



The electron-capture origin of supernova 2018zd

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In the transitional mass range (~8-10 solar masses) between white dwarf formation and iron core-collapse supernovae, stars are expected to produce an electron-capture supernova. Theoretically, these progenitors are thought to be super-asymptotic giant branch stars with a degenerate O + Ne + Mg core, and electron capture onto Ne and Mg nuclei should initiate core collapse¹⁻⁴. However, no supernovae have unequivocally been identified from an electron-capture origin, partly because of uncertainty in theoretical predictions. Here we present six indicators of electron-capture supernovae and show that supernova 2018zd is the only known supernova with strong evidence for or consistent with all six: progenitor identification, circumstellar material, chemical composition⁵⁻⁷, explosion energy, light curve and nucleosynthesis8-12. For supernova 2018zd, we infer a super-asymptotic giant branch progenitor based on the faint candidate in the pre-explosion images and the chemically enriched circumstellar material revealed by the early ultraviolet colours and flash spectroscopy. The light-curve morphology and nebular emission lines can be explained by the low explosion energy and neutron-rich nucleosynthesis produced in an electron-capture supernova. This identification provides insights into the complex stellar evolution, supernova physics, cosmic nucleosynthesis and remnant populations in the transitional mass range.

On 2018 March 2.49 (UT dates are used throughout), we discovered AT 2018zd 13 at an unfiltered optical magnitude of 17.8 in the outskirts of NGC 2146 (redshift z=0.002979 (ref. 14)), where pre-explosion Hubble Space Telescope (HST) and Spitzer Space Telescope images yield a faint progenitor candidate (Extended Data Figs. 1 and 2, and Methods). Combined with our pre-discovery

detection at 18.1 mag on 2018 March 1.54, we estimate an explosion epoch of 2018 March $1.4\pm0.1~(\sim3\,\text{h})$ before the first detection; Extended Data Fig. 3) and use it as a reference epoch for all phases. At 4.9 d post explosion, we classified AT 2018zd as a young type II (hydrogen rich) supernova (SN), designating it SN 2018zd¹⁵. Over time, SN 2018zd developed a plateau and broad Balmer-series P Cygni lines in the optical light curves and spectra (respectively), further classifying it as a type II-P (plateau) SN (Extended Data Figs. 3 and 4). The luminosity distance of NGC 2146 is uncertain, ranging from 11 Mpc to 18 Mpc in the literature ¹⁶. Thus, we apply the standard candle method and adopt a distance of $9.6\pm1.0\,\text{Mpc}$ (Methods). Because of the wide distance range, we focus mainly on distance-independent measurements.

Unlike Fe core-collapse (CC) SN explosions of red supergiant (RSG) stars, electron-capture (EC) SN explosions of super-asymptotic giant branch (SAGB) stars are robustly realized by first-principle simulations, facilitated by the steep density gradient outside the degenerate core. Simulations consistently predict explosion energy ($\sim 2 \times 10^{50}$ erg) and 56 Ni yield ($\sim 3 \times 10^{-3} M_{\odot}$, with an upper limit $\lesssim 10^{-2} M_{\odot}$) that are an order of magnitude lower than those observed for typical Fe CCSNe^{8,9,11}, but are consistent within the lowest-mass Fe CCSNe (Supplementary Information). Despite the low explosion energy, the low mass and large radius of an SAGB star result in a light-curve morphology virtually identical to that of type II-P SNe, except for a larger drop (~ 4 mag) from the plateau to the radioactive decay tail, owing to the low 56 Ni production 10 .

Among a sample of well-observed type II SN light curves¹⁷ (Fig. 1), SN 2018zd fits in the type II-P morphology and shows the largest plateau drop (~3.8 mag). Even among a sample of low-luminosity type II-P SNe¹⁸ that often show larger plateau drops

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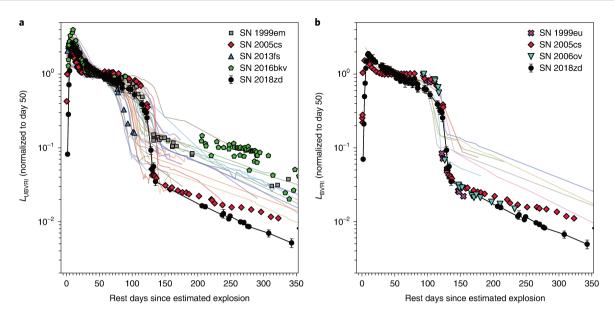


