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A Uniform Type Ia Supernova Distance Ladder with the Zwicky Transient Facility: Absolute Calibration Based on the Tip of the Red Giant Branch (TRGB) Method

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ABSTRACT

The current Cepheid distance ladder measurement of H_0 is reported to be in tension with the values inferred from the cosmic microwave background (CMB), assuming standard model cosmology. However, the tip of the red giant branch (TRGB) reports an estimate of H_0 in better agreement with the CMB. Hence, it is critical to reduce systematic uncertainties in local measurements to understand the origin of the Hubble tension. In this paper, we propose a uniform distance ladder, combining SNe Ia observed by the Zwicky Transient Facility (ZTF) with a TRGB calibration of their absolute luminosity. A large, volume-limited, sample of both calibrator and Hubble flow SNe Ia from the *same* survey minimizes two of the largest sources of systematics: host-galaxy bias and non-uniform photometric calibration. We present results from a pilot study using existing TRGB distance to the host galaxy of ZTF SN Ia SN 2021rhu (aka ZTF21abiuvdk). Combining the ZTF calibrator with a volume-limited sample from the first data release of ZTF Hubble flow SNe Ia, we infer $H_0 = XX \pm 6.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, an 8.3% measurement. The error budget is dominated by the single calibrator SN in this pilot study. However, the ZTF sample includes already five other SNe Ia within ~ 20 Mpc for which TRGB distances can be obtained with HST. Finally, we present the prospects of building this distance ladder out to 80 Mpc with JWST observations of more than one hundred SNe Ia.

Keywords: cosmology: observations - supernovae

1. INTRODUCTION

Over the last decade, remarkable increase in accuracy obtained by a broad range of independent cosmological observations has provided compelling support for our current standard Λ cold dark matter (ΛCDM) model. This concordance cosmology successfully explains the measurements of fluctuations in the temperature and polarization of the cosmic microwave background (CMB) radiation (Planck Collaboration 2020) as well as observations of large-scale structure and matter fluctuations in the universe, e.g. baryon acoustic oscillations (BAO; Macaulay et al. 2019).

With improved accuracy of recent observations some discrepancies have been noted. The *prima facie* most significant tension is between the CMB inferred value of the Hubble constant (H_0) and the direct measurement of the local value of H_0 (Riess et al. 2021). The local measurements are based on a calibration of the absolute luminosity of Type Ia supernovae (SNe Ia) using independent distances to host galaxies of nearby SNe Ia, known

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as the "cosmic distance ladder". This claimed tension, if confirmed, it could provide evidence for of new fundamental physics beyond the standard model of cosmology. It could, however, be a sign of unknown sources of systematic error. Currently, the local H_0 methods have slight differences in their values. The tip of the red giant branch (TRGB; Freedman 2021) and Cepheid (Riess et al. 2021) distance scales yield values of 69.8 ± 1.7 and 73.04 ± 1.04 kms^{-1}Mpc^{-1}, respectively. Understanding these differences is important to discerning whether the tension is a sign of novel physics or a yet-to-be-revealed systematic error. To date, only the TRGB and Cepheid measurements have measured distances to $\mathcal{O}(10)$ host galaxies of SNe Ia.

Circumventing the two largest, known sources of systematic error is key to achieving the percent level precision in the local distance scale and resolving the Hubble tension. Firstly, Cepheid variables strongly prefer young, star-forming environments. This has been shown to bias the inferred SN Ia luminosity, and hence H_0 (Rigault et al. 2020), though the size of this effect is currently debated (Jones et al. 2018). While the current Cepheid distance ladder addresses this issue by evaluating H_0 from only the Hubble flow SNe Ia in low stellar mass hosts, it is important to measure H_0 using a volume-limited calibrator and Hubble flow sample of SNe Ia in all types of host galaxies, given the profound cosmological implications of the Hubble tension. TRGBs, unlike Cepheid variables, are found in both old and young environments, hence, can probe SN Ia host galaxies of all morphological types in a given volume. The TRGB is a well-understood standard candle, arising from the core helium flash luminosity at the end phase of red giant branch (RGB) evolution for low-mass stars (Freedman et al. 2019; Jang et al. 2021; Freedman 2021). Furthermore, TRGB stars, found in the outskirts of galaxies, are less prone than Cepheids to biases from crowding, and are also comparatively less sensitive to reddening systematics, a potential contribution to the Cepheid H_0 measurements (e.g., Mortsell et al. 2021).

