

ENGRAVE follow-up of a type IIb supernova spatially coincident with the sub-threshold gravitational wave trigger S250818k

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ABSTRACT

The candidate gravitational wave (GW) event S250818k was one of only three non-retracted LIGO-Virgo-KAGRA public alerts issued during the fourth observing run of the network (O4) with a binary neutron star (BNS) merger classification probability exceeding one percent. This triggered a prompt search for a potential electromagnetic (EM) counterpart in the large localization error region (949 deg² projected in the sky at the 90% credible level). The transient supernova (SN) 2025ulz discovered by the *Zwicky* Transient Facility (ZTF) during the search, attracted a great deal of attention due to a potential spatial and temporal coincidence, and due to its initial fast decay and featureless spectrum. Here, we report on the follow-up of this transient by the Electromagnetic counterparts of gravitational wave sources at the Very Large Telescope (ENGRAVE) Collaboration. We conducted an extensive multi-wavelength observational campaign, which led to the spectral classification of the transient as a type IIb SN, indicating that it is unrelated to the candidate GW event. In this article, we describe our observing strategies, data reduction, and interpretation. All of our results confirm and strengthen our classification of the source, and also show that shock-cooling tails associated with type IIb SNe are one of the most prominent contaminants in kilonova searches.

Key words. gravitational waves – techniques: imaging spectroscopy – techniques: photometric – supernovae: general – supernovae: individual: SN 2025ulz

1. Introduction

The current international ground-based gravitational wave (GW) detector network comprises the two advanced Laser Interferometer Gravitational wave Observatories (aLIGO, Aasi et al. 2015), advanced Virgo (Acernese et al. 2015) and KAGRA (Somiya 2012), operated by the LIGO-Virgo-KAGRA Collaboration (LVK hereafter). During the fourth observing run (O4) of the network, which concluded on 18 November 2025, the LVK issued public alerts¹ for GW candidates found during real-time processing of detector data through a number of search pipelines. The pipelines produced triggers with an associated false alarm rate (FAR): a compact binary coalescence (CBC) GW candidate was considered ‘significant’ if the associated FAR was less than a threshold that depends on the specific search, and ‘low significance’ if the FAR was higher, but still lower than two per day. For searches that targeted binary neutron star (BNS) mergers, the threshold was one event per seven months; for searches that

targeted sub-solar mass (SSM) binary mergers, it was one per two years. Over the 2.5 years of O4, only two significant public alerts (excluding retracted ones) for GW candidates with a BNS merger classification probability larger than one percent were issued: S230529ay (LVK Collaboration 2023) and S250206dm (LVK Collaboration 2025a).

On 18 August 2025 at 01:20:06 UT, a low-significance public alert (with a FAR of about one every six months) was issued for a CBC GW candidate, S250818k, which was found in a search of aLIGO and Virgo data. Two LVK Preliminary GCN notices² were sent out within 5 minutes. The online analysis attributed the event to a terrestrial source (i.e. noise) with 71% probability, or to a BNS merger with 29% probability. A neutron star – black hole (NSBH) or a binary black hole (BBH) binary merger origin were both highly unlikely (<1% probability).

For low-significance alerts in O4, no GCN circular was normally issued by the LVK Collaboration. However, after rapidly covering the GW localization region (skymap hereafter), the *Zwicky* Transient Facility (ZTF) announced the discovery of an

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¹ <https://emfollow.docs.ligo.org/userguide/index.html>

² https://gcn.gsfc.nasa.gov/notices_l/S250818k.lvc

optical transient plausibly associated with S250818k (Stein et al. 2025). This led the LVK to release a GCN circular to confirm the properties of the GW candidate event (LVK Collaboration 2025b). Assuming an astrophysical origin, the quoted probability that at least one of the compact objects was a neutron star (NS) with a mass above one solar mass (HasNS) is $>99\%$, and the probability that matter remained outside the final compact object (HasRemnant) is $>99\%$. According to the circular, the source chirp mass³ falls with the highest probability in the range $(0.1, 0.87) M_{\odot}$, indicating that the lighter component would be of a sub-solar mass.

An additional GCN circular was sent out on 20 August 2025 with an updated sky localization and other inferences based on parameter estimation (LVK Collaboration 2025c). The updated skymap has a 90% credible region of 949 deg^2 (somewhat larger than the 786 deg^2 of the previous skymap), and the posterior mean and standard deviation of the luminosity distance⁴ are $237 \pm 66 \text{ Mpc}$ (a more detailed account of the S250818k localization is reported in Appendix A).

The ZTF follow-up observations began approximately 2.7 hours after the GW trigger, using the Palomar 48-inch telescope (P48), and they covered 25.2% of the localization probability (Stein et al. 2025). A total of 58 transient candidates were identified and vetted by the ZTF team. A single transient passed all vetting criteria: SN 2025ulz (initially identified as AT 2025ulz), located in what initially appeared to be a passive galaxy with only a photometric redshift of $z = 0.091 \pm 0.016$ (corresponding to a luminosity distance $D_L = 435^{+82}_{-80} \text{ Mpc}$, adopting the cosmological parameters from Planck Collaboration VI 2020).

From a Keck spectrum, Karambelkar et al. (2025) determined the presumed host galaxy redshift to be $z \approx 0.0848$ based on host emission lines ($D_L \sim 399 \text{ Mpc}$). This made it consistent within 2.5σ of the distance estimate for S250818k at that sky position, which improved to 2σ in the updated skymap from the offline parameter estimation (LVK Collaboration 2025c). Further imaging by Gemini GMOS-N and Pan-STARRS confirmed the fading of the source (O'Connor et al. 2025a; Hall et al. 2025b; Gillanders et al. 2025a), strengthening the case for a rapidly fading, reddening source spatially and temporally coincident with S250818k. Our ENGRAVE Collaboration observed the source with the Very Large Telescope (VLT; see Sect. 2), confirming the host redshift of $z = 0.0848$ (Banerjee et al. 2025a; in Sect. 2.2.1 we provide a refined estimate with error bars), but any assessment of the source at that stage was challenging due to host galaxy contamination, which proved difficult to estimate in the absence of deep pre-explosion templates. During these first 2–4 days, the source was observed intensively from the X-ray to the radio, but none of the GCN announcements reported definitive multi-wavelength detections or kilonova-like (KN-like) signatures. Finally, a photometric rebrightening was initially detected by two separate instruments and announced on 23 and 24 August (Freeburn et al. 2025; Angulo et al. 2025) and confirmed with consistent daily Pan-STARRS coverage (Gillanders et al. 2025b). On the latter day, we also announced the results of our observations with the Multi-

Unit Spectroscopic Explorer (MUSE) integral-field spectrograph (Banerjee et al. 2025b), which allowed for a better handling of the host galaxy contamination (see Sect. 2.2.3). The spectrum at the source position showed a prominent broad feature that we identified as a P-Cygni profile of $H\alpha$, similar to what was observed in young type II or IIb supernovae (SNe; see Sect. 3.2).

Possible transient radio emission at the position of SN 2025ulz was reported based on MeerKAT observations (Bruni et al. 2025a,b), but subsequent reprocessing of the datasets instead suggested a constant flux density, with no clear evidence for variability. This pointed to the more likely scenario where the radio emission is due to star formation in the host galaxy (Rhodes et al. 2025; see also our Sect. 3.3). Together with the lack of significant X-ray emission (Hall et al. 2025b; Becerra et al. 2025; O'Connor et al. 2025b), the SN nature of SN 2025ulz emerged as the most likely explanation. After an intense phase of global observations and GCN reporting over the first 10 days following S250818k, preliminary results were reported in a number of preprints: Gillanders et al. (2025c) reported the Pan-STARRS and Asteroid Terrestrial-impact Last Alert System (ATLAS; Tonry et al. 2018; Smith et al. 2020) coverage of the skymap and a well-sampled SN 2025ulz light curve which clearly showed a behaviour similar to known type IIb SNe; Franz et al. (2025), Yang et al. (2026), and Hall et al. (2026b) also favoured the SN interpretation over a KN-like signature, while Hall et al. (2025a) analysed the host galaxy spectra in comparison to other DESI galaxy spectra and potential hosts of the source of S250818k; O'Connor et al. (2025b) presented radio and X-ray limits, ruling out an afterglow interpretation of the re-brightening and excluding a GW170817-like afterglow within viewing angles of $\theta \lesssim 12.5^\circ$ (see also our analysis in Sect. 3.2.3); and, finally, Kasliwal et al. (2025a), while also favouring the type IIb SN interpretation, drew attention to the low chirp mass of S250818k and qualitatively discussed their multi-wavelength dataset in the context of a ‘superkilonova’ scenario, where sub-solar mass NSs form and merge via disk fragmentation within a core-collapse SN (Piro & Pfahl 2007; Metzger et al. 2024; Chen & Metzger 2025).

In this work, we present SN 2025ulz observations primarily obtained through the ENGRAVE VLT Large Program and supplemented with other associated datasets. Our data ultimately favour a type IIb SN interpretation for the source, in chance temporal coincidence with the GW candidate event. Throughout the paper we adopt the best-fit cosmological parameters from Planck Collaboration VI (2020).

2. Observations and data reduction

2.1. Optical and NIR imaging

We imaged SN 2025ulz with the FORS2 and HAWK-I instruments at the ESO Very Large Telescope (VLT) at Cerro Paranal, Chile, and with the Alhambra Faint Object Spectrograph and Camera (ALFOSC) on the Nordic Optical Telescope (NOT) in La Palma, Spain. Additionally, we made use of publicly available *Hubble* Space Telescope (HST) observations of the source. We describe below our observing campaign and data reduction. The results of these observations are summarized in Table B.1.

2.1.1. VLT/FORS2

We observed SN 2025ulz on 21 and 22 August 2025, approximately 3 and 4 days after the GW event, using VLT/FORS2. Observations were obtained in the *R*, *I*, and *z* bands, with

³ The chirp mass of a binary is defined as $m_c = (m_1 m_2)^{3/5} / (m_1 + m_2)^{1/5}$, where m_1 and m_2 are the gravitational masses of the binary components.

⁴ We note that the sky-position-conditional distance posterior in LVK skymaps is represented as a skewed Gaussian, $p(d) \propto d^2 \exp(-(d - \mu)^2 / 2\sigma^2)$, where d is the distance and μ and σ are sky-position-dependent location and scale parameters (Singer et al. 2016). The average over the whole sky has a more general shape, but it is also most often best described by the same skewed Gaussian.

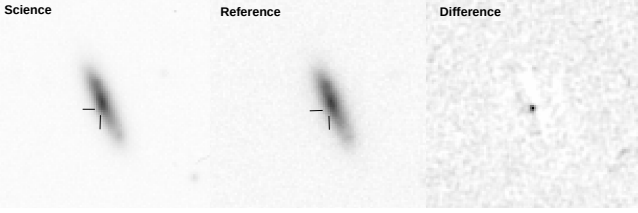


Fig. 1. VLT/FORS2 difference imaging. *Left:* $25'' \times 25''$ cutout of our FORS2 *I*-band image of SN2025ulz and its host galaxy, taken on 21 August. *Middle:* Deep template constructed from Pan-STARRS data (see text). *Right:* Residual from difference imaging.

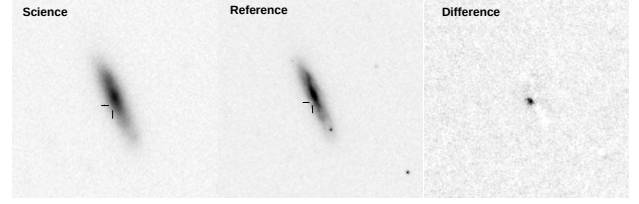


Fig. 2. VLT/HAWK-I difference imaging. Similar to Fig. 1 but showing a $24'' \times 24''$ cutout of our HAWK-I *K*-band image taken on 22 August (*left*), the template based on the F160W HST image (*middle*; see text), and the resulting difference imaging residual (*right*).

exposure times of 180, 180 and 120 seconds, respectively. All imaging data were reduced with ESOReflex (Freudling et al. 2013), employing bias and flat-field frames acquired on the same night and with the same instrumental configuration.

Astrometric and photometric calibration, as well as template subtraction and PSF-forced photometry, were performed using EC-SuperNOva Photometry (ECSNOoPY⁵). For template subtraction, we used the Pan-STARRS deep reference images presented by Gillanders et al. (2025c)⁶. These stacked reference images have total exposure times of 960 s, 4445 s, and 6720 s in the *r*, *i* and *z* bands, respectively. Using these deep templates enabled robust host-galaxy subtraction and accurate photometric measurements of the residual transient emission in the difference images (see Fig. 1).