Fig. 1 Normalized pseudobolometric light curves. **a**, Comparison of the normalized pseudobolometric (UBVRI; Supplementary Information) light curve of SN 2018zd with a well-observed type II SN sample¹⁷ (transparent lines), including archetypal SN 1999em, low-luminosity SN 2005cs and early-flash SN 2013fs, along with low-luminosity and early-flash SN 2016bkv⁷⁷. **b**, Comparison of the normalized pseudobolometric (BVRI) light curve of SN 2018zd with a low-luminosity type II-P SN sample¹⁸, including SNe 1999eu and 2006ov with the largest plateau drops ever (to our knowledge). Error bars denote 1 σ uncertainties. Because of the distance uncertainty of SN 2018zd, we normalize each light curve to day 50 and make the comparisons distance independent. SN 2018zd shows the largest plateau drop and is comparable to that of SNe 1999eu and 2006ov, indicating an intrinsically low ⁵⁶Ni production.

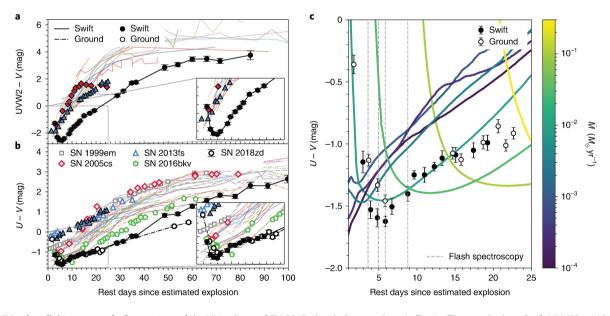


Fig. 2 | UV-colour light curves. a,b, Comparison of the UV colours of SN 2018zd with the sample as in Fig. 1a. The panels show Swift UVW2 -V (**a**) and Swift and ground-based U-V colour evolution (**b**). Note the pronounced sharp blueward colour evolution of SN 2018zd over the first ~5 d, shown in the insets, suggesting a possible delayed shock breakout through dense CSM. **c**, Comparison of the U-V colour of SN 2018zd with our MESA + STELLA CSM models (Methods and Extended Data Fig. 6) assuming a typical constant wind velocity of 20 km s⁻¹ (Fig. 3), colour-coded by the mass-loss rate. To reproduce the observed early blueward evolution, $\dot{M} \approx 0.01 \, M_{\odot} \, \text{yr}^{-1}$ for the last ~10 yr before the explosion is required. The observed flash-spectroscopy epochs (Fig. 3) are marked by the vertical dashed lines and are consistent with the blueward colour evolution. Error bars denote 1 σ uncertainties.

than other type II subclasses (Fig. 1), SN 2018zd is comparable to SNe 1999eu and 2006ov with the largest drops ever observed, indicating an intrinsically low $^{56}\mathrm{Ni}$ production. For SNe 1999eu and 2006ov, the lack of additional data prevents the investigations of other ECSN indicators; the light curves alone cannot be conclusive evidence (see Methods for the light-curve degeneracy). The tail

decline rate of SN 2018zd is consistent with the 56 Co heating rate, and an estimated 56 Ni mass is $(8.6\pm0.5)\times10^{-3}\,M_{\odot}$ at the assumed luminosity distance of 9.6 Mpc (Extended Data Fig. 3). This is larger than the canonical 56 Ni yield for ECSNe, but still within the upper limit (see also Supplementary Information for the effect of distance uncertainty).

