SNe II the rescue: Determination of H_0 with Type II supernovae in the Hubble Flow

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Abstract: One of the most significant questions in today's cosmology is the cause of the Hubble tension, which is the apparent discrepancy between the early- and late-Universe Hubble constant values. While there are multiple techniques for measuring distances, most of them rely on the use of numerous subsequent empirical calibrations, known as the cosmic distance ladder. Here, we demonstrate the use of Type II supernovae (SNe II) as cosmic distance indicators, eliminating the need for external calibrations. This is done by modeling their spectral time series using radiative transfer simulations, estimating physical parameters directly. We utilize a dedicated sample of 24 SNe II observed through a Large Project on ESO VLT UT1 to calculate a new independent value for H0.

The use of SNe II as distance indicators was introduced by Kirschner & Kwan (1974), using a method that relates the physical size of the SN, measurable from its spectral features, to its brightness. The method was first used to infer an H_0 based on a sample of SNe II by Schmidt et al. (1994). Since then, it was shown that the use of radiative transfer models to estimate physical parameters is necessary to reduce systematic effects (Baron et al. 2004, Dessart & Hillier 2005). Vogl et al. (2024) demonstrated that SNe II indeed provide a viable path for measuring H_0, estimating H_0 = 74.9 +/- 1.9 km / s / Mpc through SNe published in the literature, while Csörnyei et al. (2023a) and (2023b) tested the internal consistency of the method and compared it to independent distance estimates.

To provide a more detailed analysis, we followed up 24 additional SNe II in the Hubble flow using VLT UT1 FORS2 (see Figs. 1 and 2). We obtained spectral time series and parallel optical photometry as well, allowing for a distance estimation utilizing only FORS2 data. This not only provides an excellent opportunity to estimate H_0, but also to investigate systematic effects in our analysis.

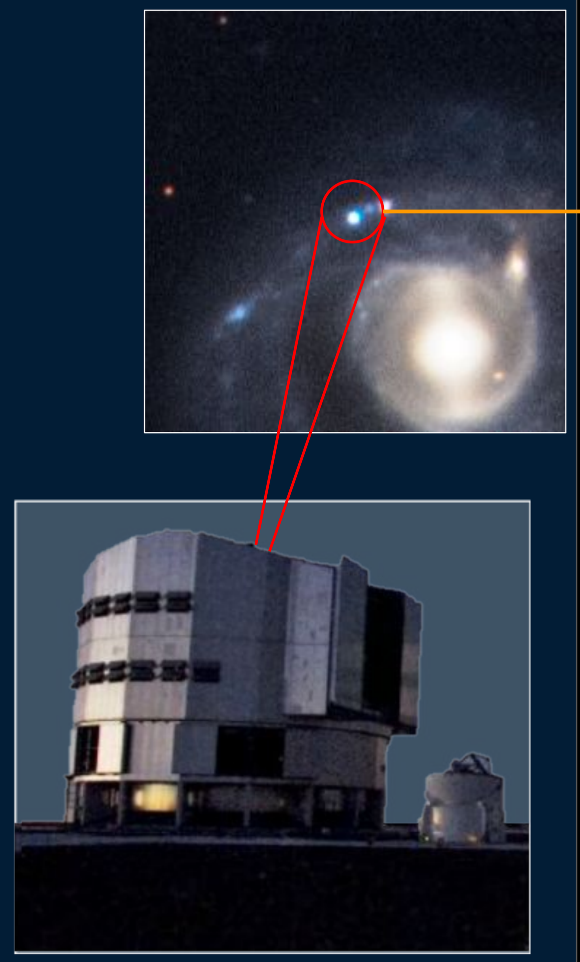


Fig. 1: Illustration of the VLT observations of a sample SN. The top plot shows a cutout of SN 2020yts from our observations with FORS2. We followed up 24 supernovae over a period of 3 years, obtaining a mean of 3-4 spectra for each at the early photospheric phase.