PSF fitting on the difference images was performed with ECSNOoPY, using its photutils-based implementation. The PSF model was constructed from isolated field stars automatically selected in each frame, and the fitting was iteratively refined at the position of SN2025ulz. The residuals were visually inspected to validate the fits. A faint but clear residual was detected at the position of SN2025ulz in both epochs. The corresponding photometric measurements are reported in Table B.1.

Photometric uncertainties were estimated through artificial star experiments: a synthetic star with brightness similar to that of the source was injected into the PSF-subtracted image at positions near, but not coincident with, the source. The simulated frames were processed through the same PSF fitting pipeline, and the dispersion of the recovered magnitudes from multiple realizations was adopted as the instrumental magnitude error. Finally, this value was combined in quadrature with the uncertainty from PSF fitting.

2.1.2. VLT/HAWK-I

We also observed SN2025ulz on the 20 and 22 August 2025, approximately 2 and 4 days after the GW event, using VLT/HAWK-I. Observations were conducted in the *K* band, with a total exposure of 690 and 2160 s in the first and second epoch, respectively. All imaging data were reduced using

ESOReflex. As no pre-explosion *K*-band images were available for host-galaxy subtraction, we used the available near-infrared observations of the transient to aid this process: the field of SN2025ulz was observed at multiple epochs with the HST using the wide-field camera (WFC3), as part of the GO-17450 and GO-17805 programmes (PI: Troja). The transient and its host galaxy were imaged in the F336W, F606W, F110W, and F160W bands between 22 and 28 August 2025. All HST images were retrieved from the Mikulski Archive for Space Telescopes (MAST) and processed with hst123 (Kilpatrick et al. 2022), including frame alignment with TweakReg, image combination with AstroDrizzle (STSCI Development Team 2012), and photometry on calibrated frames using DOLPHOT (Dolphin 2016).

We used the F160W image obtained on 28 August 2025 to model and subtract the source at the source position. The host offset is approximately 0.9 arcsec, allowing an effective removal of the SN contribution from the host galaxy. We used ECSNOoPY to perform PSF fitting on the transient position in the F160W image, and the resulting residual was adopted as the reference frame for host-galaxy subtraction in the HAWK-I *K*-band data. Despite the mismatch in bandpass, the subtraction successfully revealed the transient in the HAWK-I image (see Fig. 2), and the PSF fitting was used to measure its magnitude in the difference images.

The photometric calibration was based on the 2MASS catalogue (Skrutskie et al. 2006), without applying any colour-term corrections. Uncertainties arising from local background variations in the difference images (obtained by subtracting the F160W frame from the *K*-band data) were propagated into the total photometric error budget. The final photometric measurements are presented in Table B.1.

2.1.3. NOT/ALFOSC

We obtained six epochs of *r*-band photometry using the ALFOSC on the NOT, starting from 20 August 2025 (Malesani et al. 2025; see our Table B.1 for the full list of observation times). The images were reduced, aligned and stacked using standard procedures. We performed image subtraction using HOTPANTS with an *r*-band template from the Legacy Survey DR10 (Dey et al. 2019). Even if the Legacy image is the deepest available for the field in the *r*-band, the NOT images in many epochs had superior seeing. This required us to convolve the NOT images with a Gaussian filter to match the Legacy full width at half maximum (FWHM), rather than the other way around. We visually inspected the subtraction residuals for correlated noise and other artefacts, which confirmed clean subtractions. In a few cases, the host galaxy subtraction was not perfect, but the residuals left were outside the radius where we

⁵ ECSNOoPY is a Python package developed by E. Cappellaro for transient photometry, PSF fitting and reference image subtraction. It extensively uses the astropy ecosystem (Astropy Collaboration 2013), particularly photutils (Bradley et al. 2024), and employs HOTPANTS (Becker 2015) for PSF-matched image differencing, SExtractor (Bertin & Arnouts 1996) for source extraction, SCAMP (Bertin 2006) for astrometric calibration and SWARP for image resampling and co-addition. A detailed description of the package is available at <http://sngroup.oapd.inaf.it/ecsnoopy.html>

⁶ The templates are publicly available at <https://ora.ox.ac.uk/objects/uuid:624c1bc5-b841-4da0-9c56-c8683454da7f>

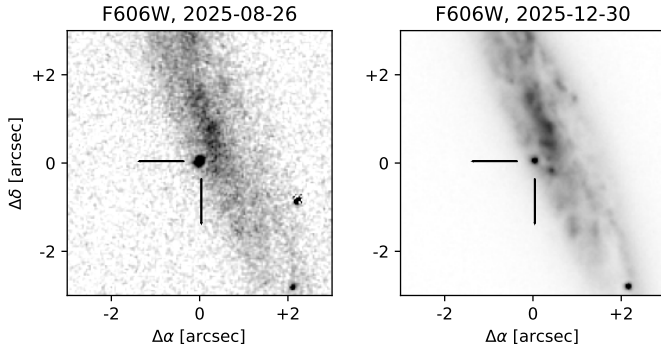


Fig. 3. HST/WFC3 F606W imaging from 26 August (*left*) and 30 December (*right*). Both panels show images of the same sky position and with the same scale, with the SN 2025ulz position indicated with tick marks. The disparity in quality between the two images is due to the different exposure times.

Table 1. Log of spectroscopic observations of SN 2025ulz.

Night	Mid-time MJD	Instrument	Grism
Aug 20	60908.02	X-shooter	UVB/VIS/NIR
Aug 20	60908.03	FORS2	300I
Aug 24	60911.02	MUSE	WFM
Aug 28	60915.00	MUSE	WFM

performed photometry, and we found they were not correlated with the transient brightness. In particular, the cleanest subtractions were obtained for the first epochs, when the transient was faintest. We performed PSF photometry using `photutils`, calibrated against PS1 photometry of field stars, using a small radius (1 FWHM). Our NOT photometry is included in Table B.1.

2.1.4. HST

To further aid our interpretation of the source, we used DOLPHOT (Dolphin 2016) to perform photometry on the HST images described in Sect. 2.1.2, obtaining magnitudes of $F336W = 23.49 \pm 0.21$ mag (22 August) and $F606W = 21.91 \pm 0.02$ mag (26 August). These measurements are consistent with those reported by Troja et al. (2025) and Franz et al. (2025) on the same data to within 0.1 mag, with the difference likely due to a different choice of background parameters and aperture radii.

We also examined a HST/WFC3/UVIS image in F606W taken on 2025 Dec 30 (PI: O'Connor), approximately 4.5 months after the discovery of SN 2025ulz. A source is still clearly visible at the position of the source (see Fig. 3), with a magnitude $F606W = 23.82 \pm 0.01$. This corresponds to an absolute magnitude of -14.1 , in good agreement with that of the Type IIb SN 2011dh at a similar phase (Ergon et al. 2014).

2.2. Spectroscopy

Spectroscopic follow-up of SN 2025ulz was obtained with VLT/FORS2, X-shooter and MUSE. A log of all spectroscopic observations is reported in Table 1, while details of the reduction and calibration of these data are given below.

2.2.1. VLT/X-Shooter

X-Shooter observations of SN 2025ulz were obtained on the night of 20 August 6×580 s and 6×600 s exposures were taken in the UVB and VIS arms, respectively, while 12×300 s exposures using on-slit nodding were used in the NIR, giving an approximate total exposure time of 1 h. A one arcsec slit was used for the UVB arm, and 0.9 arcsec slits in the VIS and NIR arms, which were oriented at a position angle of -160.7 deg (i.e. parallactic angle). The X-Shooter data were reduced following standard techniques, using the ESO X-Shooter pipeline running under `esorex` (ESO CPL Development Team 2015). Processed calibrations appropriate to the science data were downloaded from the ESO archive using the `calselector` service and used during the reduction. To correct for telluric absorption, we used the `molecfit` package (Smette et al. 2015) to model the atmospheric transmission. The reduced spectrum is shown in Fig. 4. Using $H\alpha$, we measured the redshift of the SN 2025ulz host galaxy to be $z = 0.0849 \pm 0.0004$.

2.2.2. VLT/FORS2

Two exposures of 1500 s each were also obtained, at a relatively high airmass (~ 2.0), with FORS2 using the 300I grism, which covers the wavelength range from 6000 Å to 10 000 Å. 2D spectra were obtained using standard `esorex` recipes, while 1D single spectra were derived using IRAF after mitigating contamination from bright sky background features. We finally stacked both exposures, producing the final spectrum visible in Fig. C.1.

2.2.3. VLT/MUSE

We also used the Multi-Unit Spectroscopic Explorer (MUSE; Bacon et al. 2010) to observe SN 2025ulz on the nights of 24 and 28 August. We reduced the data using a custom version of the ESO pipeline and standard `esorex` recipes, and used the `IFUana1` package (Lyman et al. 2018) to analyse and post-process the data. The MUSE cube was astrometrically aligned with images containing SN 2025ulz by using stars that were common to the MUSE white image and reference images. We extracted the spectrum in a circular aperture centred at the astrometrically transformed location of SN 2025ulz. The aperture diameter was chosen approximately equal to the FWHM as measured on point sources in the field ($1.2'' = 6$ pixels for 24 August; $1.8'' = 10$ pixels for 28 August). We experimented with different ways of removing the galaxy background: a circular annulus centred on SN 2025ulz with inner radius of $1.2''$ and outer radius of $1.8''$; three different apertures at nearby galaxy locations (marked with different colours in Fig. 5), after correcting for the rotation of the galaxy by applying velocity offsets. Without applying these offsets, host galaxy lines such as $H\alpha$ would subtract badly, contributing noise and residuals to the final spectra. Figure 5 shows the resulting spectra for SN 2025ulz for all methods, demonstrating that all choices produce similar results. We conclude that the transient spectrum is not dependent on the details of the background removal.

2.3. Radio observations

We observed the position of SN 2025ulz at radio wavelengths with the Karl G. Jansky Very Large Array (VLA), the MeerKAT, the upgraded Giant Metrewave Radio Telescope (uGMRT) and the enhanced Multi Element Remotely Linked Interferometer Network (e-MERLIN). A summary of our observation epochs,

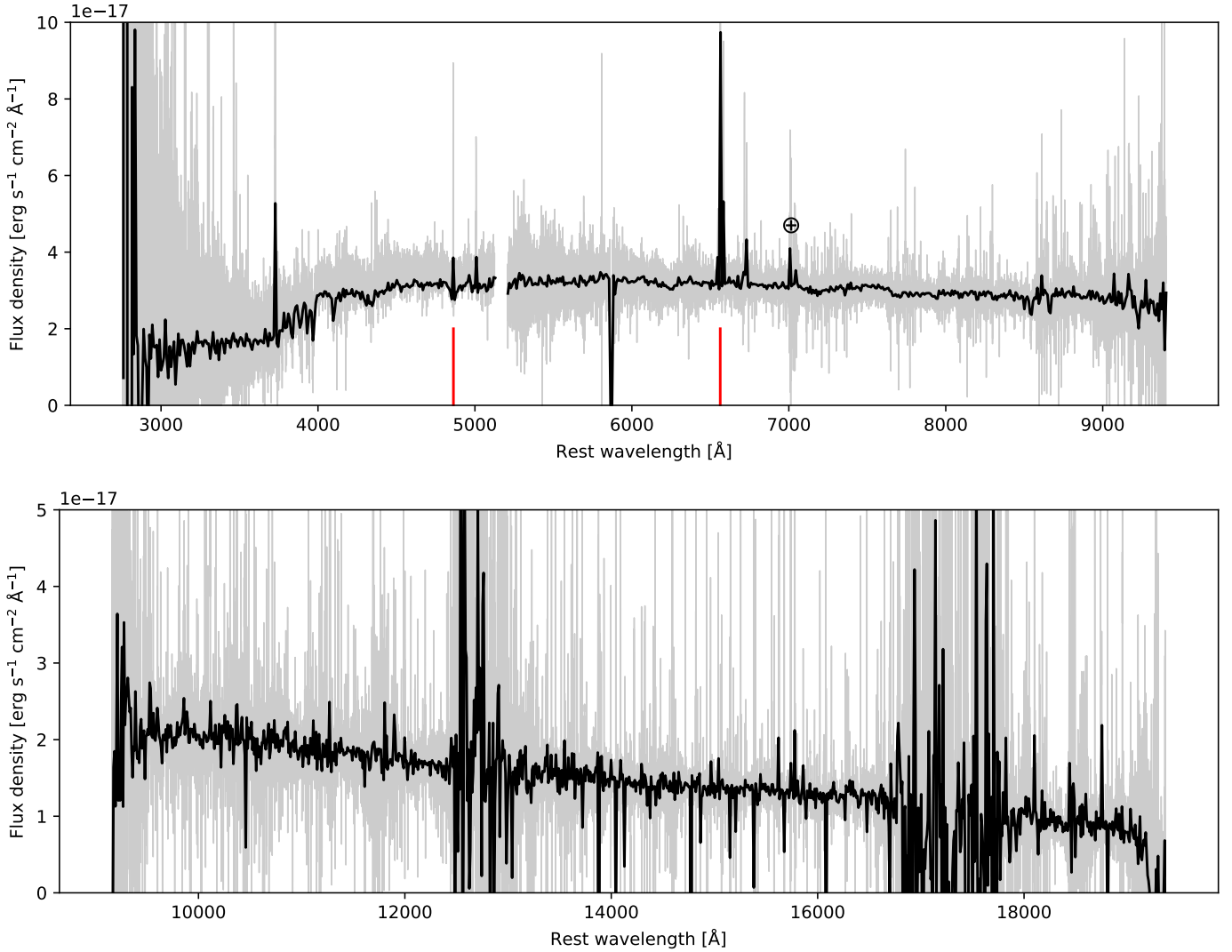


Fig. 4. VLT/X-shooter spectrum of SN 2025ulz taken on the night of 20 August, plotted in the rest frame. *Top:* UVB and VIS arms. *Bottom:* NIR arm. In both cases, the reduced spectrum at the native pixel sampling is shown in light grey, the black line is after the spectrum is averaged and re-binned to 10 Å sampling. Red lines mark the position of H α and H β , while the residual left after correction of the telluric A band is marked with an $\oplus$ symbol.

setup, and results is given in Table B.2. Below we detail the observing strategies and data reduction.