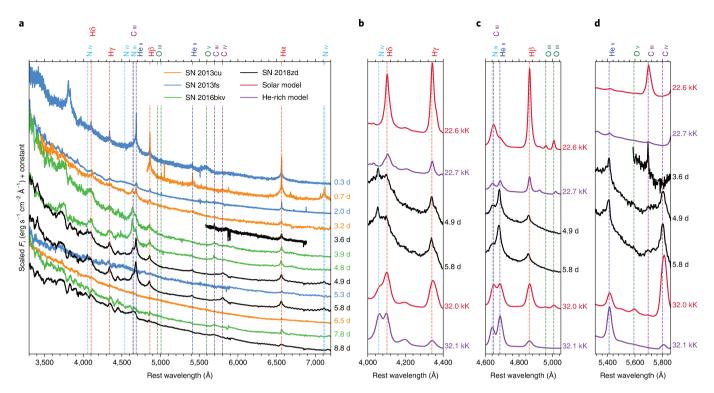


Fig. 3 | Flash spectral time series. a, Comparison of the flash spectral time series of SN 2018zd with that of well-sampled type II-P SNe 2013fs²¹ and 2016bkv⁷⁷, and type IIb (mostly stripped H-rich envelope) SN 2013cu⁷⁸. SN 2018zd exhibits the persistent flash features (≥9 d), while most of the flash features in the other SNe disappear within ~5 d after the explosion. **b-d**, Comparison of the flash spectral time series at three different zoomed-in wavelength regions of SN 2018zd with the scaled and resampled flash spectral models of solar-abundance (X_H = 0.70, X_{He} = 0.28, X_C = 3.02 × 10⁻³, X_N = 1.18 × 10⁻³, X_O = 9.63 × 10⁻³) and He-rich (X_H = 0.18, X_{He} = 0.80, X_C = 5.58 × 10⁻⁵, X_N = 8.17 × 10⁻³, X_O = 1.312 × 10⁻⁴) atmospheres with \dot{M}_{mod} = 3 × 10⁻³ \dot{M}_{\odot} yr⁻¹ and v_{mod} = 150 km s⁻¹ (the densest CSM with the finest temperature grid spacing)²². The temperatures are constrained to be within ~20,000 K (at 3.6 d) to 30,000 K (at 4.9-5.8 d) from the MESA + STELLA UV-colour models (Fig. 2). The observed features are expected to be narrower and stronger if resolved, as ρ_{obs}/ρ_{mod} = (\dot{M}_{obs}/v_{obs})/(\dot{M}_{mod}/v_{mod}) = 25 with \dot{M}_{obs} = 0.01 \dot{M}_{\odot} yr⁻¹ from the UV colours and assuming v_{obs} = 20 km s⁻¹ (the wind P Cygni components of SN 2018zd are not resolved, only giving an upper limit v_{obs} < 76.3 km s⁻¹ from the highest spectral resolution of C III λ 5696 at 3.6 d). On the basis of the model comparisons, the line ratios of N IV/H δ > 1 (**b**) and He II/H β > 1 (**c**), the transition from C III to C IV (**d**) and the lack of O III and O V lines (**c**, **d**) observed in SN 2018zd suggest He-, C- and N-rich, but O-poor CSM composition.

As SAGB stars are thought to have mass-loss rates $(\dot{M}\approx 10^{-4}~M_{\odot}~\rm yr^{-1})$ a few orders of magnitude higher than those of RSG stars of similar initial mass⁵, the circumstellar material (CSM) density is expected to be a few orders of magnitude higher, as it scales as $\rho_{\rm CSM} \propto \dot{M}/\nu_{\rm wind}$, assuming constant wind mass loss with similar SAGB and RSG wind velocities $^{19}~\nu_{\rm wind}$. Compared with RSG stars, the CSM composition of SAGB stars can be He-, C-and N-rich, but O-poor, depending on the efficiency of the SAGB dredge-up and dredge-out that bring the partial H- and He-burning products to the stellar surface 6,7 .

In a sample of type II SN ultraviolet (UV) colours¹⁷, SN 2018zd stands out, reaching the minimum in U-V colour (that is, becoming bluer until) ~5 d after the explosion (Fig. 2), which suggests a possible delayed shock breakout through dense CSM. In such a case, a photosphere initially forms inside the unshocked optically thick CSM²⁰; this provides an additional power source leading to the bluer colour when the shock front is propagating through the CSM (see Extended Data Fig. 5 for the same effect on the photospheric velocity). Our MESA+STELLA CSM light-curve models (Methods and Extended Data Fig. 6) show that $\dot{M}\approx 0.01~M_{\odot}~\rm yr^{-1}$ for the last ~10 yr before the explosion is required to reproduce the early-time U-V colour of SN 2018zd, assuming a typical constant¹⁹ $v_{\rm wind}=20~\rm km\,s^{-1}$ (Fig. 2). Since the estimated mass loss is a few orders of magnitude greater than that expected from SAGB or RSG winds, it is probably dominated by eruptive events^{5,6}.