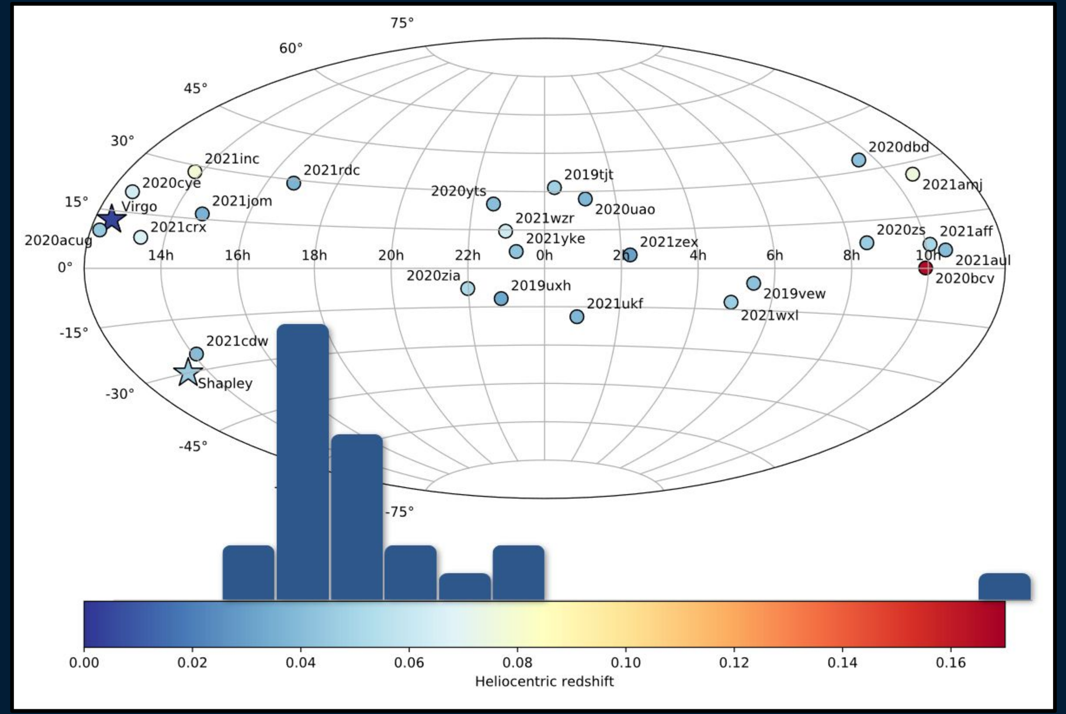


Fig. 2: On-sky and redshift distribution of the supernova sample acquired through our programme. The measured redshifts of the objects colour the individual dots. The histogram at the bottom displays the redshift distribution. As shown, through dedicated observations, we assembled a supernova sample that is well within the Hubble flow; hence, their recession velocities should not be significantly influenced by the peculiar motions of their host galaxies.

To carry out the H_0 measurement, multiple inputs are needed. Beyond the spectra that can be modeled, one needs to know the brightness in the supernova simultaneously in a well-defined photometric system, which will be compared to the absolute magnitude estimated by the radiative transfer modeling. While it is not a requirement, having a high-precision estimate of T_0 (as shown in Fig. 3) also decreases modeling uncertainties, allowing for sub-10% distance measurements per SN.