Secondly, the current sample of SNe Ia for H_0 measurements is derived from several (> 20) different combinations of telescopes, instruments and filters (e.g. Scolnic et al. 2021; Riess et al. 2021). Although there have been significant efforts to cross-calibrate the heterogeneous systems (Brout et al. 2021), there are irreducible uncertainties associated with the data where the filters, instruments and *even telescopes* no longer exist. In light of these outstanding sources of error, it is imperative to have a volume limited sample of calibrator and Hubble flow SNe Ia observed with the *same* instrument.

Addressing these issues, here, we present a uniform distance ladder, with both calibrator and Hubble flow SNe Ia observed by the Zwicky Transient Facility (ZTF; Bellm et al. 2019; Graham et al. 2019), calibrated based on the TRGB method. As both calibrator and Hubble flow rungs of the distance ladder with the same instrument, we only rely on a relative photometric calibration, which is a significantly simpler task than controlling the absolute calibration of an SN Ia sample. In this pilot study, we present ZTF calibrator SNe Ia within a nearby volume of $D_L < 20$ Mpc and measure preliminary distances, where possible, for those SNe Ia using tip of the red giant branch. In the long term, we need, assuming the current number of primary anchors, a ZTF calibrator sample of ~ 100 SNe Ia to get to $\sim 1\%$ precision and accuracy on H_0 to resolve the tension. With the James Webb Space Telescope (JWST) scheduled to start taking data in mid-2022, we can feasibly extend the calibrator rung to $D_L \sim 80$ Mpc. ZTF has already observed well-sampled light curves for more than one hundred SNe Ia in this distance range. Therefore, within the $D_L \leq 80$ Mpc volume we will no longer be limited by the rate of SNe Ia in galaxies to obtain calibrator distances, currently a limiting factor for the largest calibrator sample (Riess et al. 2021).

2. DATA AND METHODOLOGY

We present the data for SNe Ia observed by ZTF in a $D_L < 20$ Mpc volume, which also have a robust reported TRGB distances. While 5 SNe Ia have adequate light curve sampling to get precise peak magnitudes, shape and colour parameters from SNe Ia, only one of them, ZTF21abiuvdk (aka SN 2021rhu) has observations of the host galaxy to get an accurate distance.

SN 2021rhu exploded in NGC 7814, at coordinates, $\alpha = 0.8143, \delta = 16.1457$, classified as an SN Ia on the Transient Name Server (TNS; Munoz-Arancibia et al. 2021; SNIascore 2021). We obtained photometry with a 1-day cadence for SN 2021rhu with ZTF, in the g, r, i filters between -14.1 and $+172.5$ days. These observations begin on July 1.404 2021 UTC. Hence, we obtained a densely sampled light curve with the ZTF observing system (Dekany et al. 2020), in multiple filters with the same system as the Hubble flow sample (as presented in Dhawan et al. 2022). The images were processed with the pipeline as detailed in Masci et al. (2019). The lightcurve, thus far, spans a large phase range from July 1.4 to November 11.11 2021. We have also obtained a well-sampled spectral time series, beginning with a classification spectrum with the SEDmachine (Blagorodnova et al. 2018; Rigault et al. 2019) on 2021-07-05. These are presented in detail in a com-