Consistent with the possible delayed shock breakout seen in the early UV colour, SN 2018zd exhibits unusually persistent (≥9d) flash features, reaching the highest ionization states at ~5 d after the explosion (Fig. 3). The strengths of flash features depend on the photospheric temperature, CSM density and CSM abundance^{21–23}. We constrain the photospheric temperature and CSM density of SN 2018zd by the MESA+STELLA UV-colour models. Then we use emission-line intensity ratios as diagnostics of CSM abundance by comparing with the flash spectral models of solar-abundance and He-rich atmospheres²² (Fig. 3; note that the line ratios are not well reproduced by either solar-abundance or He-rich models alone²³, and a mixture of both with higher density needs to be modelled for a more detailed abundance analysis). On the basis of the model comparisons, we estimate He-, C- and N-rich, but O-poor CSM mass fractions of $X_{\text{He}} \approx 0.3 - 0.8$, $X_{\text{C}} \approx 3 \times 10^{-3}$, $X_{\text{N}} \approx 8 \times 10^{-3}$ and $X_{\text{O}} \approx 10^{-4}$, which is more consistent with an SAGB than an RSG atmosphere^{6,7}.

Since the core composition and explosion nucleosynthesis are different from Fe CCSNe (but see Supplementary Information for some caveats on the low-mass end), ECSNe are expected to show distinct nebular spectral features: stronger Ni than Fe lines due to a more stable ⁵⁸Ni yield than radioactive ⁵⁶Ni (a parent nuclide of ⁵⁶Fe) from the innermost neutron-rich ejecta (electron fraction $Y_{\rm e} \lesssim 0.49)^{11,12}$; weak O, Mg and Fe lines owing to the thin (~0.01 M_{\odot}) O+C shell, which is further burned to Fe-group elements^{8,9}; and weak C lines because of the efficient dredge-up/out reducing most

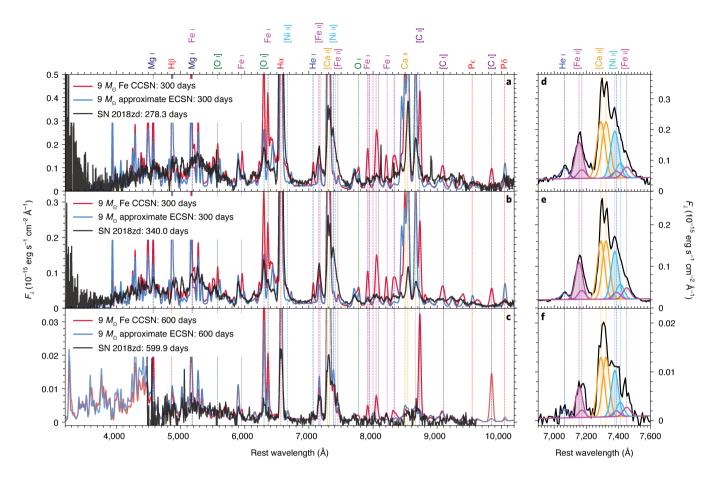


Fig. 4 | Nebular spectral time series. a-c, Comparison of the nebular spectral time series at three different epochs of SN 2018zd with the scaled (by 56 Ni mass and phase) and resampled $9\,M_{\odot}$ Fe CCSN and 'approximate ECSN' (excluding the He-core composition from the Fe CCSN) models¹². The large number of narrow lines at ≲5,500 Å and strong Ca lines in the models are known issues. The weak [Ni II] lines in the models are from the primordial Ni (solar abundance), as Ni nucleosynthesis is not taken into account. In ascending order of wavelength, note the weak Mg I] λ 4571, Mg I] λ 5180 + Fe I λ 5180, [O I] λ 5577, Fe I λ 5950, [O I] λ 6300, 6364 + Fe I λ 6364, O I λ 77774, Fe I cluster 7,900-8,500 Å, [C I] λ 8727, [C I] λ 9100 and [C I] λ 9850, as well as the low line ratio of [O I] λ 6300, 6364/[Ca II] λ 7291, 7323 < 1 observed in SN 2018zd. He I λ 7065 is weaker in the approximate ECSN model than in the observed spectra; the emission from the dredged-up/out elements (for example, He and N) in the H-rich envelope may be underestimated by the model. **d-f**, Simultaneous Gaussian fits to He I λ 7065, [Fe II] λ 7155, [Fe II] λ 7172, [Ca II] λ 7291, [Ca II] λ 7323, [Ni II] λ 7378, [Fe II] λ 7388, [Ni II] λ 7412 and [Fe II] λ 7452 at three different epochs (Supplementary Information). Note the stronger [Ni II] λ 7378 (the blue shaded region) than [Fe II] λ 7155 (the pink shaded region), yielding [Ni II]/[Fe II] = 1.3-1.6. The weak C, O, Mg and Fe lines combined with the strong Ni lines observed in SN 2018zd are consistent with the ECSN chemical composition and nucleosynthesis.

of the He-rich layer before the explosion^{5–7} (N lines are hard to be constrained in type II-P SNe, as [N II] $\lambda\lambda$ 6548, 6583 are hidden by strong H α). For low-mass progenitors (\lesssim 12 M_{\odot}), a low line ratio of [O I]/[Ca II] is expected owing to the low O-core mass^{24,25}.