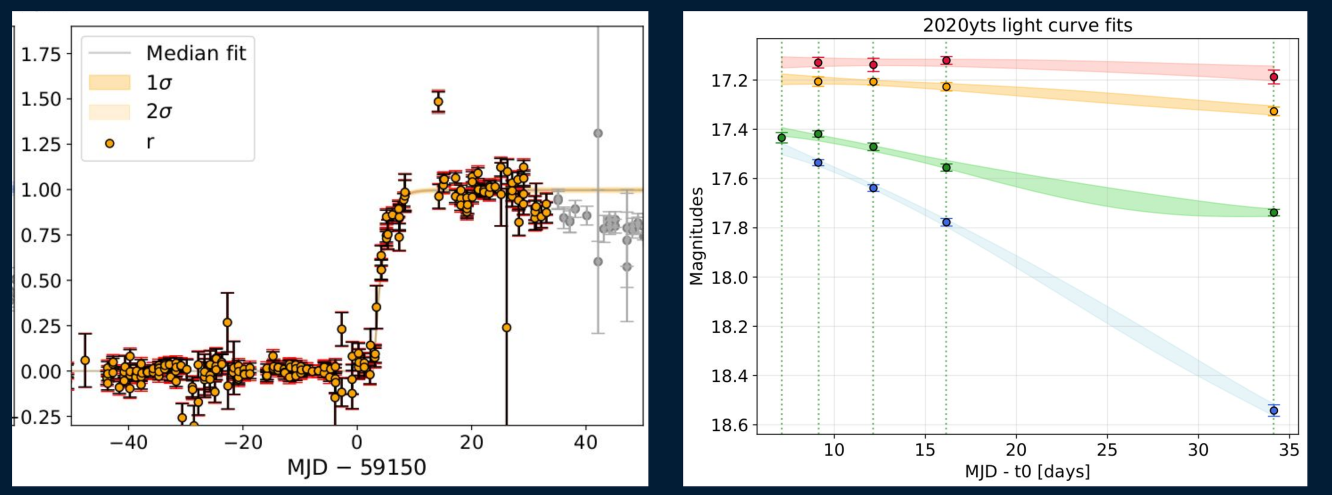
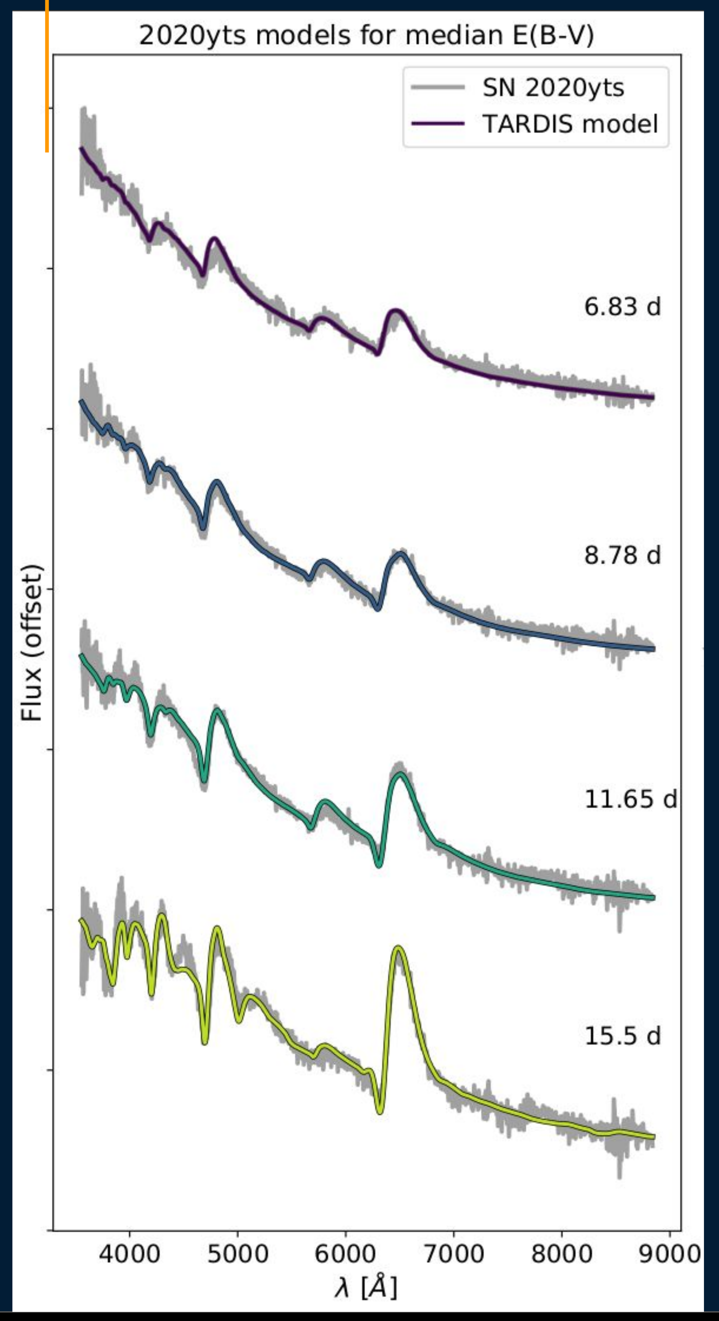


***Fig. 3:* (Left)** Estimation of the time of explosion for SN 2020yts based on fitting its early light curve from the Zwicky Transient Facility (ZTF, Bellm et al. 2019). Here, we assume an inverse exponential model for the flux. This modeling enables a T_0 precision of less than a day.

(Right) Fitting of the FORS2 light curves of SN 2020yts using Gaussian Processes. These fits are used to correct photometric imperfections and to estimate the brightnesses of the supernova at the individual spectral epochs (marked with green dashed lines on the plot).