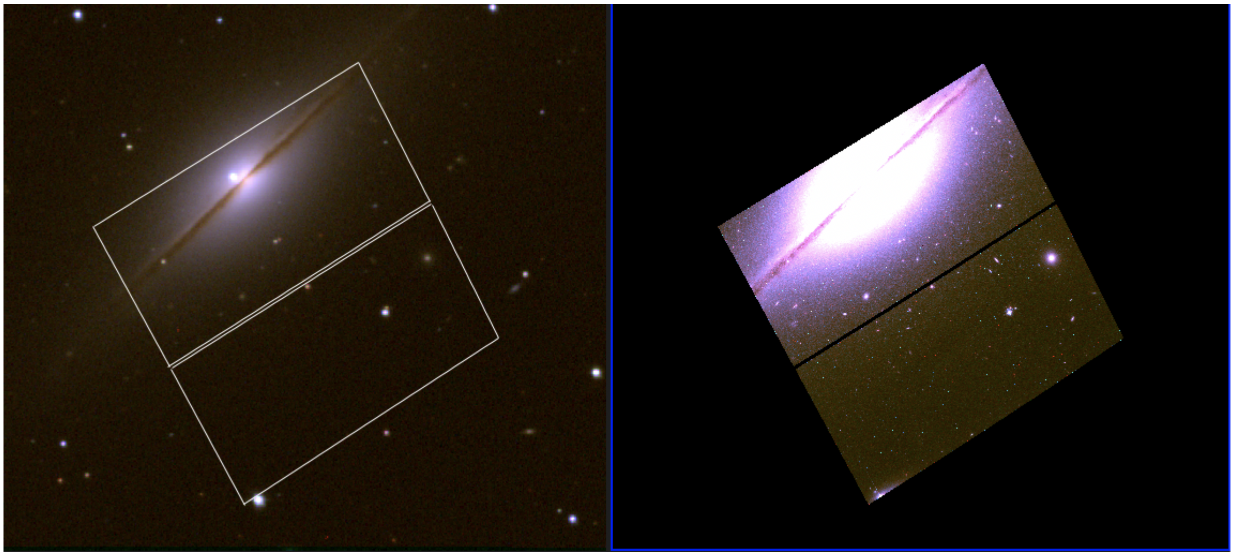

Figure 1. (Left) A combined red-green-blue image of SN 2021rhu from the ZTF data with one of the HST fields for the TRGB distance overplotted. (Right) A zoom in into the HST data of the host galaxy NGC 7814 Field 01 in the F606W filter with ACS.

panion paper (Harvey et al. in prep). Figure 2 shows a maximum-light spectrum obtained with the SPectrograph for the Rapid Acquisition of Transients (SPRAT; Piascik et al. 2014) on the Liverpool Telescope (LT; Steele et al. 2004).

SNe Ia distances are inferred from light curve peak luminosity, shape and colour. The most widely used lightcurve fitting algorithm, which we adopt for our analysis, is the Spectral Adaptive Lightcurve Template - 2 (SALT2; Guy et al. 2007). This model treats the colour entirely empirically, without distinguishing the intrinsic and extrinsic components. We use the most updated, published version of SALT2 (SALT2.4, see Guy et al. 2010; Betoule et al. 2014) as implemented in `sncosmo` v2.1.0[1] (Barbary et al. 2016), identical to the lightcurve inference of the Hubble flow sample in Dhawan et al. (2022). In the fitting procedure, we correct the SN fluxes for extinction due to dust in the Milky Way (MW). Extinction values for the SN coordinates derived in Schlafly & Finkbeiner (2011) were applied, using the galactic reddening law proposed in Cardelli et al. (1989), with a total-to-selective absorption ratio, $R_V = 3.1$, the canonical MW value.