2.3.1. VLA

We acquired a broadband observation of SN 2025ulz with the VLA on 29 August 2025 at 01:49:37.4 UT ($\delta t = 10.9$ days) as part of our programme 22A-414 (PI: Schulze). The observation was obtained in the B configuration, in a standard phase referencing mode, for a total on-source time of ~ 50 minutes at the mean frequency of 3 GHz (S-band), and for 18–20 minutes at the mean frequencies of 6 GHz (C-band), 10 GHz (X-band) and 15 GHz (Ku-band). We used 8-bit samplers for S-band and 3-bit samplers for C, X and Ku-bands; 3C 286 = J0137+3309 was selected as the bandpass and flux density calibrator, and J1602+3326 as the complex gain calibrator. We reduced the data using the VLA calibration pipeline packaged with CASA v.6.6.1.17 (McMullin et al. 2007). After manually inspecting the data, we further flagged antennae with bad solutions as well as additional weak radio-frequency interference and then

re-ran the pipeline. We imaged each band individually using wsclean (Offringa et al. 2014; Offringa & Smirnov 2017) with Briggs weighting of 0.0. We further performed phase-only self-calibration on S- and C-band data using a sky model dominated by the nearby bright source ($\sim 2.5'$ away, visible in Fig. C.2) to suppress its residual sidelobe artefacts at the location of SN 2025ulz. We found no evidence of a significant detection at the location of the source (i.e. within one synthesized beam) in any of the images, down to 3σ upper-limits of ~ 21 , 24, 27, and 21 μ Jy in S, C, X, and Ku-band, respectively (also reported in Table B.2), consistent with the limits reported by Franz et al. (2025), O’Connor et al. (2025b).

Statistically significant radio emission from the host galaxy, localized in a region slightly north of SN 2025ulz, is evident in the S-band image. To better recover this diffuse emission and enhance surface brightness sensitivity, we re-imaged each band using a Briggs weighting of 0.5 (the resulting image is shown in Fig. 6). Even with this weighting, no radio emission above 2σ is detected from the galaxy in C, X, and Ku bands. In the new S-band image, we used the Contours generator

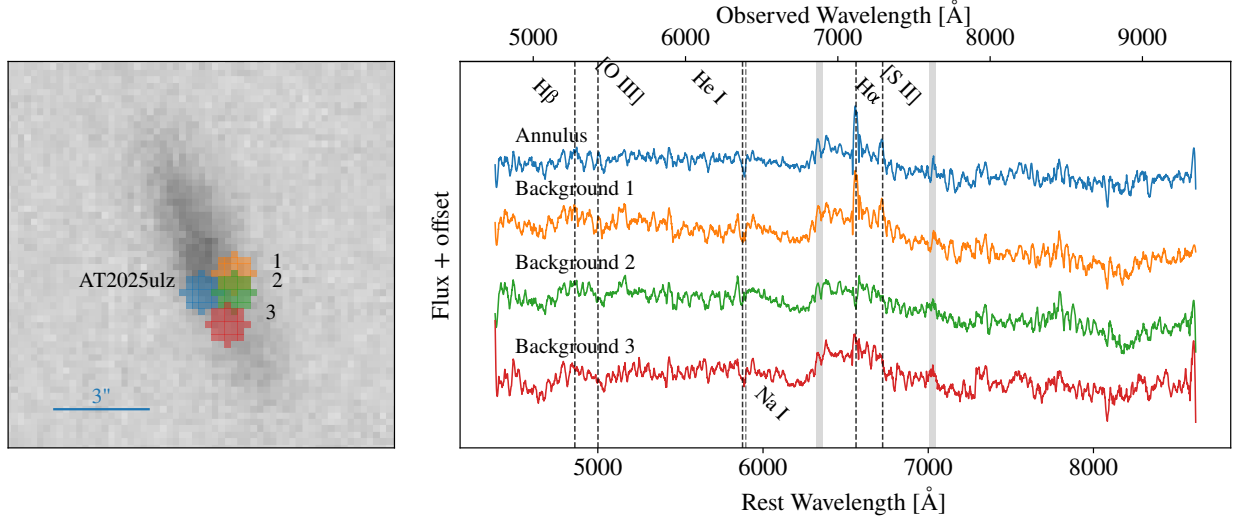


Fig. 5. *Left:* Host of SN 2025ulz observed with MUSE on the night of 24 August. The blue aperture marks the spaxels for extracting the transient spectrum at the location of SN 2025ulz. The other regions were used to estimate and remove the host galaxy background. *Right:* Spectra of SN 2025ulz for different extractions and host galaxy removal, including a circular annulus and the background apertures shown in the left panel (colour-coded similarly). All extraction methods result in broadly similar spectra with the same features, including a prominent broad H α P-cygni profile. Grey shaded bands indicate regions of telluric absorption.

in CARTA to visualize the emission morphology, and defined an elliptical region enclosing all emission within the 2σ contour level (shown with dark green dashed lines in Fig. 6). This region, centred at 15:51:54.19 +30:54:10.02 (at a projected distance of ~ 2.5 kpc from SN 2025ulz), has dimensions of approximately $2.7'' \times 1.1''$ in our image. We used the `imstat` task in CASA to measure an integrated flux density of 37 ± 8 uJy within this region, where the uncertainty includes statistical and 5% systematic contributions added in quadrature. For a quick comparison with MeerKAT results in Sect. 2.3.2, we also measured the integrated flux density within a $3.5'' \times 3.5''$ region (which corresponds to the MeerKAT synthesized beam for the observation of 28 August; see Table B.2), obtaining 60 ± 20 uJy from the VLA data, consistent with MeerKAT measurements.

2.3.2. MeerKAT

We acquired observations of SN 2025ulz with MeerKAT at three epochs from 21 August 2025 to 13 September 2025 (3 to 26 days after the GW) under programme ID SCI-20241101-GB-01 (PI: Bruni) at 3 GHz (S4 band). Observations were also performed at 1.28 GHz (L-band) in the last epoch. The first epoch in the S-band had a total duration of ~ 2 h, while the second and third lasted ~ 4 h. The L-band observation lasted ~ 2.5 h. We used J1939–6342 as flux and bandpass calibrator, while J1609+2641 as phase reference at both frequencies. Data were processed with the `oxkat` pipeline (Heywood 2020). We obtained a detection in all epochs and frequencies. The emission position is consistent with the host galaxy of SN 2025ulz, and is marginally resolved only at S-band. However, the angular resolution was not sufficient to resolve a possible transient radio counterpart. Since S-band flux densities for the different epochs are consistent within errors, we also produced a deeper image combining the calibrated visibilities for the second and third epochs, which had the best UV coverage. In this way, we improved the RMS to about 3 μ Jy/beam, and derived a flux density of 71 ± 8 μ Jy. The flux density in the L-band is 116 ± 14 μ Jy.

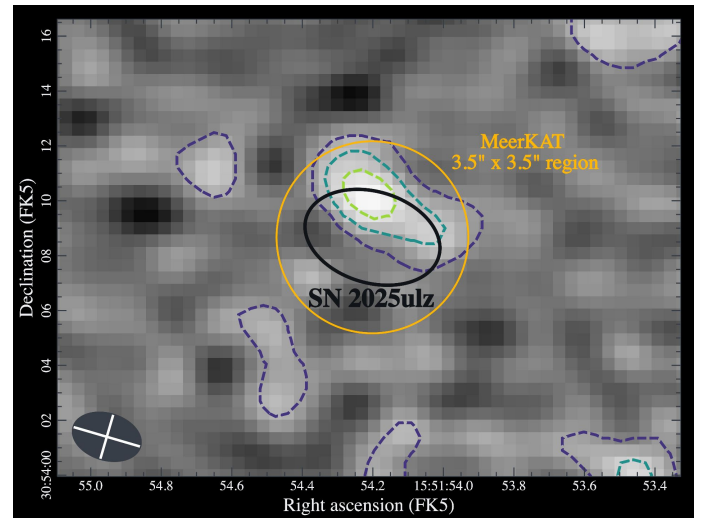


Fig. 6. Cleaned VLA S-band image using Briggs weighting of 0.5. Self-calibration was used to reduce contamination from the bright source visible in the lower-right corner of Fig. C.2. At the location of SN 2025ulz, no significant emission is present within one synthesized beam (black ellipse). The 1, 2 and 3σ contours are respectively shown as purple, blue and green dashed lines, respectively. The emission enclosed within the 2σ (blue-dashed) contour has an integrated flux density of 37 ± 8 uJy. For comparison, MeerKAT synthesized beam for the observation of 28 August is shown as a yellow circle, and the VLA synthesized beam is displayed in the bottom-left corner of the inset.

2.3.3. uGMRT

Single-epoch observations with the uGMRT were carried out 8 days post GW event, at 1.4 GHz (L-band), under project 48_097 (PI: Bruni). The total duration of the observation was ~ 2 h. We used 3C 286 as flux and bandpass calibrator. Data were reduced with the SPAM pipeline (Intema 2014). Image was restored with a Briggs 1.0 weighting scheme, allowing us to

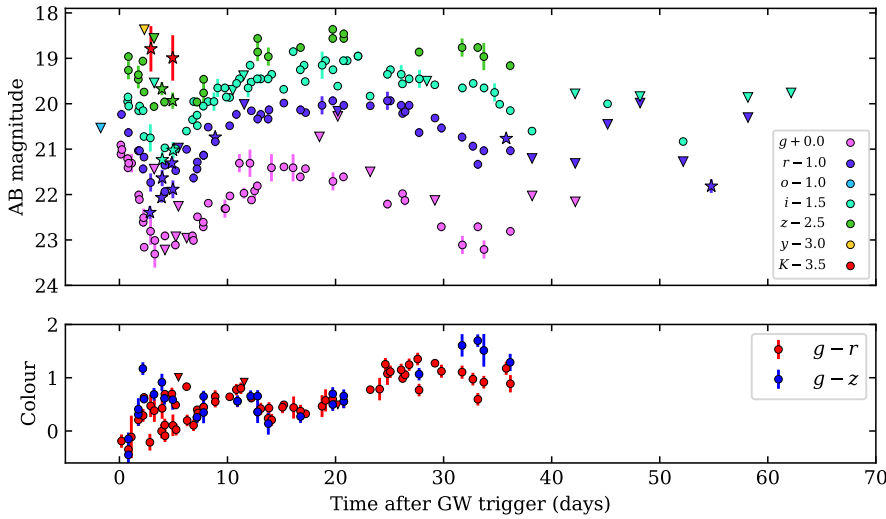


Fig. 7. Multi-band light curves and colour evolution of SN 2025ulz. *Top:* estimated AB magnitudes of SN 2025ulz in selected bands (colour-coded and offset, for presentation purposes, as indicated in the legend – o is the ATLAS ‘orange’ band Tonry et al. 2018, where the most constraining pre-explosion limit is available) are shown by star symbols (data from this work) and circles (data compiled from Table 2 of Gillanders et al. 2025c and Table 2 of Kasliwal et al. 2025a), with error bars showing the one-sigma errors. Triangles represent three-sigma limiting magnitudes from observations that did not yield a detection. The data are corrected for dust extinction in the Milky Way, assuming $E(B - V) = 0.028$ (Schlegel et al. 1998; Schlafly & Finkbeiner 2011). *Bottom:* $g - r$ (red) and $g - z$ (blue) colour evolution of SN 2025ulz constructed subtracting the r and z band magnitudes from a piecewise-polynomial fit of the g band data (see text). Error bars represent 68% credible ranges, while triangles are 95% credible upper limits.

reach an RMS of $23 \mu\text{Jy}/\text{beam}$. No detection of the transient or the host was achieved, resulting in a 5σ upper limit of $115 \mu\text{Jy}$.

