Roman CCS White Paper

Exploring the obscured transient universe

Roman Core Community Survey: *High Latitude Wide Area Survey*

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Abstract: Characterization of dust-obscured transient populations in luminous and ultraluminous infrared galaxies (LIRGs and ULIRGs, respectively) is of great interest for our understanding of galaxy formation and evolution. Both tidal disruption events (TDEs) and supernovae (SNe) have an important role in driving outflows and regulating star formation as they occur at extremely high rates in (U)LIRGs and TDEs can also provide an important means of feeding the supermassive black holes (SMBHs). LIRGs and especially ULIRGs are locally very rare but dominate the comoving star-formation rate (SFR) density beyond z = 1. Local examples of such galaxies have been observed to host powerful SN factories within their innermost nuclear regions where massive stars with relatively short lifetimes are being formed in large numbers. The bulk of this star formation is heavily obscured by interstellar dust and such SNe have only been accessible by radio and infrared (IR) observations with a sufficiently high spatial resolution. Also, most (U)LIRGs are known to harbor at least one SMBH, and recent studies have identified strong candidates for heavily dust-obscured TDEs in their nuclei; in fact, such transients can outshine the entire galaxy nucleus at near-IR wavelengths, where hot dust can dominate over the quiescent emission for a significant period of time. In this White Paper we explore the potential of turning the Nancy Grace

Roman Space Telescope (NGRST) into an efficient discovery machine of dust-obscured transients in (U)LIRGs at levels not possible in any previous surveys. For this we discuss the advantage of including the F213 filter in the High Latitude Wide Area Survey, as well as dividing the observations into separate epochs that are well spaced in time.

Introduction

Over the past couple of decades time-domain studies have revealed powerful SN factories in several nearby LIRGs ($L_{IR} = 10^{11-12}\ L_\odot$) and ULIRGs ($L_{IR} = 10^{12-13}\ L_\odot$). Their high SFRs result in massive stars exploding as core-collapse SNe with rates a couple of orders of magnitude higher than observed in any "ordinary" spiral galaxy. LIRGs also often harbor at least one SMBH, and variability linked to the accretion has been observed in the form of AGN flares and, more recently, also in the form of tidal disruptions of stars causing very luminous and long-lasting nuclear outbursts, especially prominent at IR and radio wavelengths. Therefore, the IR emission of (U)LIRGs cannot be expected to stay constant over time, and substantial variability is anticipated on time scales of months to years. This topic has been recently reviewed extensively in Perez-Torres et al. (2021).

Dust-obscured supernovae in LIRGs and ULIRGs

In the circumnuclear regions of (U)LIRGs the bursts of star formation are expected to yield high rates of core-collapse SNe. Adopting an empirical relation between the galaxy IR luminosity and core-collapse SN rate from Mattila & Meikle (2001) we expect core-collapse SN rates in the range ~0.3–30 yr^{-1} for galaxies with L_{IR} in the 10^{11} to $10^{13}\ L_\odot$ range. Much of the star formation in (U)LIRGs is obscured by large amounts of dust, and therefore the SNe exploding in these regions are mostly not accessible by optical observations. Furthermore, the fraction of the star formation (and hence also SNe) hidden from optical observations in (U)LIRGs increases rapidly toward redshift z ~ 1 (e.g., Magnelli et al. 2013) potentially biasing the interpretation of SN rate measurements as a function of redshift (e.g., Mattila et al. 2012; Dahlen et al. 2012; Strolger et al. 2015). Even in the local Universe, the SN population of (U)LIRGs is not very well characterized due to the combination of large dust extinctions and difficulties in detecting the often faint sources against the bright and complex nuclear background.

Radio observations are not affected by dust extinction, and radio SNe have been detected in local (U)LIRGs by interferometric observations with sub-arcsecond angular resolution (e.g., Smith et al. 1998; Perez-Torres et al. 2009; Ulvestad et al. 2009). Not all core-collapse SNe, however, make sufficiently luminous radio sources to be detectable at the distances of the nearest (U)LIRGs, further motivating their detection and study at shorter wavelengths as well. The strongly reduced extinction ($A_K = 0.11 A_V$) makes near-IR *K*-band (2.2 μm) imaging well-suited for the detection and study of dust-obscured SNe (e.g., Mattila & Meikle 2001; Mannucci et al. 2003). Because of the concentration of star formation (and thus of the SNe) within their central regions, high spatial resolution (FWHM = 0.1" or better) has turned out to be essential for the detection of SNe in these regions. This can be achieved either with ground-based Adaptive Optics (AO)-assisted imaging or with observations from space.

