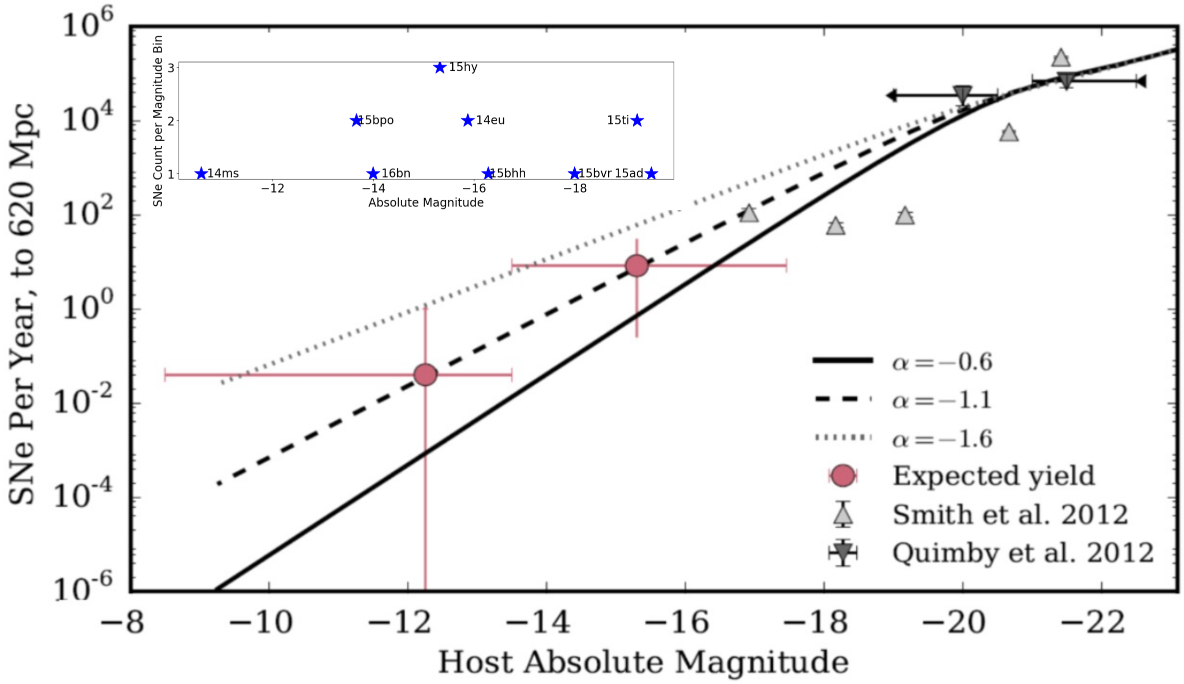

Figure 3. The number of supernovae seen per year out to a distance of 620 Mpc, or a redshift $z = 0.13$. The curves predict that supernovae will be found in the galaxies according to the prescription of Conroy & Bullock (2015). We then fill galaxies into the volume according to the Schechter function, using slopes of $\alpha = -0.6, -1.1, -1.6$ for the faint end of the LF. Previous works (Smith et al. 2012; Quimby et al. 2012) only used very shallow surveys based on small telescopes, which were insensitive to much fainter dwarfs. The "Expected yield" points assume that all supernovae out to that volume will be detected, which given the detection limits of the 3Pi and ASAS-SN transient surveys is not correct, particularly for type II SNe. The inset plot at top shows the supernova host galaxies we found in our APO program. As can be seen, most of those are in a range of absolute magnitudes not before surveyed.