2.1. *TRGB distance estimate*

NGC 7814 was observed with the Advanced Camera for Surveys (ACS) on HST covering a total of seven fields as part of the GHOSTS survey (Radburn-Smith et al. 2011). Here, we reanalyse the data using a pipeline by the Carnegie-Chicago Hubble (CCHP; Freedman et al. 2019) program which implements its own point-spread function (PSF) fitting photometry based on DOLPHOT (Dolphin 2000) modeling synthetic PSFs with TinyTim (Krist et al. 2011). The details of the pipeline can be found in Jang et al. (2021). We select fields 3,4,5 from the entire dataset since fields 1 and 2 are close to disk of the galaxy and hence, susceptible to high crowding and extinction, whereas fields 6 and 7 are very sparse and hence, it is difficult to identify the TRGB. We perform artificial star tests by injecting 180,000 stars into the FLC images and recover them using DOLPHOT. The artificial stars have a similar colours range to blue RGB stars of $0.6 < F606W - F814W \leq 1.6$. We populate stars within a brightness range of $25 < F814W \leq 29$ mag. To mimic the observed spatial distribution and luminosity function (LF), we place more stars in the inner region of the galaxy. The LF was binned with a width of 0.01 mag and smoothed with a Gaussian kernel of 0.1 mag. The edge detection is derived from the first derivative of the scale smoothed LF (see Hatt et al. 2017, for details). We find a Milky Way extinction corrected tip at $F814W_{\rm TRGB} = 26.81 \pm 0.054$ mag. Details of the tests, the impact of assumptions on the various components of the pipeline and consistency with distances reported in the literature are presented in a companion paper (Jang 2022 in prep). Using the absolute calibration of the TRGB magnitude from multiple primary as reported in Freedman (2021), $M^{\rm TRGB}_{\rm F814W} = -4.049 \pm 0.038$ (see also, Li et al. 2022, for a new calibration from the Milky Way) and we obtain a distance of $\mu = 30.86 \pm 0.07$ mag.

[1] https://sncosmo.readthedocs.io/en/v2.1.x/

We combine the calibrator data with the ZTF DR1 Hubble flow sample (Dhawan et al. 2022). TRGB stars are found in all types of SN Ia host galaxies and therefore, the TRGB-calibrated sample will be volume limited. To have a completely volume-limited distance ladder, we also only fit the volume-limited Hubble flow sample from ZTF DR1. We conservatively take the sample to be complete to $z \leq 0.06$. This selection cut reduces the Hubble flow sample from 200 to 98 SNe Ia.

3. RESULTS

We fit the SALT2 light-curve model to the calibrator SN and get the peak luminosity, light-curve width and colour. We note that since SALT2 is not well defined at wavelengths redder than 7000 Å, we only fit the g and r filters (e.g. Jones et al. 2019). SN 2021rhu has SALT2 parameters $m_B = 12.22 \pm 0.033$, light-curve shape $x_1 = -2.074 \pm 0.025$, and colour, $c = 0.054 \pm 0.028$. While the x_1 and c are within the range of typical cosmological cuts, it has a low x_1 value which is also seen in peculiar, fast-declining SNe Ia. However, the light curves of SN 2021rhu show a clear shoulder in the r band and a second peak in the i band (Figure 2), characteristic of normal and transitional SNe Ia used for cosmology (Hsiao et al. 2015). We also compute the colour-stretch parameter, s_{BV}, with the `SNooPY` method, since it is shown to be better at parametrising the fast declining SNe Ia (Burns et al. 2014). We find $s_{\rm BV} = 0.72$ consistent with normal/transitional SNe Ia, appropriate to use for cosmology (Burns et al. 2018). It is also spectroscopically similar to transitional SNe Ia like SN 2011iv (Foley et al. 2012), which have been used for estimating H_0 (Freedman et al. 2019), thus, this object is consistent with the cosmological sample of SNe Ia.

Here, we present the formalism for inferring H_0. The absolute magnitude of SNe Ia, M_B, is given by

$$m_B^0 - \mu_{\rm host} = M_B \tag{1}$$

where m_B^0 is the *standardized* apparent peak magnitude of the SN Ia and $\mu_{\rm host}$ is the distance modulus to the host galaxy based on the TRGB method. The Hubble flow SNe Ia measure the intercept of the magnitude-redshift relation, a_B. Ignoring higher order terms, the intercept is given by

$$a_B = \log cz + \log\left[1 + \frac{(1-q_0)z}{2} - \frac{(1-q_0-3q_0^2+j_0)z^2}{6}\right] - 0.2 m_B^0. \tag{2}$$