AO-assisted near-IR searches have produced a number of SNe within the LIRG nuclear regions with a wide range of host galaxy extinctions, from A_V ~ 0 up to 16 mag (for more details see Kankare et al. 2008, 2012, 2021; Kool et al. 2018). A systematic mid-IR monitoring of a large number of very nearby (< 35 Mpc) galaxies was carried out with Spitzer by the SPIRITS survey (see Jencson et al. 2019) that also produced the IR discoveries of two core-collapse SNe in a nearby LIRG. More recently, Fox et al. (2021) performed a systematic search at 3.6μm for dust-extinguished SNe in the nuclear regions of forty LIRGs within 200 Mpc, resulting in the detection of five SNe not discovered by optical searches. The spatial resolution of Spitzer was, however, not optimal for searching for obscured SNe within the nuclear regions of (U)LIRGs.

Dust-obscured tidal disruption events in LIRGs and ULIRGs

In a stellar tidal disruption event (TDE) a star is torn apart by the tidal forces close to the SMBH, generating a bright flare of X-ray, UV and optical radiation (see Gezari 2021 for a review). TDEs occurring in relatively dust-free nuclear environments are quite routinely discovered by optical wide field surveys (e.g., van Velzen et al. 2020). IR observations have on the other hand also revealed strong TDE candidates within the dusty nuclear regions of (U)LIRGs. Arp 299-B AT1 was discovered in the near-IR *K*-band as a result of systematic monitoring of a small sample of nearby LIRGs for SNe (Mattila et al. 2018). This event turned out to be extremely energetic (above 10^{52} erg radiated in the IR) and evolved slowly over 10 years of observations (see Fig. 1). Based on the properties of a resolved radio jet detected in deep, high spatial resolution VLBI observations its likely origin was found to be an energetic TDE obscured by large amounts of dust. The IR SED and its evolution were found to be consistent with absorption and re-radiation of the TDE's UV/optical light by dust in the polar regions of the AGN torus (i.e. an IR echo). More recently, Kool et al. (2020) reported their AO-assisted *K*-band discovery and multi-wavelength follow-up of another IR-luminous nuclear transient in a LIRG. The authors also found a dust-obscured TDE to be the most plausible scenario given the combined IR and radio evolution of this transient.

Reynolds et al. (2022) have investigated this population of luminous IR transients by performing a systematic search in the mid-IR data from the NEOWISE survey of the WISE satellite. They used the NEOWISE data to detect and characterize all luminous and smoothly evolving transients in a sample of 215 nearby (U)LIRGs and reported three new cases in addition to the previously known transients Arp 299-B AT1 and AT 2017gbl (see Fig. 1). The IR emission of these transients was found to be consistent with re-radiation of emission at shorter wavelengths by hot dust and they suggested these transients to be part of a dust-obscured population of TDEs that have remained out of reach of optical surveys. Their observed rate of (1.6-4.6) × 10^{-3} yr^{-1} (U)LIRG^{-1} is over an order of magnitude higher than the rate of large-amplitude flares shown by AGN in the optical, and significantly higher than optical TDE rates.

Extending the High Latitude Wide Area Survey to *K*-band and time-domain

In this White Paper we explore the potential of turning the NGRST into an efficient discovery machine of dust-obscured transients in (U)LIRGs at quantities not possible in any previous surveys. Due to the limited field of view, AO-assisted observations from the ground or space-based observations with e.g. the JWST can only target one (U)LIRG at a time, significantly limiting the number of targets that can realistically be monitored for transients. NGRST has the potential to completely change this field. Here we show that a very substantial number of dust-obscured transients may be detected if (i) the HLWAS observations are spread across separate epochs ~6-12 months apart in time; and (ii) the F213 filter is added to the survey, allowing efficient characterisation of the detected transients using color information.

To investigate the detectability of dust-obscured core-collapse SNe and IR-luminous nuclear transients we have assumed 150 sec on-source exposure times in the four near-IR filters (F106, F129, F158, F184) included in the baseline HLWAS spanning the range from 0.93-2.00 μm. To demonstrate the potential of extending the HLWAS to 2.3 μm we have also included the F213 filter in our consideration, assuming the same on-source exposure time as for the other filters. In Figs. 2 and 3 we compare the corresponding 5-sigma limiting magnitudes with core-collapse SN template spectra and with SEDs of the IR-luminous nuclear transients Arp 299-B AT and AT 2017gbl. For Fig. 2 we reddened the SN spectra with values of A_V ranging from 10 to 50 magnitudes. We estimated the largest distances to the SN still allowing a successful detection in the reddest HLWAS filters + F213. For this we assumed that a transient 2x brighter than the 5-sigma limit would still be detectable by image subtraction between two epochs of NGRST imaging. In Fig. 3 we compare the SEDs of the two IR-luminous nuclear transients moved to z = 0.5 and 1.0 with the HLWAS 5-sigma limiting magnitudes, also including the F213 filter in the comparison.