True nebular spectral models of ECSNe are difficult to produce, but they can be approximated by removing the He core from an Fe CCSN simulation. Here we use such a model¹², which we call the 'approximate ECSN' model. Comparison of the nebular spectra of SN 2018zd with the 9 M_{\odot} models¹² favours the approximate ECSN model over the Fe CCSN model, especially through the weak C, O, Mg and Fe lines (Fig. 4). In addition, the low line ratio of [O I] $\lambda\lambda6300$, 6364/[Ca II] $\lambda\lambda7291$, 7323 < 1 observed in SN 2018zd indicates a low-mass progenitor.

Although quantitative analysis to derive the masses of Ni and Fe requires detailed radiative-transfer simulations, we can obtain a rough estimate of the line ratio expected from ECSNe. For normal Fe CCSNe where Ni and Fe are dominantly produced in the same layer, [Fe II] overwhelms [Ni II] in the emission from the innermost region²⁴. In ECSN models¹¹, however, there is a layer of Ni-rich (neutron-rich) material, emitting predominantly [Ni II], inside

the outer mixture of Ni and Fe. In this situation where the Ni-rich and Fe-rich regions are physically separated, $[Ni \, II]/[Fe \, II]$ roughly reflects the mass ratio of Ni and Fe in the entire ejecta²⁵, which is 1.3–3.0 in the ECSN models¹¹. The observed $[Ni \, II] \lambda 7378/[Fe \, II] \lambda 7155$ ratio of 1.3–1.6 in SN 2018zd (Fig. 4) is indeed within the expected range. In principle, clumping, fluorescence, and/or shock excitation could enhance $[Ni \, II] \lambda 7378$ such that $[Ni \, II] \lambda 7378/[Fe \, II] \lambda 7155$ overestimates the Ni/Fe mass ratio²⁶, but we leave a detailed theoretical study to future works.

SN 2018zd fulfils the expected characteristics and is strong evidence for the existence of ECSNe and their progenitor SAGB stars (see Supplementary Information and Extended Data Fig. 7 for other previously suggested ECSN candidates). With SN 2018zd, we roughly estimate an ECSN rate of 0.6–8.5% of all CCSNe, corresponding to a narrow SAGB progenitor mass window of $\Delta M_{\rm SAGB} \approx 0.06-0.69\,M_{\odot}$ (Methods and Extended Data Fig. 8). Theoretically, the evolutionary path to SAGB stars is uncertain owing to the high sensitivity of nuclear burning on complex dredge-up/out and mass-loss mechanisms of piving a variety of expected mass windows at different metallicities (for example, $\Delta M_{\rm SAGB} \approx 0.2-1.4\,M_{\odot}$ at solar metallicity of

Their final fate may vary from CC to thermonuclear ECSNe depending on the electron-capture rates and oxygen flame speed in the degenerate core 27,28 , resulting in different nucleosynthetic yields and galactic chemical evolution 29 . The CC ECSNe are expected to leave low mass, spin and kick-velocity neutron stars 30 , forming a low-mass peak ($\sim\!1.25\,M_\odot$) in neutron star mass distribution 31 and low-eccentricity ($\sim\!0.2$) gravitational wave source population 32 . Therefore, using SN 2018zd as an ECSN template, future statistical studies with homogeneous samples from large surveys will be able to further reveal the evolution of SAGB progenitors and the influence of ECSNe on the kinetic and chemical composition of the Universe.