To model the spectral time series of supernovae and obtain their luminosities, we utilize the radiative transfer code TARDIS (Kerzendorf et al. 2014), which has been adapted for hydrogen-rich supernovae by Vogl et al. (2019). The fits are calculated in an automated fashion, using the spectral emulator designed by Vogl et al. (2020) that efficiently calculates a model spectrum for a given parameter set by effectively interpolating between input model spectra. This enables the maximum-likelihood-based fitting of the spectra against the physical parameters.



This process is displayed in Fig. 4, which shows the FORS2 spectral time series of SN 2020yts, along with the calculated radiative transfer models. Beyond the physical parameters, the emulator yields an estimate for the total reddening along the line of sight, accounting for both the Milky Way and the host galaxy reddening (see Fig. 5). Given that the reddening towards the supernova should remain the same between spectral epochs, we combine these reddening estimates with a prior based on Milky Way reddening (take from Schlegel et al. 1998) to obtain a precise value for the total reddening, along with the distance.

Fig. 4: Fitted spectral time series of SN 2020yts. In the current emulator framework, we can model SN II spectra from the early photospheric phase until approximately 25 days after the explosion. Until this time, the SN ejecta is almost fully ionized, allowing for simplified modeling using snapshot models instead of modeling the full evolution of the SN as a whole. That said, every model here are treated independently, yielding independent luminosity estimates each. These luminosity estimates are then combined with the interpolated apparent magnitude values (Fig. 3) to obtain distance estimates.

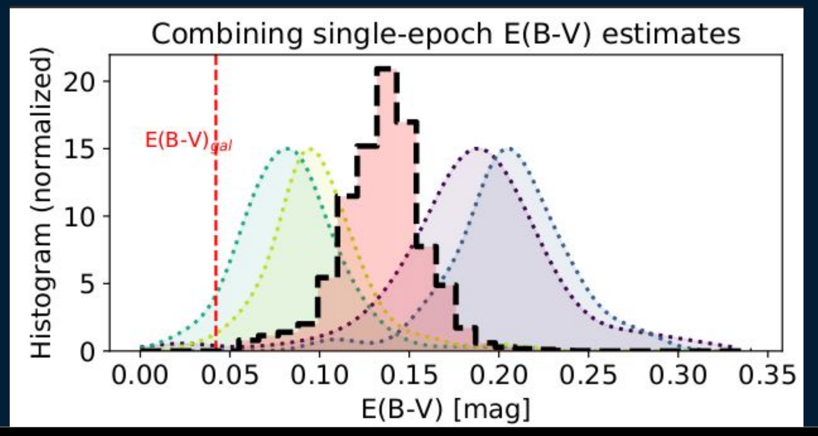


Fig. 5: Combining the redshift estimates obtained from the fitting in Fig. 4. Each histogram corresponds to the fit with the same colour from Fig. 4. The red line marks the Galactic reddening estimate. The red histogram is the combined estimate. This step ensures consistency between epochs and increases the accuracy of the distances.