The IR luminosities of all the (U)LIRGs listed in the IRAS Revised Bright Galaxy Sample (Sanders et al. 2003) correspond to a total intrinsic rate of core-collapse SNe of about 250 yr^{-1} (Kool et al. 2018). However, a total of only a few tens of core-collapse SNe have been reported in these galaxies over the past few decades. Here, we have used Magnelli et al. (2013) results on the evolution of the number density (and comoving IR luminosity density) of LIRGs and ULIRGs as a function of redshift to estimate the intrinsic rates of dust-obscured CCSNe and IR-luminous nuclear transients that occur within the volume covered by the HLWAS (see Tables 1 and 2). The IR luminosities of LIRGs and ULIRGs were integrated over the volume covered in the 1700 deg^2 field of view of the baseline HLWAS. The corresponding core-collapse SN rates were then calculated following an empirical relation between the galaxy IR luminosity and the core-collapse SN rate from Mattila & Meikle (2001). These estimates include all the core-collapse SNe that occur within the given volumes and we have not attempted to estimate the actual rates of detection. While the HLWAS has a sufficient sensitivity to detect very highly obscured (A_V up to 30 mag) CCSNe within ~90 Mpc it can detect CCSNe with a substantial extinction of A_V = 10 up to a distance of ~250 Mpc (see Fig. 2) in several filters. Therefore, we expect that a significant fraction of the CCSNe will still remain undetected due to the very large host galaxy extinctions, putting many of these SNe out of reach of even the NGRST observations. We expect the HLWAS to have a sufficient sensitivity to detect IR luminous nuclear transients similar to Arp 299-B AT1 (Mattila et al. 2018) and AT 2017gbl (Kool et al. 2018) up to z ~ 0.7 (see Fig. 3) in several filters.

For the detection and characterisation of IR-luminous nuclear transients we consider a cadence of ~6-12 months to be suitable given their long-lasting light curves (see Fig. 1). Although dividing the HLWAS observations into two epochs already allows the detection of a large number of transients in multiple filters, having more epochs would provide very valuable information on their light curves and on the evolution of their blackbody temperatures. For the detection of dust-obscured SNe a similar low cadence will be suitable, but due to their faster light curve evolution we do not expect NGRST to provide useful information on their light curve evolution, only on their colors. Instead, light curves or spectra can be obtained using dedicated follow-up observations with facilities including the JWST.

In Figs. 2 and 3 we show that including observations also in the F213 filter would provide additional color information that would be very useful for the characterization of the detected transients. In the case of dust-obscured SNe the color information is crucial for providing information on the extinction towards the SN. In the case of nuclear transients the additional color information is necessary for reliable estimates of dust temperatures from the observed SEDs of the transients.

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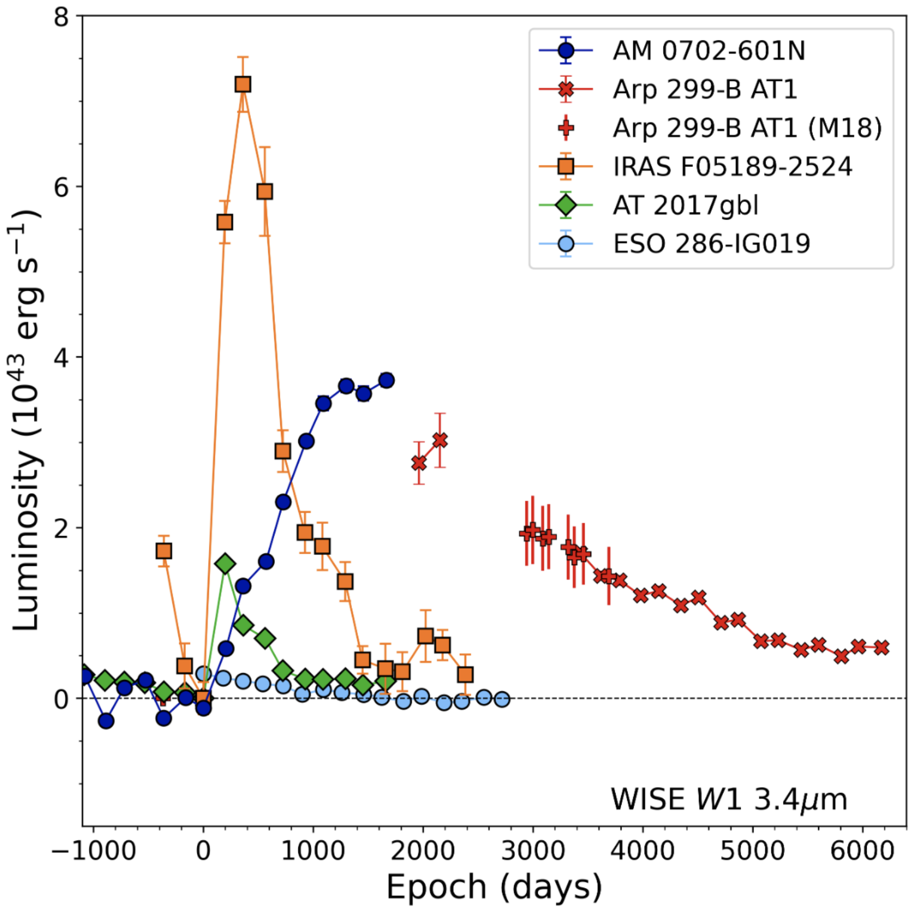