We fix q_0, j_0 to the standard values of -0.55 and 1 respectively, since the low-z SN Ia sample alone cannot constrain them. We note that while cosmological studies with SNe Ia correct the redshifts for the Hubble flow sample accounting for peculiar motion due to local large scale structure, this effect has been shown to be a sub-dominant source of error in measuring H_0 (Peterson et al. 2021), which is especially true here since only a single calibrator dominates the error budget. m_B^0 is expressed in terms of the light-curve parameters and corrections as

$$m_B^0 = m_B + \alpha x_1 - \beta c - \delta_{\mu-\rm bias} \tag{3}$$

where α and β are the slopes of the width-luminosity and colour-luminosity relations, respectively, and $\delta_{\mu-\rm bias}$ is the bias correction needed to account for selection effects and other sources of distance bias. Following the formalism of Brout et al. (2022), the canonical term for the host galaxy "mass-step" correction is absorbed in the bias correction $\delta_{\mu-\rm bias}$ (see also Brout & Scolnic 2021). Since both the calibrator described by equation 1 and the Hubble flow SNe Ia described by equation 2 are constructed to be volume-limited, such that they both have the *same* mass-step correction, the $\delta_{\mu-\rm bias}$ term will cancel out.

The error for each SN includes fit uncertainty from the SALT2 covariance matrix ($\sigma_{\rm fit}$), the peculiar velocity error ($\sigma_{\rm pec}$) and $\sigma_{\rm int}$.

$$\sigma_{\rm m}^2 = \sigma_{\rm fit}^2 + \sigma_{\rm pec}^2 + \sigma_{\rm int}^2 \tag{4}$$

For $\sigma_{\rm pec}$ we derive the magnitude error from a velocity error of 300 km s^{-1} (Carrick et al. 2015) We use `PyMultiNest` (Buchner et al. 2014), a python wrapper for `MultiNest` (Feroz et al. 2009) to derive the posterior distribution on the parameters. With the current calibrator, we find, $H_0 = XX \pm 6.4\,{\rm km\,s^{-1}\,Mpc^{-1}}$. We also fit for H_0 using the entire Hubble flow DR1 sample and find $H_0 = YY \pm 6.0\,{\rm km\,s^{-1}\,Mpc^{-1}}$, a small difference of $0.65\,{\rm km\,s^{-1}\,Mpc^{-1}}$. This uncertainty is not significantly smaller when using the entire gold sample for ZTF DR1 compared to the volume limited one. This is because the main source of uncertainty is from having on a single calibrator object.

We also infer the corrected peak magnitudes with `SNooPy` (Burns et al. 2014). While `SNooPy` uses a light-curve template as opposed to a spectral template for SALT2, it is trained with a larger sample of transitional SNe Ia similar to SN 2021rhu, hence, we compare H_0 values from both methods. We compute distances to both the Hubble flow SNe Ia and SN 2021rhu with the `EBV_model2`. Using the same analysis method for the SALT2 fitted distances, we infer an H_0 value of $YY \pm 6.1\,{\rm km\,s^{-1}\,Mpc^{-1}}$, a difference of $0.65\,{\rm km\,s^{-1}\,Mpc^{-1}}$ from the value using SALT2. This difference is significantly smaller than the uncertainty on H_0 from either method. Moreover, since `SNooPy` has a well-sampled training set to build the i-band template