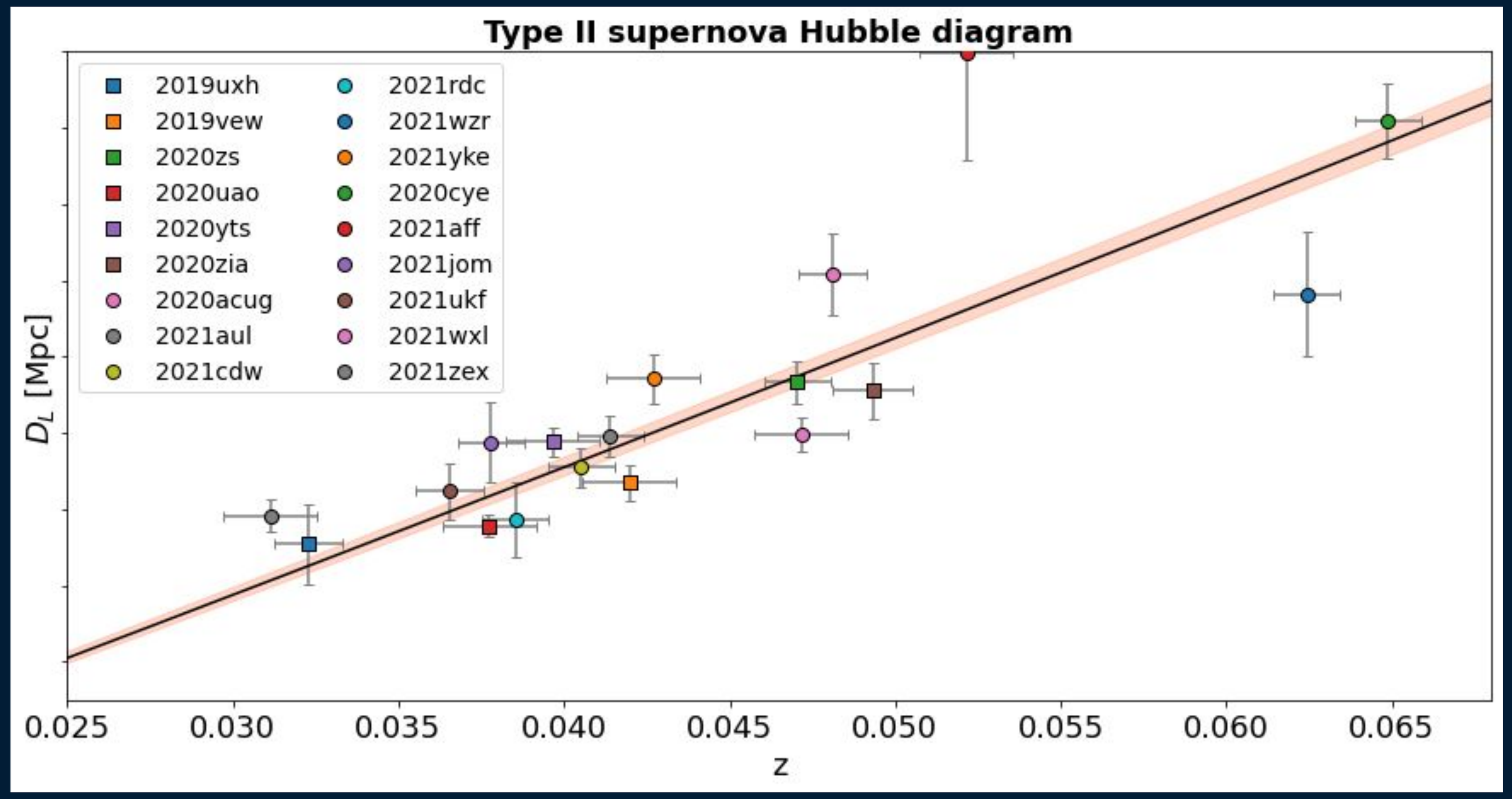


Fig. 6: Blinded Hubble diagram built from the distances estimated to the individual Type II supernova collected in our Large Programme. The curve shows a blinded fit to the Hubble diagram along with the uncertainty bands. Aside from the full sample fits, subgroups of objects will be defined based on data quality and supernova properties to investigate systematic effects present in our method, before presenting the H_0 estimates.

Estimated distances to each of the sample SNe enable the construction of a Hubble diagram that is entirely independent of other techniques. Fig. 6 shows the blinded Hubble diagram obtainable from the supernova sample collected in our Large Programme. In the next few months, the primary focus of the work will be to constrain systematic effects present in our sample, which can arise due to modeling imperfections, and to define a final sample for estimating the Hubble constant.

Summary and Conclusion: In this work, we showed that Type II supernovae are indeed promising distance indicators that can provide an independent view on the Hubble tension. We modeled the spectral time series of supernovae observed in our ESO VLT Large Programme, obtaining precise distance estimates for each of the SNe. These distances will then be combined into a final Hubble constant estimate. Given the high-quality dataset and in-depth characterization of the observations, this analysis will also enable a detailed examination of the systematics affecting the modeling approach, providing critical input for future uses of the method.

References:

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Baron et al. 2004, ApJ, 616, 91
Bellm et al. 2019, PASP, 131, 8002
Csörnyei et al. 2023, A&A, 672, 129
Csörnyei et al. 2023, A&A, 678, 44
Dessart & Hillier, A&A, 439, 671
Kirshner & Kwan, 1974, ApJ, 193, 27
Kerzendorf et al. 2014, MNRAS, 440, 387
Schlegel et al. 1998, ApJ, 500, 525
Schmidt et al. 1994, ApJ, 432, 42
Vogl et al. 2019, A&A, 621, 29
Vogl et al. 2020, A&A, 633, 88
Vogl et al. 2024, arXiv:241104968

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