Figure 1: Luminosity evolution of IR luminous transients in (U)LIRGs in the WISE W1 (3.4μm) band from Reynolds et al. (2022). Host-subtracted 3.6μm points of Arp 299-B AT1 observed by Spitzer are included from Mattila et al. (2018).

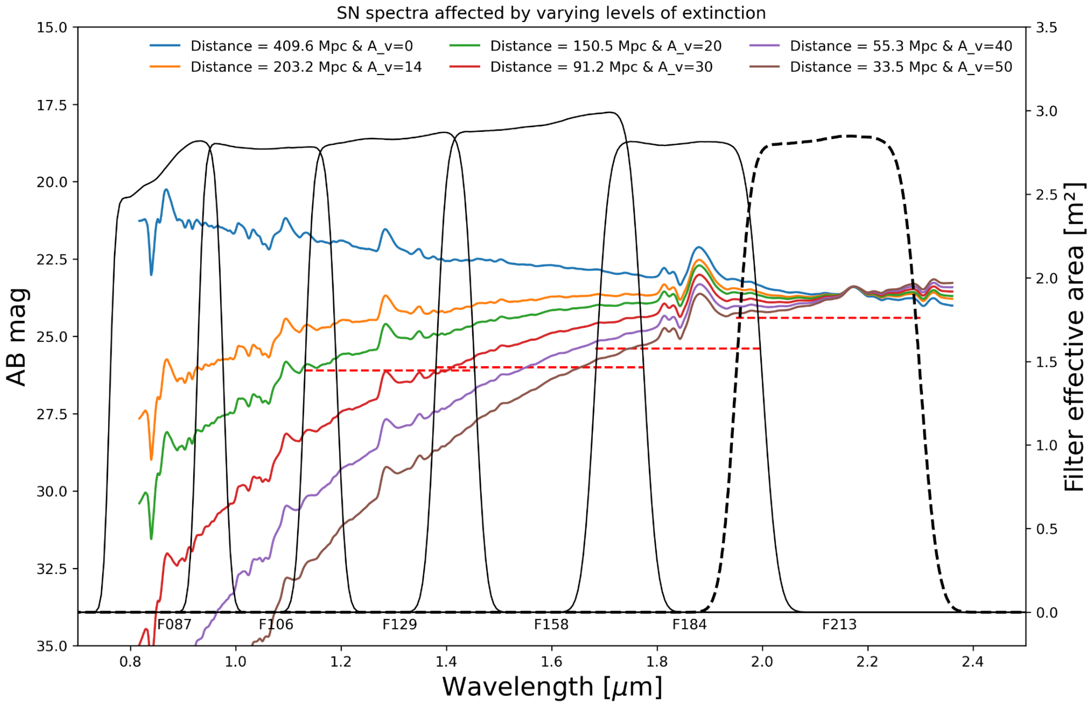

Figure 2: Template spectra at an epoch of 104 days from Davis et al. (2019) of a Type IIP SN in the IR. The intrinsic absolute magnitude of the SN follows Mattila & Meikle (2001). The distance of the SN is set so that the SN will be detected at the conservative limiting *K*-band AB magnitude of 23.65 (twice the flux of the 5-sigma limit), given a certain extinction and distance. The red dashed lines show the 5-sigma limiting magnitudes for the assumed HLWAS 150s on-source exposures in *F129, F158, F184* and *F213* bands.