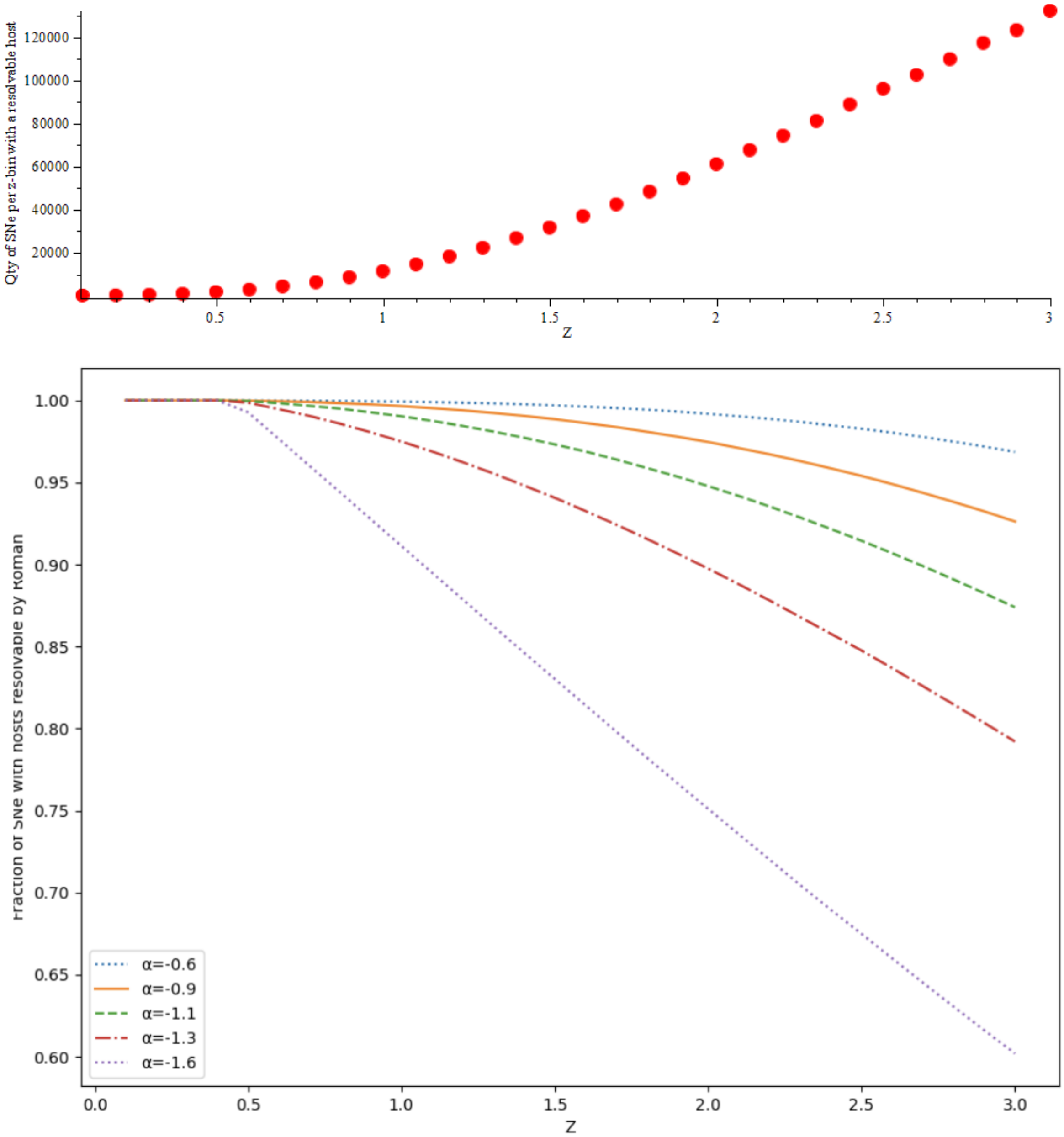

Figure 4. *Top*: Number of resolvable SNe hosts per z-bin. Each bin has a width of $z = 0.1$, extending from $z = 0.03$, and measured is the expected quantity of supernovae within the z-bin range, multiplied by the fraction of galaxies fainter than $m = 29$, as weighed by total luminosity. We use a slope $\alpha = -1.1$ and an (arbitrary) upper limit of 10 L_* for the LF, and assumes that all SNe are detected out to $z = 3$, and a uniform spatial distribution. *Bottom*: Fraction of SN hosts detected, as a function of redshift. The assumptions are the same as for the top panel of this figure, and are plotted with varying LF slope. The missing host galaxies are all at the faint end of the galaxy LF.

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