2.3.4. e-MERLIN

Observations were also performed with the e-MERLIN under programme CY20210 (PI: Bruni). They were carried out at C-band (5.1 GHz) for one epoch on 19 September 2025 (31 days post-GW), including the following antennas: Lo, Mk2, Pi, Da, Kn, De, Cm. The phase calibrator was 1605+3001, while 1331+3030 was adopted for amplitude calibration. The total duration of the observing run was ~ 11 h. Data were processed with the e-MERLIN pipeline (Moldon 2021), and imaging was performed with CASA (McMullin et al. 2007) at the central frequency of 5.1 GHz, adopting natural weighting. The RMS was $26 \mu\text{Jy}/\text{beam}$. The source was not detected, and the corresponding 5σ flux density upper limit is $130 \mu\text{Jy}$.

3. Interpretation

3.1. Light curve and colour evolution

The top panel of Fig. 7 shows the light curves of SN 2025ulz in multiple bands, constructed by combining our data with those from Gillanders et al. (2025c, their Table 2) and Kasliwal et al. (2025a, their Table 2). To visualize the colour evolution of the source, we divided the g -band light curve in three time segments (0 to 3.5 days; 3.5 to 17 days; 17 to 35 days) and fitted a third-degree polynomial to each segment, requiring continuity at the matching ends. We then subtracted the r and z band magnitude measurements from the g -band model evaluated at the corresponding time to construct the $g - r$ and $g - z$ colour estimates shown in the bottom panel of Fig. 7. We note that the colour evolution constructed in this way looks somewhat noisy: this is likely the consequence of the presence of data obtained with different host galaxy subtraction approaches in our diverse dataset.

The early evolution of SN 2025ulz was very rapid: the initial detections by ZTF in the g and r bands, taken 0.13 and 0.19 d after the GW trigger respectively, were the brightest in the first few days, at $g \sim 21$ and $r \sim 21.3$ magnitudes, respectively (Kasliwal et al. 2025a); subsequent photometry in g , r , i and z

bands all showed rapid fading in the first 3 days. The colour evolution in the first 2 days showed rapid reddening, with both $g - r$ and $g - z$ going from around -0.5 at 1 d to $g - r \approx 0.2$ and $g - z \approx 0.5$ at 2 d, respectively. From 4 d onwards, a re-brightening was observed in all optical bands until ~ 20 d, with the colour evolution turning slightly towards bluer colours in the 10–20 day range, before continuing to redden more slowly until the last detections around ~ 37 d, as shown in the bottom panel of Fig. 7.

The initial rapid fading and colour evolution towards the red of SN 2025ulz are reminiscent of AT 2017gfo (Gillanders et al. 2025c), though some details are critically different (e.g. Tanvir et al. 2017). Notably, the g , r and i -bands show a much shallower decline in SN 2025ulz (see e.g. Fig. 3 of Hall et al. 2025a), while only the z -band has a similar slope. In other words, though the initial colour evolution revealed significant reddening, it was not as extreme as that of AT 2017gfo, particularly past the first 2 days. However, theoretical modelling of KN emission (e.g. Kawaguchi et al. 2020) suggests a relatively diverse range of observable evolutions, depending on merger scenario, viewing angle, ejecta mass, composition and the nature of the remnant. Given that the only confirmed KN with data at these early times is AT 2017gfo, such differences in the initially qualitatively similar evolution do not immediately invalidate the possibility that SN 2025ulz was a KN.

Conversely, the subsequent re-brightening across all bands is not predicted by any current KN model, particularly on a timescale of ~ 30 days (e.g. Pognan et al. 2026). Both AT 2017gfo and the KN AT 2023vfi (Gillanders et al. 2023; Gillanders & Smartt 2025; Levan et al. 2024; Yang et al. 2024) show rapid fading on these timescales, and consistently redder colours in time. Considering SN 2025ulz as an isolated event with no other emitting components, the optical light curves are therefore not compatible with KN models (see Sect. 3.5). The presence of a gamma-ray burst (GRB) afterglow may be invoked in order to explain the optical evolution past 4 days (e.g. Fig. 5 of Hall et al. 2025a). However, such an afterglow component is ruled out by non-detections in radio and X-ray (O’Connor et al. 2025b).

The initial fast fading in all bands, followed by a re-brightening to a second peak at ~ 15 – 20 days after the first

detection, assumed to be at or close to the moment of explosion, is similar to previously observed type IIb SNe. Comparison of broadband light curve evolution reveals that SN 2025ulz evolved in a qualitatively similar fashion to several other IIb SNe: 1993J, 2008ax, 2011dh, and 2016gkg (Gillanders et al. 2025c). While some details differ between these objects, such as first and second peak absolute magnitudes, and exact timescales on which they evolve, this is to be expected. The first light curve peak and rapid decline is expected to arise from shock breakout and cooling, while the second peak arises from ^{56}Ni decay heating of the ejecta, the evolution of which is significantly different from the expected r-process heating of KN ejecta.

3.2. Spectra

3.2.1. Transient classification

While the first spectra obtained on the night of 20 August (2 days after the GW trigger) are mostly featureless (Figs. 4 and C.1), the spectra obtained with MUSE on the nights of 24 and 28 August (6 and 10 days after the GW trigger) present sufficient structure to allow a spectroscopic classification. SN 2025ulz shows a broad $\text{H}\alpha$ emission feature, accompanied by clear P-Cygni absorption, as well as $\text{H}\beta$ at the same velocity. These are features characteristic of Type II SNe, including Type IIb at early phases. We have cross-correlated the SN 2025ulz spectra with those of other transients using the SuperNova IDentification – Spectral Analysis and Guided Exploration (SNID-SAGE; Stoppa & Smartt 2026; Blondin & Tonry 2007). We found good agreement with early spectra of SNe IIb, including those of SN 2016gkg and SN 2011dh, which have shown prominent shock cooling phases before their main radioactive peak (Arcavi et al. 2011; Bersten et al. 2012; Ergon et al. 2014; Arcavi et al. 2017; Tartaglia et al. 2017).

For the spectrum of Aug 24, SNID-SAGE provides a Type II classification with high confidence, and a preferred subtype of IIb. Eight out of twelve top-matches are SNe IIb and their phases cluster between -17 and -14 days, with one outlier at $+5$ days. The confidence provided by SNID-SAGE for a Type II classification versus the next-best alternative (a tidal disruption event, TDE; Gezari 2021) is $+99\%$. For the spectrum of Aug 28, SNID-SAGE formally provides a medium confidence for a Type II classification, with only $+42\%$ relative to the next-best alternative (again a TDE). We note, of course, that a TDE classification is inconsistent with every other observable of this transient and we do not consider it further. In fact, this just highlights that there is no other viable SN classification beyond a Type II for SN 2025ulz. This time, 18 of the 31 top matches are of Type IIb, while the remaining 13 are of Type IIP or IIL. The phases for SN IIb top-matches are distributed within -8.0 ± 4.7 days. This is perfectly in line with the date of observation, which is -8 days before the main peak of SN 2025ulz. Figure 8 shows the spectral matches of SN 2025ulz with those of well-studied SNe IIb at early phases. The spectroscopic classification of SN 2025ulz is therefore secure and unambiguous.

3.2.2. Host galaxy metallicity and star formation rate

From the integral-field MUSE spectra, we constructed two oxygen abundance maps of the galaxy based on the empirical calibration of the O3N2 and N2 indicators provided by Marino et al. (2013). Both maps are nearly uniform, with $8.46 \leq 12 + \log(\text{O}/\text{H}) \leq 8.54$, indicating a moderately sub-solar metallicity of $0.6\text{--}0.7 Z_{\odot}$ (assuming $12 + \log(\text{O}/\text{H}) = 8.69 \pm 0.04$ for the

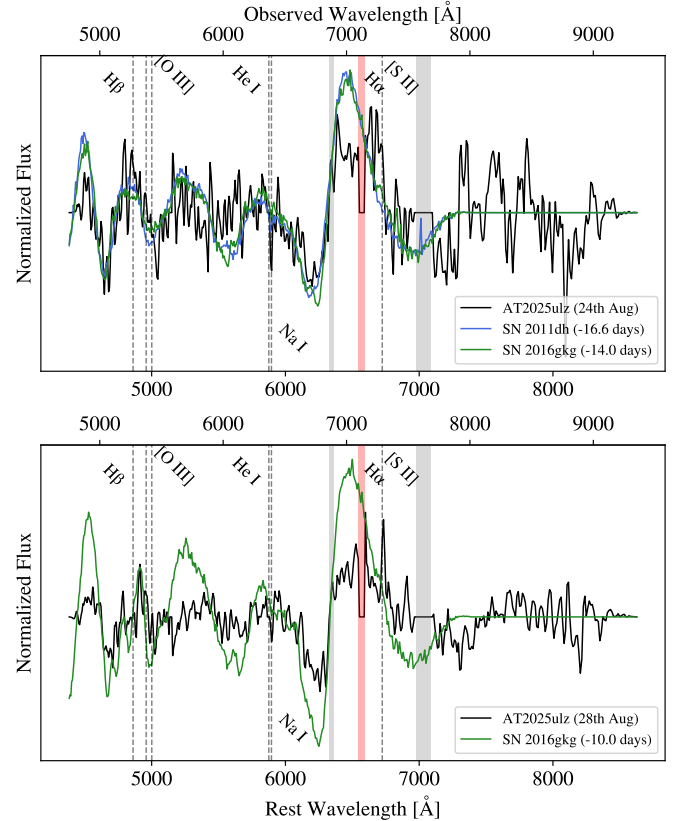


Fig. 8. Comparisons of the MUSE spectra obtained on 24 August (*top*) and 28 August (*bottom*) with early spectra of type IIb SNe, produced by SNID-SAGE. The shaded regions mark host galaxy lines (red) and telluric features (grey) that have been masked out. Dashed lines mark the locations of typical SN features. The overall match is very good and the classification of SN 2025ulz as a Type II SN, with IIb as the favoured subtype, is unambiguous.

Sun; see Asplund et al. 2021). At the position of SN 2025ulz, the metallicity is $12 + \log(\text{O}/\text{H}) = 8.51 \pm 0.01$.

From the $\text{H}\alpha$ emission line luminosity in the spatially integrated spectrum, we estimated the star formation rate (SFR) of the galaxy based on Eq. (2) of Kennicutt (1998), obtaining $\text{SFR} = 1.6 \pm 0.5 M_{\odot} \text{ yr}^{-1}$. The error is conservatively taken as 30% of the central value, reflecting the dispersion in the calibration that follows from using different initial mass functions and models of stellar evolution and atmosphere.

3.2.3. Radio limits on SN/KN emission

If SN 2025ulz was associated with a BNS merger that produced a GRB jet, early radio observations would allow constraints on the jet observing angle. Assuming a Gaussian jet expanding into a uniform interstellar medium (Lamb & Kobayashi 2017), with the same global and microphysical parameters as those found for GW170817 in previous works (Gianfagna et al. 2024; Ryan et al. 2024), the uGMRT, e-MERLIN, MeerKAT⁷, and VLA observations constrain, under our simplifying assumptions, the inclination of the jet to be larger than about 12° (see Fig. 9).

⁷ MeerKAT formally yields a detection, but this is consistent with constant emission from star formation in the host galaxy (see Sect. 3.3). Hence we use $3 \times \text{RMS}$ as an upper limit in this section, assuming that variable radio emission at this level would have been distinguishable from the constant component.

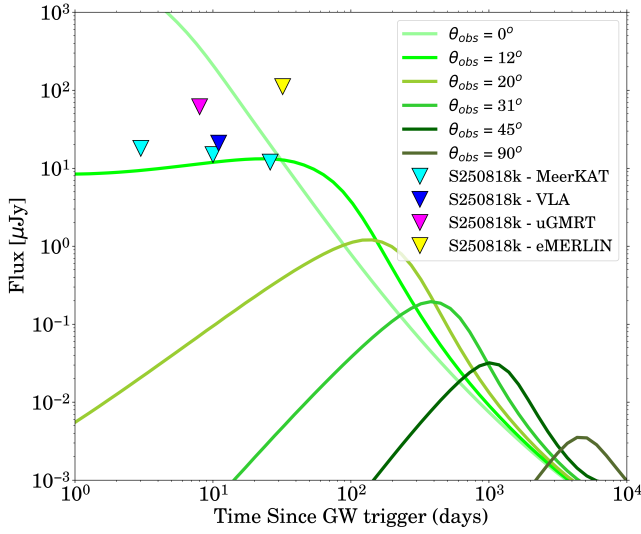


Fig. 9. Gaussian jet afterglow model light curves at 3 GHz. Different viewing angles (given in the legend) are represented with different shades of green. 3σ upper limits from VLA and MeerKAT at 3 GHz are represented in blue and cyan inverted triangles respectively. We note that the e-MERLIN (in yellow) and uGMRT (in magenta) observations are rescaled to 3 GHz assuming an afterglow spectral slope of -0.6 (Troja et al. 2019; Hajela et al. 2022).