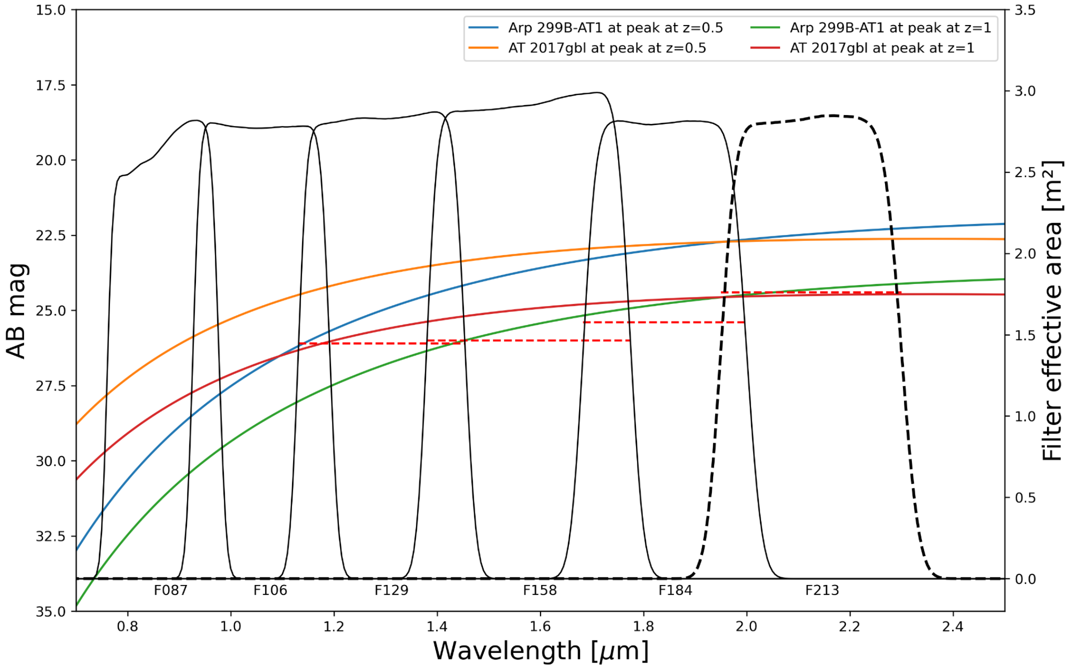

Figure 3: The SEDs of the IR-luminous nuclear transients AT 2017gbl and Arp 299B-AT1 at peak represented here by blackbodies moved to a redshift of 0.5 and 1.0. The red dashed lines show the 5-sigma limiting magnitudes for the assumed HLWAS 150s on-source exposures in *F129, F158, F184* and *F213* bands.

Distance [Mpc]	$\mathrm{L_{IR}}(total)[10^{12}L_{\odot}]$	CCSNe yr^{-1}
<100	1.3	3.4
100-200	8.8	24
200-300	24	64
300-400	46	125

Table 1: Total IR luminosities of LIRGs and ULIRGs as a function of redshift from Magnelli et al. (2013) integrated over the volume covered in the 1700 deg^2 field of view of the baseline HLWAS are listed in col. 2. The corresponding core-collapse SN rates in these LIRGs and ULIRGs, following the empirical relation between the galaxy IR luminosity and core-collapse SN rate from Mattila & Meikle (2001), are listed in col. 3. While the HLWAS has a sufficient sensitivity to detect very highly obscured ($A_V \sim 30$) CCSNe only within ~90 Mpc it can detect CCSNe with a substantial extinction of $A_V = 10$ up to a distance of ~250 Mpc (see Fig. 2) in several filters.

z	# LIRGs+ULIRGs	Luminous transients yr^{-1}
<0.1	630	1.0-2.9
0.1-0.4	80 000	130-370
0.4-0.7	520 000	830-2400

Table 2: Number of LIRGs and ULIRGs as a function of redshift following Magnelli et al. (2013) included in the volume covered in the 1700 deg^2 field of view of the baseline HLWAS are listed in col. 2. The corresponding IR luminous nuclear transient rates in these LIRGs and ULIRGs following Reynolds et al. (2022) are listed in col. 3. We expect the HLWAS to have a sufficient sensitivity to detect IR luminous nuclear transients similar to Arp 299-B AT1 (Mattila et al. 2018) and AT 2017gbl (Kool et al. 2018) up to z ~ 0.7 (see Fig. 3) in several filters.