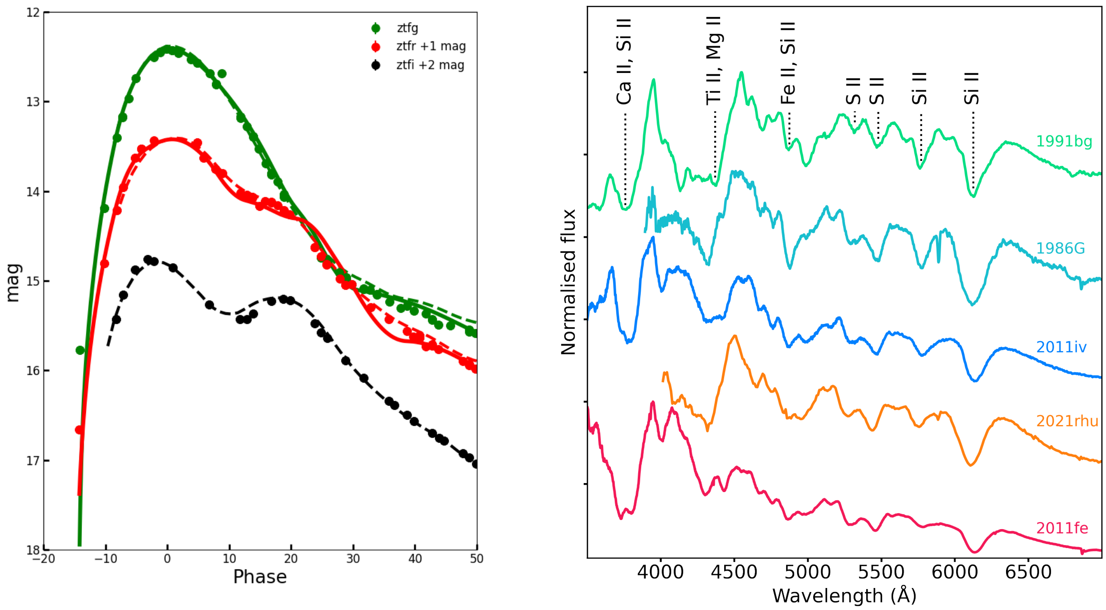

Figure 2. (Left): Lightcurve of SN 2021rhu in the g,r,i filters (filled circles) along with the SALT2 model fit to the g,r filters overplotted (solid) and the SNooPy model fit to the g, r, i filters (dashed). The plot has truncated this the phase at which the SALT2 model is defined. (Right) A maximum light spectrum of SN 2021rhu (orange), in comparison with the peculiar, subluminous SN 1991bg (green; Filippenko et al. 1992), transitional SN 1986G (cyan; Cristiani et al. 1992) and SN 2011iv (blue; Foley et al. 2012), the latter has been used as a calibrator object and the normal SN 2011fe (red; Parrent et al. 2012). The most common spectral features of intermediate mass and iron group elements of SNe Ia at maximum light are shown as dotted lines. We find that the near maximum light spectrum of SN 2021rhu is very similar to transitional SNe Ia (see also Harvey et al. in prep.)

we also infer H_0 from the g, r, i filter combination and find a value of $YY \pm 6.0\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, a difference of 0.684 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$ from the fiducial case.

4. DISCUSSION AND CONCLUSION

We present an estimate of H_0 from a uniform distance ladder using the same survey for the calibrator sample as a homogeneous, untargeted Hubble flow sample. We use a TRGB distance to a nearby host galaxy of an SN Ia with high-cadence data in the ZTF g, r, i filters. The current uncertainty is not sufficient to weigh in on the Hubble tension. We note that even a factor of 2 reduction in the Hubble flow sample by imposing the volume limit does not impact the uncertainty on H_0 the error currently is driven by the low number of ZTF SNe Ia with robust, independent distances. However, this can be increased with HST observations for nearby host galaxies. In the $D_L < 20$ Mpc volume, one where we can achieve completeness relatively quickly, there are 5 more SNe Ia with well-sampled light curves, a sample expected to increase by $\sim 1-2$ per year for the remainder of ZTF. These SNe are

1. ZTF19aacgslb (SN 2019np) in NGC 3254
2. ZTF20abijfqq (SN 2020nlb) in NGC 4382 (M85)
3. ZTF20abrjmgi (SN 2020qxp) in NGC 5002
4. ZTF21aaabvit (SN 2021J) in NGC 4414
5. ZTF21aaqytjr (SN 2021hiz) in UGC 7513

All the SNe Ia listed above have coverage in the g, r, i filters beginning from at least two weeks before maximum light and extending beyond +70 days. We note that even this small volume sample, there are early-type host galaxies like NGC 4382, for which other methods like Cepheid variables are not viable to obtain distances. In this volume, the number of calibrator SNe Ia is limited by the rate of SNe Ia exploding in the universe. The ZTF calibrator sample within the 20 Mpc volume, accumulated till date, is however, sufficient to measure H_0 to $\sim 3\%$ accuracy using only HST for TRGB observations. In our analyses, we only infer the SN Ia light-curve parameters using g and r filters since SALT2 is not optimal for redder wavebands. In future studies, we will implement improved SNe Ia models, e.g. SALT3 (Kenworthy et al. 2021), trained with high-cadence ZTF SN Ia data in the redder wavebands to measure SN Ia distances.