Hence, radio observations alone cannot rule out the possibility that an off-axis GRB was produced. This conclusion agrees with O'Connor et al. (2025b).

KN ejecta are also expected to produce a radio afterglow. However, the fastest tail of the KN ejecta is expected to decelerate on timescales of $\sim$ months to years (e.g. Nakar & Piran 2011), making it irrelevant to test KN afterglow models with the available observations.

Supernovae IIb are sometimes detected in radio, although this is highly dependent on the density of the circumstellar medium into which they explode (Chevalier 1982; Chevalier & Soderberg 2010). Radio emission of a sample of SNe IIb is represented in Fig. 10. Given the early time of the radio observations and the relatively large distance, the upper limits obtained with the VLA, MeerKAT, e-MERLIN, and uGMRT do not conflict with the interpretation of SN 2025ulz as a Type IIb SN.

In a recent preprint, O'Dwyer et al. (2026) report later detections in radio at 6 GHz and 10 GHz, around 100 days after the GW. As shown in their Fig. 2, the implied luminosity is in good agreement with that of other type IIb SNe, where the emission most likely arises from the interaction of the ejecta with a circumstellar medium. Hence, these observations support our interpretation of the source. The authors also claim that the emission can be alternatively explained by a relativistic jet with a viewing angle $\theta_{\text{obs}} \sim 32^\circ$. This is consistent with our conclusion that a jet, if present, should have $\theta_{\text{obs}} \gtrsim 12^\circ$, although we note that they assume different jet structure and microphysical parameters than those adopted here.

3.3. Radio emission as due to star formation

While some of our radio observations did provide evidence of emission close to the location of SN 2025ulz, overall we did not find clear signs of variability. It is instructive to estimate the

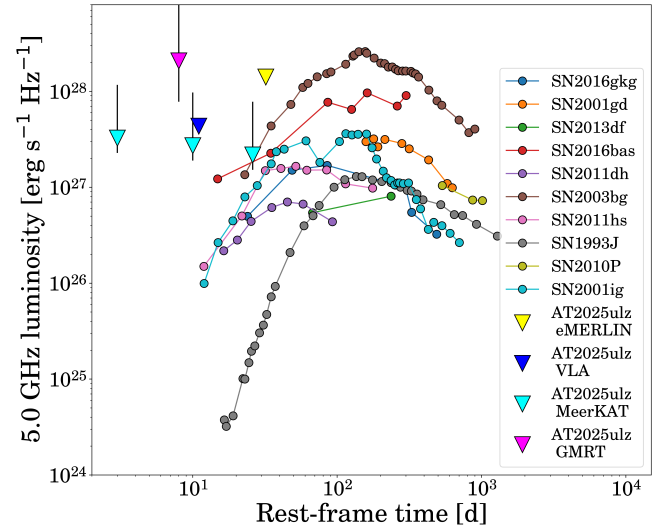


Fig. 10. 5 GHz luminosity density of the radio emission from type IIb SNe. Upper limits for SN 2025ulz are represented with inverted triangles. The e-MERLIN upper limit at 5.1 GHz is represented in yellow, while the VLA upper limit at 6 GHz is represented in blue. The uGMRT (1.2 GHz) and MeerKAT (3 GHz; estimated as $3 \times \text{RMS}$) upper limits are in magenta and cyan respectively. The vertical error bars show the flux variation assuming two different spectral slopes of -0.7 and $+2.5$, typical of radio SN. Data for the SNe are from Nayana et al. (2022), Weiler et al. (2007), Soderberg et al. (2006), Ryder et al. (2004), Bietenholz et al. (2021), Kamble et al. (2016), Krauss et al. (2012), Bufano et al. (2014), Stockdale et al. (2007), Romero-Cañizales et al. (2014).

SFR of the galaxy that would be needed to produce the emission observed. Following Murphy et al. (2011), the host galaxy SFR can be estimated as

$$\text{SFR} \sim 0.64 \left(\frac{L_{1.4 \text{ GHz}}}{10^{28} \text{ erg s}^{-1} \text{ Hz}^{-1}} \right) \text{ M}_\odot \text{ yr}^{-1}. \quad (1)$$

Taking the MeerKAT flux measurement of $F_{1.3 \text{ GHz}} = 116 \pm 14 \mu\text{Jy}$ and assuming a luminosity distance $D_L = 399 \text{ Mpc}$, we estimate a total $\text{SFR} = 1.3 \pm 0.2 \text{ M}_\odot \text{ yr}^{-1}$. This estimate is in excellent agreement with that obtained from MUSE spectroscopy in Sect. 3.2.2, strengthening the interpretation of the radio emission detected in our observations as being entirely produced by SFR.

3.4. Volumetric rate of SN 2025ulz-like events

We can roughly estimate the volumetric rate of SN 2025ulz-like events by assuming this to be the only such transient within the ZTF S250818k search volume. The ZTF search covered a sky area $\Omega_{\text{ZTF}} \sim 168 \text{ deg}^2$ looking for fast-evolving transients associated with galaxies at a distance compatible with the GW event. Taking the 2σ distance uncertainty range of S250818k as being comprised between the 2.5th and 97.5th percentiles of the sky-marginalized distance posterior, $[d_{2.5\%}, d_{97.5\%}] \approx [120, 410] \text{ Mpc}$ (from the Bayestar skymap available at that time; see also Appendix A), the search volume is $V_{\text{ZTF}} \sim (\Omega_{\text{ZTF}}/4\pi \text{ sr}) \times \frac{4\pi}{3}(d_{97.5\%}^3 - d_{2.5\%}^3) \approx 1.1 \times 10^6 \text{ Mpc}^3$. Available pre-discovery upper limits constrain the age of SN 2025ulz at discovery to $\lesssim 1 \text{ day}$ (Gillanders et al. 2025c). Given the observed light curve, the source would have been detectable at the ZTF search typical limit (22 mag, Stein et al. 2025) for around two more days. The likelihood of finding one event with a volumetric rate

density R within a volume V_{ZTF} and a time $\Delta t \sim 3$ days or less after its explosion is given by the Poisson probability $p(1|\lambda) = \lambda \exp(-\lambda)$ with expected number $\lambda = V_{\text{ZTF}} \Delta t R$. From Bayes' theorem, adopting the Jeffreys prior for the Poisson probability $\pi(\lambda) \propto \lambda^{-1/2}$, the posterior probability on the volumetric rate is then

$$p(R) \propto \pi(\lambda) \lambda \exp(-\lambda) \propto R^{1/2} \exp(-V_{\text{ZTF}} \Delta t R). \quad (2)$$

At the 90% credible level, the volumetric rate of SN 2025ulz-like events is therefore in the range $2 \times 10^{-5} \lesssim R/\text{Mpc}^{-3} \text{ yr}^{-1} \lesssim 4 \times 10^{-4}$. This is in good agreement with the $z \lesssim 0.1$ core-collapse supernova (CCSN) volumetric rate $R_{\text{CCSNe}} \sim 10^{-4} \text{ Mpc}^{-3} \text{ yr}^{-1}$ (e.g. Frohmaier et al. 2021; Ma et al. 2025; Pessi et al. 2025), with the lower end of the estimate being roughly compatible with the rate of type IIb SNe, which is around ten percent of the total CCSNe.

3.5. Light curve modelling

As reconstructed in the introduction, early observations of SN 2025ulz initially attracted the attention of the community due to the rapid brightness and colour evolution, which was considered by some as consistent with a KN (Karambelkar et al. 2025; Perley et al. 2025; Kasliwal et al. 2025b). While the re-brightening between 3.5 and 20 days is not expected in a KN scenario, one could hypothesize that a long-lived NS merger remnant with a long spin-down timescale could provide the necessary energy to power the second peak (e.g. Sarin et al. 2022), or that the afterglow of an off-axis GRB jet could be responsible for that emission (but see O'Connor et al. 2025b). To test such a scenario and the general compatibility with a KN hypothesis, we started by fitting a KN model to data up to 4 days post GW trigger. We employed a two-component ejecta model following prescriptions in Villar et al. (2017) with updated heating rates (Sarin & Rosswog 2024). We included an additional contribution from cooling emission of putative material that was shocked and cast into a cocoon following the propagation of a relativistic jet through the KN ejecta (Piro & Kollmeier 2018; Nicholl et al. 2021). Each ejecta component is described by an ejecta mass, a characteristic velocity, and a grey opacity. The mass of the shocked material in the cocoon was assumed to be a fraction, f_{shock} (between 0 and 1) of the mass of the first ejecta component, with an opening angle θ_{cocoon} (between 15 to 30 deg and a shock breakout timescale (effectively the timescale for the jet to reach the breakout radius) t_{shock} (between 0.1 to 20 s). To test our preferred scenario, that of a type IIb SN, we used a one-zone radioactive decay model combined with shock cooling following prescriptions in Arnett (1982), Pinto & Eastman (2000), Piro et al. (2021). Both models are implemented in REDBACK (Sarin et al. 2024) and predict a luminosity and temperature evolution, but not a detailed spectrum. For simplicity, we adopted a blackbody description of the spectrum at all times. We left the explosion time as a free parameter in the SN scenario, while we fixed it to the GW trigger time in the KN model fit. In all fits we included the host-galaxy extinction, parameterized by $A_{V,\text{host}}$ as a free parameter.

The models were tested against the combined photometry from this work, Gillanders et al. (2025c) and Kasliwal et al. (2025a), a subset of which is shown in Fig. 7, with a systematic error contribution of 0.05 mag added in quadrature to the statistical errors of all data points to capture differences due to filter transmission curves. For the KN model, we only considered data up to 4 days after the GW trigger. We defined the posterior probability density of the model parameters assuming a standard

Gaussian likelihood, and used REDBACK to evaluate the models and perform a nested sampling of the posterior through the PYMULTINEST (Feroz et al. 2009; Buchner 2016) sampler, using the BILBY interface (Ashton et al. 2019).

The left panel of Fig. 11 shows the results of fitting the KN plus cocoon cooling emission model (solid lines) and the KN-only model (dashed lines) to the data of the first 4 days. While the KN plus cocoon cooling provides a relatively good fit by eye, the inferred parameters are not consistent with expectations for a BNS or NS-BH merger (see the corner plot in Fig. C.3), where we would expect masses on $\lesssim 0.05$ and opacities above $1 \text{ cm}^2 \text{ g}^{-1}$ for both components (Metzger 2020). In particular, the posterior median and 68% credible ejecta mass, velocity and grey opacity of the first component are $M_{\text{ej},1} = 0.10^{+0.04}_{-0.03} M_{\odot}$, $v_{\text{ej},1} = (0.05 \pm 0.003) c$ and $\kappa_1 = 0.78^{+0.14}_{-0.12} \text{ cm}^2 \text{ g}^{-1}$. The corresponding parameters of the second component are $M_{\text{ej},2} = 0.18^{+0.14}_{-0.11} M_{\odot}$, $v_{\text{ej},2} = (0.21^{+0.09}_{-0.08}) c$, with an opacity of $\kappa_2 = 27 \pm 11 \text{ cm}^2 \text{ g}^{-1}$. Finally, the fraction of material in the shocked cocoon is $f_{\text{shock}} = 0.28^{+0.10}_{-0.16}$, with an opening angle of 24^{+4}_{-5} deg and a shock time, $t_{\text{shock}} = 15.8^{+2.6}_{-3.2}$ s. Turning the cocoon shock cooling emission off results in a KN prediction that does not fit the first g and r band data points post GW trigger (see the dashed lines in Fig. 11) but otherwise has consistent parameters. The combined ejecta properties of the two components are not consistent with expectations for dynamical ejecta or winds produced by an accretion torus in the aftermath of a BNS merger, even in the presence of a long-lived NS (e.g., Metzger 2020). In particular, the inferred opacity for the first component is lower than expected for r-process elements and far more consistent with a supernova, meanwhile the second component is also extremely massive. When stricter priors that reflect realistic expectations for a KN are imposed, such as ejecta masses below $0.1 M_{\odot}$ and opacities above $1 \text{ cm}^2/\text{g}$, then the KN model struggles to explain the first peak and subsequent decline without a significant additional emission component, such as shock-heated cocoon from jet-ejecta interaction (Nicholl et al. 2021; Gillanders et al. 2025c). These results disfavour a KN interpretation for the data, at least with models with grey opacity and diffusion-based one-zone approximations applied here.

Figure 11 shows a comparison of our Type IIb SN shock cooling and radioactive decay model with the g , r and i band light curves of SN 2025ulz. Only these bands are shown in the figure for simplicity, but the fits were performed to the entire dataset. The figure demonstrates that a SN model describes the data well. We provide a corner plot of the posterior probability of the model parameters in Fig. C.4. We derived a total SN ejecta mass of $M_{\text{ej}} = 2.2^{+0.21}_{-0.20} M_{\odot}$, with a ^{56}Ni fraction of $f_{\text{Ni}} = 0.07^{+0.004}_{-0.007}$ (corresponding to a mass $M_{\text{Ni}} = 0.14 \pm 0.01 M_{\odot}$). The characteristic ejecta velocity is $v_{\text{ej}} = 11,270^{+410}_{-434} \text{ km s}^{-1}$. The grey opacity is $\kappa = 0.32^{+0.02}_{-0.03} \text{ cm}^2 \text{ g}^{-1}$, and the kinetic energy is $E_{\text{K}} = 1.7^{+0.27}_{-0.24} \times 10^{51} \text{ erg}$. The shock cooling model requires an envelope radius of $106^{+457}_{-85} R_{\odot}$. We also constrained the explosion time of the supernova to be -1.6 ± 0.15 days before the GW trigger.

The inferred ejecta mass, ^{56}Ni mass, kinetic energy, and the envelope radius are broadly consistent with those inferred by Kasliwal et al. (2025a) and with previous estimates for Type IIb supernovae (e.g. Taddia et al. 2018). We find that the posterior rails against the prior limit on the opacity of $0.35 \text{ cm}^2 \text{ g}^{-1}$, but this is likely due to the simplifications in the modelling, such as the assumption of a blackbody SED.

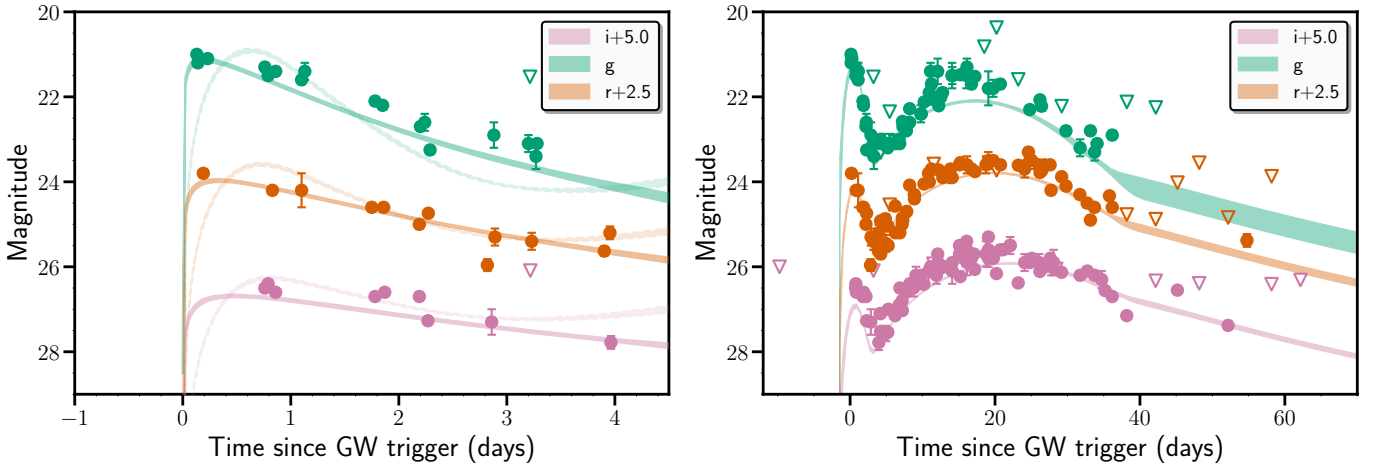


Fig. 11. *Left:* Fit to the first four days of photometry after the GW trigger of SN 2025ulz with two-component KN models. Solid lines refer to the KN plus cocoon cooling model, while the dashed lines are for the KN-only model (see text). The shaded bands contain, at each fixed time, the 68% credible interval of the posterior samples in the g band (green), r band (orange, offset by +2.5 mag for presentation purposes) and i band (offset by +5.0 mag). Circles with error bars show detections from our compiled dataset; triangles show 3σ upper limits. *Right:* Same but in this case the model is shock cooling plus radioactive decay, and the fit is performed including all data up to 60 days after the GW trigger (see text).

4. Discussion and conclusions

4.1. Viability as a GW counterpart

As shown in Sect. 3.2, despite the challenges associated with the background removal, the spectroscopic classification of SN 2025ulz as a type II SN, with SN I Ib as the preferred subtype, is solid. This classification is further strengthened by our rate calculations (Sect. 3.4) and by the results of light curve modelling (Sect. 3.5). Therefore, we can conclude that the appearance of SN 2025ulz is entirely consistent with a type I Ib SN. The probability of a chance association between such a SN and the candidate GW event can be estimated as follows. Assuming 10% of the CCSN population to be of type I Ib (see Sect. 3.4) yields a volumetric rate density $R_{\text{SN I Ib}} \sim 10^{-5} \text{ yr}^{-1} \text{ Mpc}^{-3}$. The probability of having at least one such event in the ZTF search volume within $\Delta t = 3$ days of any random point in time by chance is then equal to $p(N_{\text{I Ib}} > 0) = 1 - \exp(-V_{\text{ZTF}} \Delta t R_{\text{SN I Ib}}) \approx 9\%$.

More generally, the probability that SN 2025ulz and S250818k are unrelated, factoring in the fact that the GW event is most likely a noise artefact, can be computed as $p_{\text{unrel}} = p_{\text{astro}} p_{\text{chance}} + (1 - p_{\text{astro}}) \approx 73.5\%$, where $p_{\text{astro}} = 29\%$ is the probability that S250818k is of astrophysical origin. These calculations show that the simplest and most conservative conclusion is that SN 2025ulz is not related to S250818k.

Given that another association between a candidate SSM BNS merger and a type I Ib SN has been claimed recently (S251112cm and SN2025adtq, with a similar p_{chance} ; Hall et al. 2026a), it is instructive to estimate how many coincidences are needed in order to claim a certain statistical significance of the association between the two classes of events. If we assume, for simplicity, that all coincidences have the same probability p_{unrel} of being unrelated, then the probability of having N random coincidences is simply⁸ p_{unrel}^N . The minimum number of such coincidences needed to claim an association between the two classes with a significance s (such that p_s is the corresponding p value) is $N = \log(p_s) / \log(p_{\text{unrel}})$. Assuming optimistically

⁸ Of course, this does not consider a trials factor that would arise in the case where a search for an association had been carried out in $M > N$ cases. Then, the post-trial probability of N random coincidences would be increased by an M -choose- N factor.

that $p_{\text{astro}} \sim 100\%$ for all events, and that $p_{\text{chance}} = 5\%$, then $N = 2$ associations are needed to claim a three-sigma significance ($p_s = 2.7 \times 10^{-3}$), or five associations for a five-sigma significance ($p_s = 5.7 \times 10^{-7}$). This agrees with the calculations of Hall et al. (2026a). If $p_{\text{astro}} = 50\%$ for all events⁹, on the other hand, a three-sigma significance would require ten associations. Hence we conclude that, from the statistical point of view, the available observations do not yet support an association between SSM BNS mergers and type I Ib SNe.

4.2. Superkilonova scenario

Our conclusions on the SN 2025ulz–S250818k association do not provide support for the ‘superkilonova’ scenario¹⁰ proposed by Kasliwal et al. (2025a). Since this scenario has recently gained increasing attention (Metzger et al. 2024; Chen & Metzger 2025; Kasliwal et al. 2025a; Hall et al. 2025a, 2026b,a; Baibhav et al. 2026), we further discuss here its viability as an explanation of our event and of the other GW events S251112cm and GW190814, which have been proposed to be associated with SN2025adtq (which exploded ~ 2 days prior to S251112cm, in a time volume that corresponds to a similar chance association probability $p_{\text{chance}} \sim 2\text{--}9\%$; Hall et al. 2026a) and SN2019npv (~ 60 days before the GW, $p_{\text{chance}} \sim 4\text{--}5\%$; Baibhav et al. 2026), respectively. First, we summarize the main elements of the scenario, for clarity. A stellar mass black hole (BH) forms from the collapse of the iron core of a rotating massive star – a collapsar (MacFadyen & Woosley 1999). Due to the fast rotation of the star, the collapsing envelope forms an accretion disk around the BH. The outer rims of the disk (at around one hundred gravitational radii and beyond)

⁹ The S251112cm event was found by the SSM search of the MBTA pipeline (All  n   et al. 2025), with a FAR of about $1/6 \text{ yr}^{-1}$. No p_{astro} was reported for this event by the LVK collaboration. If the relation between p_{astro} and FAR for SSM events is similar to that of BNS events, then the FAR of S251112cm does indeed correspond to a $p_{\text{astro}} \sim 50\%$ (see Fig. 11 of All  n   et al. 2025).

¹⁰ This should not be confused with the processes described in Siegel et al. (2022), for which the term ‘super-kilonova’ was initially coined.

are prone to fragmentation. Due to the partial neutronization of the disk, fragments somewhat lighter than a solar mass can overcome the electron degeneracy pressure and form SSM NSs (Piro & Pfahl 2007). Some of these light NSs can end up in a binary due to migration or three body interactions, and merge before spiralling into the central BH (Metzger et al. 2024). For what concerns GW emission, the basic predictions of this scenario are one or more SSM BNS mergers, followed by the eventual inspiral of their remnants (which can be NSs or light BHs) into the central BH. The time separation between a SSM BNS merger and the final high-mass-ratio merger in this scenario can range from hours (Metzger et al. 2024) to days (Hall et al. 2026a) or even months (Baibhav et al. 2026).

As for electromagnetic emission, the collapsar scenario is generally expected to lead to a stellar explosion driven by a jet launched by the central BH or high-velocity outflows from the accretion disk (MacFadyen & Woosley 1999; Metzger et al. 2024). SSM BNS merger remnants themselves could take the form of highly magnetized, highly spinning proto-NSs, which could release a large fraction of their rotational energy in the form of a relativistic wind (Metzger et al. 2024), further powering the explosion. Such an engine-driven explosion is usually expected to be more energetic than a standard neutrino-driven SN, and it could present peculiar features such as non-thermal emission (in the radio and/or the X-rays) arising from relativistic external shocks or long-lasting central engine activity, in addition to the usual nickel-decay-powered emission, but no definite predictions have been made yet in this respect, to our knowledge.

In the case of S250818k and also S251112cm, the predicted GW emission from the high-mass-ratio merger between the SSM BNS remnant and the central BH has not been detected. Proponents of the scenario attributed this to the duty cycle limitations of the GW detectors, which presumably caused these signals to be missed (Hall et al. 2026a). Similarly, the lack of SSM BNS merger signals prior to the high-mass-ratio GW190814 event was attributed to the excessive distance of the source, which would have made these signals too weak to trigger the GW detector searches (Baibhav et al. 2026). Therefore, while none of the three cases presents GW emission that fully adheres to the predictions of the scenario, this does not suffice to falsify the model.

Because of the less definite predictions for the electromagnetic emission, it is more difficult to make strong statements in that regard. Still, it seems natural to expect a SN caused by a collapsar to present some distinguishing features with respect to ordinary neutrino-driven SNe, at least in terms of energetics and ejecta mass. Indeed, GRB-associated broad-lined type Ic SNe – the prototypical collapsar-driven SNe – show clear signs of high ejecta velocities (in excess of 0.1 c) and large ejecta masses (of the order of several solar masses), which translates to kinetic energies in excess of 10^{52} erg (Cano et al. 2017). Both SN 2025ulz and SN 2025adtq, on the other hand, have been successfully modelled as type IIb SNe with ejecta masses of a few $M_{\odot}$ and kinetic energy of 10^{51} erg or less (see Sect. 3.5 and Kasliwal et al. 2025a; Hall et al. 2026a), and their spectra do not present broad lines indicative of high expansion velocities. As discussed in Sect. 3.2.3, the radio emission at the SN 2025ulz position detected by O’Dwyer et al. (2026) is in line with that of other type IIb SNe. Kasliwal et al. (2025a) claimed a peculiar colour evolution for SN 2025ulz, but the comparison with known type IIb SNe in Fig. 5 of Gillanders et al. 2025c instead does not seem to show any unusual behaviour. The lack of any clear peculiarity in these SNe must be interpreted as either evidence that most CCSNe are the result of a collapsar – which we consider to be very unlikely – or that these are just ordinary

neutrino-driven SNe, which again conflicts with the superkilonova interpretation. SN2019npv has not been studied in a similar detail, but we note that also in this case the available spectrum does not feature broad lines, and the identified P-Cygni feature at $1.08 \mu\text{m}$ is consistent with a modest expansion velocity of 7000 km/s (Andreoni et al. 2020).