Future TRGB observations with the near infrared camera (NIRCam) on JWST can extend the calibra-

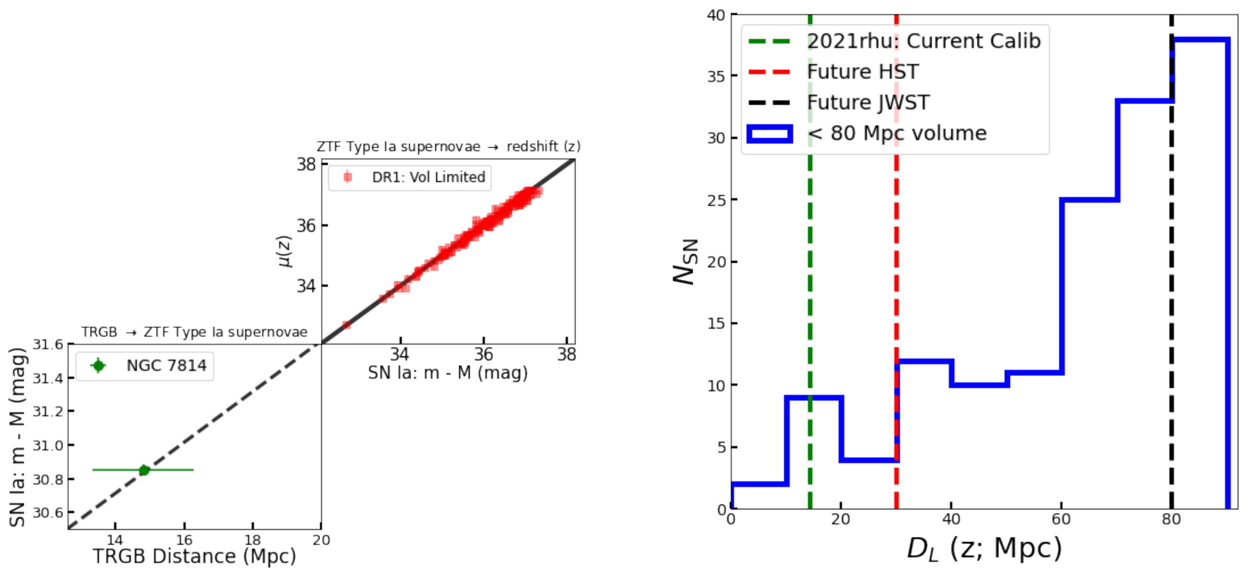

Figure 3. (Left): The current ZTF distance ladder with SN 2021rhu in NGC 7814 (green; the TRGB distance is plotted in linear scale instead of a distance modulus) and the Volume Limited Hubble flow sample from ZTF DR1 (red). We emphasize that all SNe Ia in this distance ladder are observed with the same survey. (Right): Histogram of luminosity distances for nearby ($z \leq 0.02$) ZTF SNe Ia with sufficient observations infer distances. Distances are computed from the redshift assuming standard cosmology from Planck Collaboration et al. (2020) with $H_0 = 67.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and q_0, j_0 of -0.55 and 1 respectively. Hence, they are only indicative. The distance for the current calibrator and the maximum distance feasible with HST and JWST are plotted as green, red and black vertical dashed lines respectively. There is a total of 114 SNe Ia with high-quality light curves in this volume, providing a large sample to build a ZTF-only distance ladder.

tor sample volume out to larger distances of up to 80 Mpc. In the volume $20 < D_L < 80$ Mpc, we have high-cadence light curves of 106 more SNe Ia already obtained (see Figure 3), expected to increase by the end of ZTF. Therefore, the complete sample of ZTF SNe Ia in a volume where JWST observations are feasible can increase the current calibrator sample by a factor of $\sim 2-3$. We emphasize that current SN Ia cosmology requires cross-calibrating several heterogeneous photometric systems (Brout et al. 2021). To get to percent level precision, it is an important cross-check to have observations of a large sample of SNe Ia on a single photometric system, that is the *same* for calibrator and Hubble flow SNe Ia. Hence, the increased statistical power and reduced systematic uncertainties from a single, untargeted survey, make this an ideal approach to resolve the H_0 tension.

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