4.3. Young type IIb SNe as interlopers

The difficulty in the search for a KN does not simply reside in the faintness or rapid fading of the source: one of the main challenges is in discriminating contaminants. In a typical search region of hundreds of square degrees, the contaminant sources are several orders of magnitude more common than KNe (Oates 2025; Fulton et al. 2025). In recent years, it has become clear that type IIb SNe are particularly pernicious in this regard: observations have demonstrated that 30–50 percent of type IIb SNe feature a shock-cooling tail (Ayala et al. 2025), where the light curve displays a rapid initial decline following shock breakout in a relatively extended progenitor, before rising in brightness again to the main ^{56}Ni -powered peak. Unfortunately, during the first few days of this shock-cooling tail, the SN has a relatively featureless spectrum (e.g. Wang et al. 2023; Subrayan et al. 2025; Xi et al. 2026; Farah et al. 2026), similarly to KNe (Pian et al. 2017).

Focusing on SNe IIb only, assuming they comprise 10% of the CCSN population (see Sect. 3.4), and further assuming only 30% of them feature a shock-cooling tail, we conservatively find that the volumetric rate of type IIb SN shock-cooling tails is about $R_{\text{SNIIb-SC}} \sim 0.3 \times 10^{-5} \text{ yr}^{-1} \text{ Mpc}^{-3}$. The 90% localization area of S250828k was $\Omega_{90\%} = 949 \text{ deg}^2$ on the sky. Assuming that anything within the 90% region and within the two-sigma GW distance uncertainty will appear as a plausible candidate, our potential search volume is therefore $V_{\text{search}} \sim 6.5 \times 10^6 \text{ Mpc}^3$ (the same calculation as in Sect. 3.4, but with a different sky area). Consequently, within this region there will be around $V_{\text{search}} \times R_{\text{SNIIb-SC}} \sim 19 \text{ yr}^{-1}$ type IIb shock-cooling tails.

The final assumption we must make is for how long a shock-cooling tail can be mistaken for a KN. Crawford et al. (2025) find that the mean duration for a cooling tail is 6 days, and so we assume that any such SN that explodes up to a week before the KN is discovered will appear as a plausible counterpart.

Putting all of this together, and modelling the occurrence of SNe as a Poissonian process, we find that there is a roughly 30% chance of one or more type IIb cooling tail interlopers in the case of S250818k, and indeed any comparable event. In fact, the probability is likely even higher: in the updated GW skymap from the offline parameter estimation (LVK Collaboration 2025c, available on the second day after the GW trigger), the SN 2025ulz distance was at the 98.8th percentile of the sky-marginalized distance posterior, showing that the community will follow up targets whose spatial association with a GW is quite marginal.

4.4. Consequences for future KN searches

It is interesting to consider the implications of the above discussion in the context of GW counterpart searches. While a 30% chance of a IIb cooling tail in a GW localization region does not appear to be a strong limiting factor, we already noted that this is likely an underestimate (and, of course, this does not take into account other contaminants such as luminous blue variable outbursts, cataclysmic variable stars in chance alignment with galaxies, and shock cooling in peculiar thermonuclear SNe). In fact, the experiences of O3 and O4 suggest that every GW will

have at least one initially plausible candidate for the counterpart that ultimately turns out to be unrelated, unless the localization of the event is particularly good (as was the case for GW190814 – Ackley et al. 2020; Abbott et al. 2020). Clearly, as large amounts of telescope time are invested in the follow-up of such events, it behoves us to try and reduce this.

A possible strategy is to take advantage of the fact that most of the localization probability is concentrated in the central region of the skymap. If we can significantly reduce the counterpart search area, then rather than expecting 0.3–1 plausible appearing interlopers, we would expect zero. In other words, if we want to find one KN, then rather than exhaustively searching the error box of one GW trigger, we should search the most probable 10–30% region of three to ten BNS mergers. Of course, such a strategy relies on GW detectors providing a steady stream of BNS alerts, as it would systematically miss 70–90% of the counterparts by definition. As provocative as it may sound, this might ultimately prove to be the most effective strategy to limit the observing time spent characterizing contaminants, in a future where BNS mergers are routinely detected by the GW network, but still with typical localizations of hundreds of square degrees.

The implication of the IIb shock-cooling tail rate is more problematic for un-triggered KN searches (e.g. Andreoni et al. 2022; Zhu et al. 2023), where an optical survey is used to look for transients that appear plausibly consistent with KNe without any high energy or GW detection. If we take a volumetric BNS rate of $\sim 10^{-8} - 10^{-7} \text{ yr}^{-1} \text{ Mpc}^{-3}$ (Abac et al. 2026), the shock-cooling tails are 30–300 times more common. In fact, the only winning move in such a scenario is to target passive galaxies. Around 70% of the mass in the local Universe lies in non-star-forming galaxies (Kelvin et al. 2014), opening the prospect of only following up on candidates found in such hosts (pre-selecting galaxies either through colour cuts or spectroscopy). The IIb shock-cooling tails are inevitably followed by luminous ^{56}Ni -powered rising light curves which peak on timescales of 20 days. These easily distinguish SNe from KNe, but if we wait for the re-brightening signature, we miss the opportunity to observe over the first 4–7 days, at which point a KN at 400 Mpc would likely be fainter than $r \sim 24$ when we realize it has not re-brightened. The era of Rubin and LSST promises many candidates, but challenges are significant, and the role of spectroscopy in rejecting contaminants remains fundamental.

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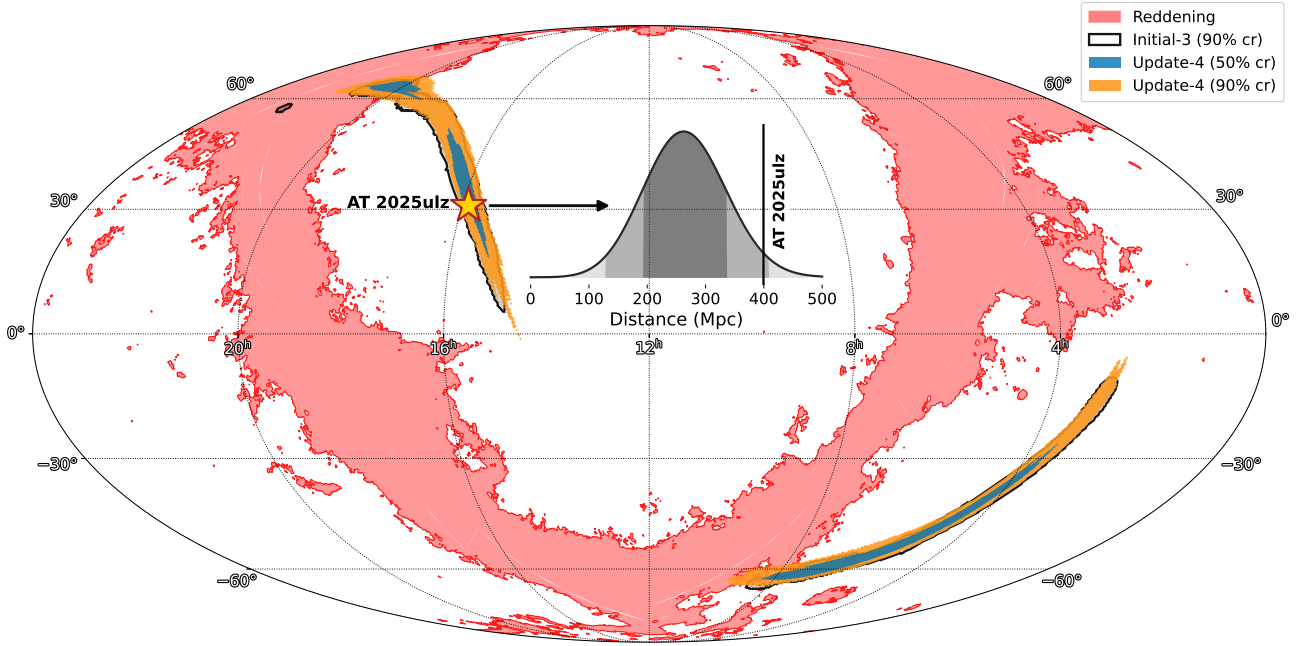


Fig. A.1. Localization of the GW event candidate S250818k. *Main panel:* Mollweide projection of the 50% and 90% credible regions of the update skymap (light blue: 50%, 276 deg²; orange: 90%, 949 deg²) and the 90% credible region of the initial skymap (black contour, 786 deg²). The red shaded region marks the sky positions for which the [Schlegel et al. \(1998\)](#) Galactic reddening map predicts $A_V > 1$. The sky position of the optical transient SN 2025ulz is marked with a yellow star. *Inset:* Distance posterior conditioned at the position of SN 2025ulz (solid black line), with the distance of the source indicated by a vertical line.

Appendix A: S250818k sky localization

Figure A.1 summarizes the sky localization of S250818k, of which we show both the 90% and 50% credible regions of the sky-projected position (constructed following [Greco et al. 2022](#)), and the sky-position-conditional distance posterior (inset, constructed following [Singer et al. 2016](#)). The sky position of SN 2025ulz is marked by a star, and its distance is marked by a vertical black line in the inset, for comparison. The LVK Collaboration issued four notices about S250818k: two preliminary notices, followed by an initial and an update notice¹¹. The latter two were accompanied by GCN circulars ([LVK Collaboration 2025b,c](#)). The plotted sky-localization areas refer to the initial circular¹² (based on the rapid parameter estimation code [Bayestar](#), [Singer & Price 2016](#)) and the update circular¹³ (based on offline full parameter estimation with [Bilby](#), [Ashton et al. 2019](#)). The sky-position-conditional distance posterior refers to the latter. The black contour in the main panel (not readily discernible because it is largely coincident with the subsequent update) marks the 90% credible region of the initial skymap, covering 786 deg². The 50% and 90% credible regions of the updated skymap are shown in light blue and orange, corresponding to sky areas of 276 deg² and 949 deg², respectively. The position of SN 2025ulz lies within the 35% credible region of the update skymap, which covers an area of 160 deg². In distance, the object falls within the 2σ interval, towards the high-distance tail of the distribution. The main panel in the figure includes a Galactic dust reddening and extinction map (red) based on [Schlegel et al. \(1998\)](#), restricted to the highest-extinction values ($A_V > 1$). The sky localization of S250818k lies largely outside these high-reddening areas, indicating that dust-related absorption effects along the line of sight had a negligible impact on the search for candidate electromagnetic counterparts.

Appendix B: Data tables

Table B.1 summarizes the results of our photometric measurements on difference images of SN 2025ulz. Table B.2 shows a log of our radio observations at the source position, with a summary of the setup and resulting flux density measurements or 5σ upper limits.

Appendix C: Additional information

Figure C.1 shows our FORS2 spectrum of SN 2025ulz from the night of Aug 20. Unfortunately, this spectrum did not provide useful information for the classification of the transient.

Figure C.2 shows a zoom-out with respect to the VLA S-band image in Fig. 6. This figure was included to demonstrate the presence of a bright nearby source which made the reduction slightly more difficult (see 2.3.1).

¹¹ <https://gracedb.ligo.org/superevents/S250818k/view/>

¹² [bayestar.multiorder.fits,2](#)

¹³ [Bilby.offline0.multiorder.fits,0](#)

Table B.1. Optical and near-infrared photometry of SN 2025ulz.

Night	Mid-time MJD	Instrument	Band	Mag
Aug 21	60909.00996	VLT/FORS2	<i>r</i>	22.70±0.15
Aug 22	60910.00380	VLT/FORS2	<i>r</i>	22.95±0.17
Aug 21	60909.01913	VLT/FORS2	<i>i</i>	22.78±0.15
Aug 22	60910.01758	VLT/FORS2	<i>i</i>	22.57±0.15
Aug 21	60908.98651	VLT/FORS2	<i>z</i>	22.21±0.10
Aug 22	60909.98656	VLT/FORS2	<i>z</i>	22.47±0.15
Aug 20	60907.96934	VLT/HAWK-I	<i>K</i>	22.30±0.50
Aug 22	60909.98755	VLT/HAWK-I	<i>K</i>	22.50±0.50
Aug 20	60907.87521	NOT/ALFOSC	<i>r</i>	23.46±0.14
Aug 21	60908.95761	NOT/ALFOSC	<i>r</i>	23.13±0.11
Aug 22	60909.91030	NOT/ALFOSC	<i>r</i>	22.37±0.11
Aug 26	60913.91633	NOT/ALFOSC	<i>r</i>	21.80±0.11
Sep 22	60940.84640	NOT/ALFOSC	<i>r</i>	21.83±0.06
Oct 11	60959.82483	NOT/ALFOSC	<i>r</i>	22.88±0.15

Notes. Magnitudes are in the AB system and not corrected for Galactic extinction.

Table B.2. Radio observations log and results.

Telescope	Date (dd-mm-yyyy)	Frequency (GHz)	FWHM (arcsec×arcsec)	P.A. (deg)	RMS (μJy/beam)	Flux density (μJy)
VLA (22A-414)	29-08-2025	3	1.97×1.37	74	7	< 21
		6	1.06×0.74	77	8	< 24
		10	0.58×0.46	56	9	< 27
		15	0.35×0.31	68	7	< 21
MeerKAT	21-08-2025	3.06	4.04×4.04	0	6	70±9
	28-08-2025	3.06	3.47×3.47	0	5	76±9
	14-09-2025	1.28	6.42×6.42	0	8	116±14
	13-09-2025	3.06	3.31×3.31	0	4	69±8
uGMRT	26-08-2025	1.23	7.24×2.19	-25	23	<115
e-MERLIN	19-09-2025	5	0.049×0.030	32	26	<130

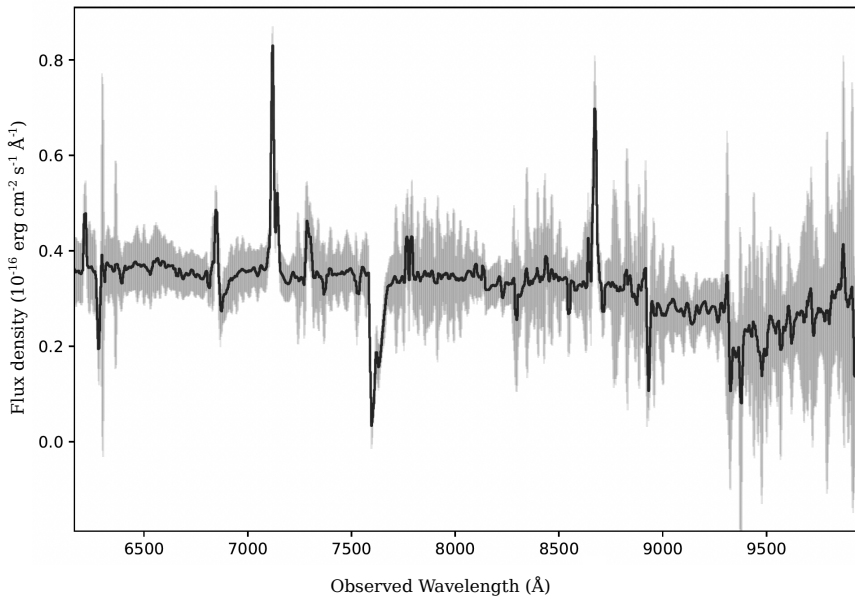


Fig. C.1. The FORS2 spectrum of SN 2025ulz taken on the night of Aug 20. We show in grey the spectrum at the native pixel sampling. The black line shows a slightly smoothed spectrum to mitigate contamination from sky line residuals.

Figure C.3 shows the corner plot demonstrating the posterior probability density of the two-component KN model parameters from the fit to photometric data up to 5 days after the GW trigger (see Sect. 3.5). Figure C.4 shows a similar plot for the shock cooling plus ^{56}Ni -decay powered SN model, fitted to the complete photometric dataset.

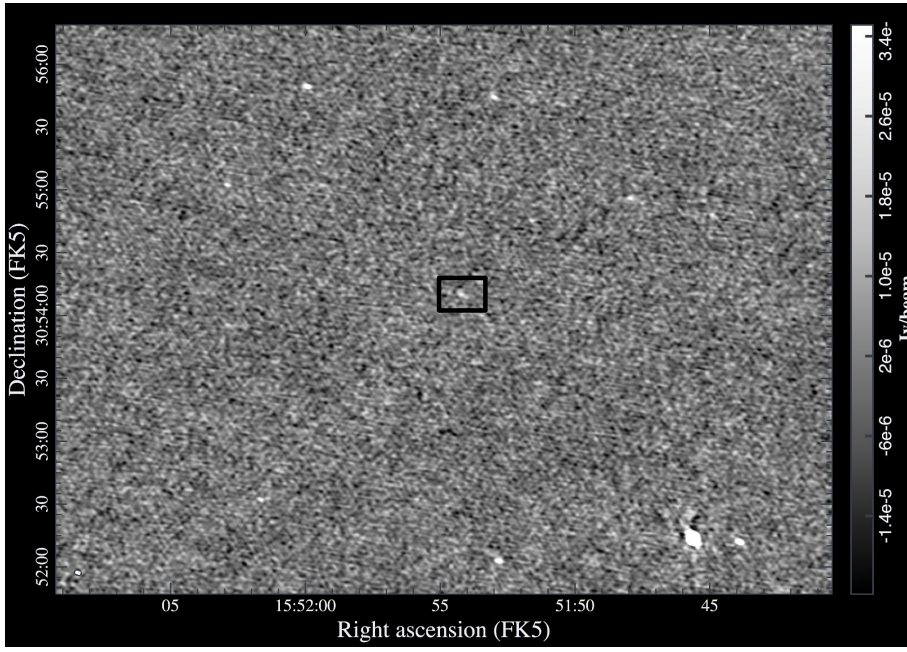


Fig. C.2. Wider-field VLA S-band image. The black rectangle in the centre shows the region covered by the image in Fig. 6. The wider field in this image shows the bright close-by source (visible in the lower-right corner) that made our analysis more complex.

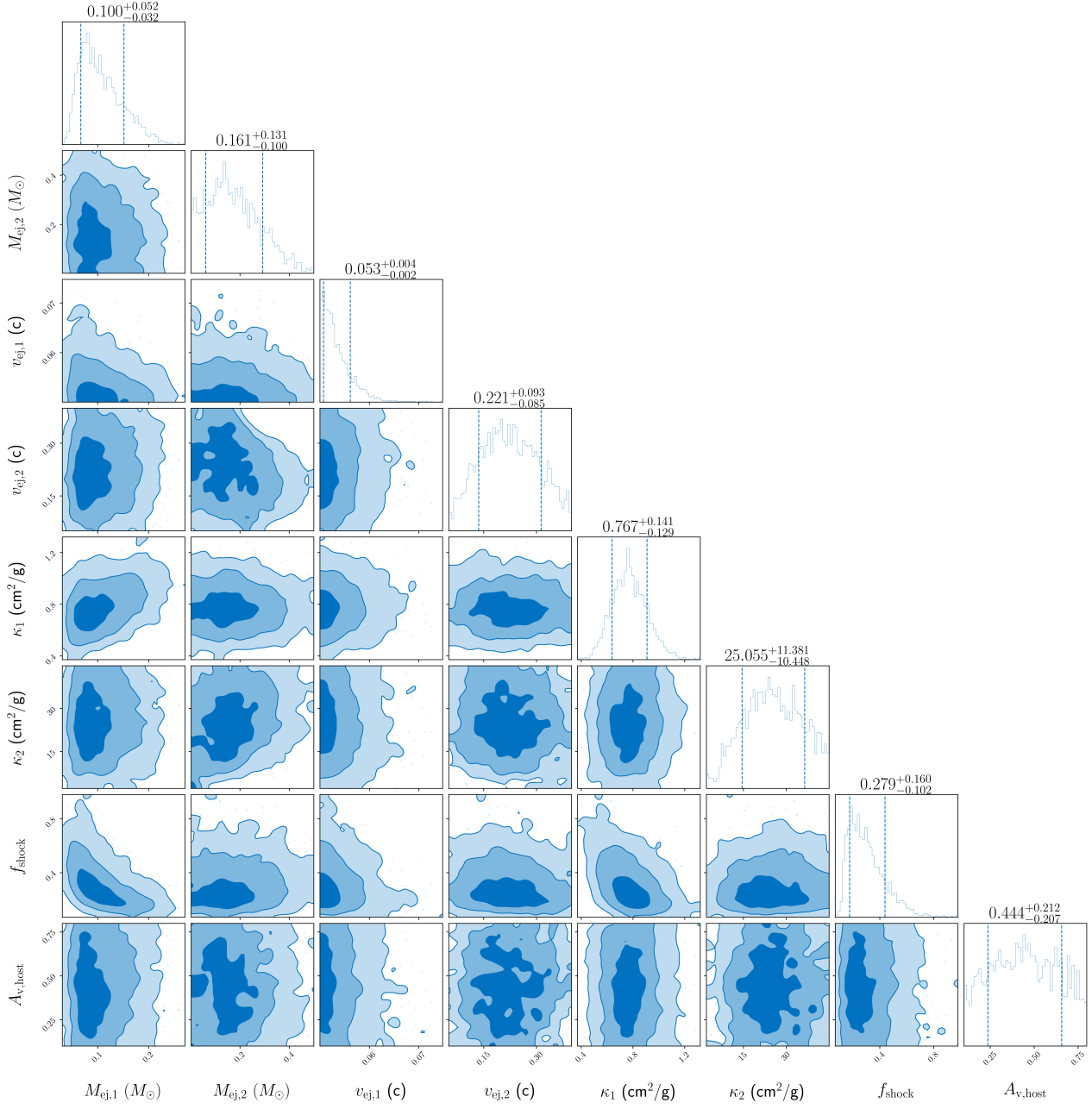


Fig. C.3. Corner plot from our fit to the photometry (shown in the left panel of Fig. 11) with a two-component kilonova model.

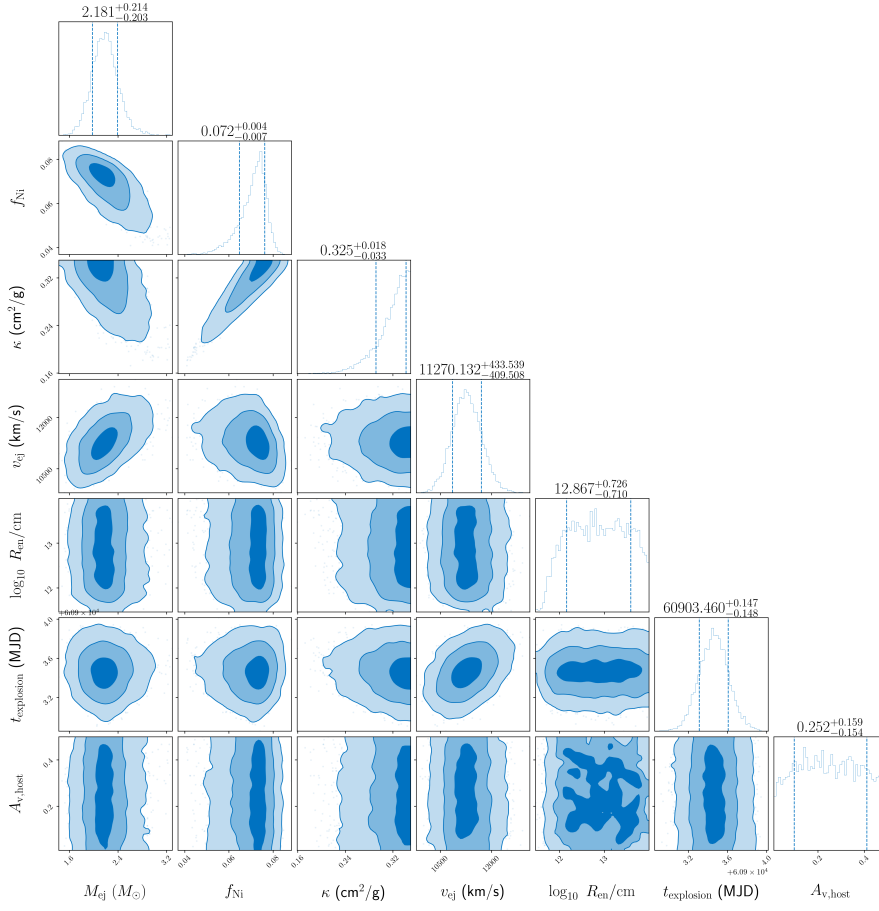


Fig. C.4. Corner plot showing salient parameters from our fit to the photometry (shown in the right panel of Fig. 11) with a shock cooling and radioactive decay model.