Methods

Extinction. We obtained the Milky Way (MW) extinction³³ of $A_{V,MW} = 0.258$ mag via the NASA/Infrared Processing and Analysis Center (IPAC) Infrared Science Archive. We measure the total Na I D EW of each host and MW component using the MMT blue channel spectra (moderate resolution of 1.45 Å) taken 3.6-53.4 d after the explosion (Extended Data Fig. 4). Since the ratio of the total Na I D EW of the host to MW varies between 1.07 and 1.25, we estimate $A_{V,host} \gtrsim A_{V,MW}$. As a cross-check, we transform the gri magnitudes of SN 2018zd to VRI magnitudes³⁴ and compare the V-I colour to that of well-observed, low-extinction type II-P SNe 1999em³⁵, 1999gi³⁶ and 2017eaw³⁷ by assuming $A_{V,host} = A_{V,MW}$ for SN 2018zd. Since the V-I colour of SN 2018zd during the photospheric phase is consistent with the other SNe, we adopt a host extinction of $A_{V,host} = A_{V,MW}$ and assume a reddening law³⁸ with $R_V = 3.1$. This extinction value is also consistent with the lower limit obtained from the spectropolarimetry (Supplementary Information). Increasing (or decreasing) the host extinction by more than 0.10 mag makes the V-I colour inconsistent with that of the other type II-P SNe. Thus, we adopt a host extinction uncertainty of ± 0.10 mag.

Luminosity distance. We apply the expanding photosphere method (EPM) 36,39 and the standard candle method (SCM) 40 using the measured Fe II $\lambda5169$ velocities and transforming the gri to VRI magnitudes 34 , which yields 6.5 ± 0.7 Mpc and 9.6 ± 1.0 Mpc, respectively. The EPM is best used at early times ($\lesssim\!30\,\mathrm{d}$) when SN emission can be approximated as a diluted blackbody in free expansion 39 . However, the early emission from SN 2018zd is dominated by CSM interaction (Fig. 2 and Extended Data Fig. 5), making the EPM unreliable. On the other hand, the SCM is based on the luminosity–velocity correlation $^{41-43}$ at day 50 when the CSM interaction is negligible, which is well reproduced by our MESA + STELLA models ('MESA + STELLA progenitor and light-curve models' section and Extended Data Fig. 6). Thus, we favour the SCM over the EPM.

It has been suggested that NGC 2146 may be farther away than the SCM estimate. There is a claim of a preliminary tip of the red giant branch (TRGB) distance obtained from archival HST Wide Field Camera 3 IR channel (WFC3/IR) data (programme GO-12206, principal investigator M. Westmoquette) that places the galaxy out at ~18 Mpc (ref. ¹⁶). We have independently reduced and analysed these same data and find that the single orbit of observations available (split between F110W and F160W) does not reach the necessary depths to make this conclusion. Even at the closer 10 Mpc distance, the archival data would not allow us to obtain a TRGB measurement owing to the short exposure times and intense levels of crowding. We also find that there are no archival HST optical data of sufficient depths to obtain a TRGB measurement.

Future SN-independent distance measurements (for example, Cepheids and TRGB with HST) will be necessary to verify the SCM estimate. We discuss the implications if the luminosity distance were larger than the SCM estimate in Supplementary Information.

HST and Spitzer progenitor detection and upper limits. We were able to locate astrometrically the site of SN 2018zd in existing pre-explosion HST archival images, specifically data obtained in bands F814W and F658N with the Advanced Camera for Surveys(ACS)/WFC instrument on 2004 April 10 (programme GO-9788, principal investigator L. Ho, with total exposure times of 120s and 700s, respectively; the F814W image consists of a single exposure), as well as in F225W with WFC3/UVIS on 2013 March 7 (programme GO-13007, principal investigator L. Armus; total exposure time of 1,500 s). We identified a potential candidate progenitor precisely by obtaining images of the SN itself on 2019 May 19 in F555W and F814W with WFC3/UVIS, as part of programme GO-15151 (principal investigator S. Van Dyk). We were able to astrometrically register the 2019 F814W image mosaic to the 2004 one using 23 stars in common, with a root-mean-square uncertainty of 0.14 ACS/WFC pixel. Furthermore, in a similar fashion we were able to match precisely the SN image with the F658N and F225W images as well; however, the progenitor candidate was not detected in either of those bands. We show the pre- and post-explosion images in Extended Data Fig. 1.

We extracted photometry from all of the HST images using the package Dolphot⁴⁴. We found that Dolphot detected and measured a source at the position of the progenitor candidate with $m_{\rm F814W} = 25.05 \pm 0.15$ mag. Unfortunately, as noted

above, the F814W pre-explosion observation consisted of only a single exposure, so it was not possible for the standard STScI pipeline to reject cosmic-ray hits in the usual way, while constructing an image mosaic from the single frame, as would normally be the case for two or more dithered exposures. In addition, we note that the flux measurement with Dolphot may be affected by the presence of cosmic-ray hits in the image at or around the progenitor site. Nevertheless, the values of both the Dolphot output parameters 'object type' (1) and 'sharpness' (-0.013) appear to point to the source being stellar-like.

To determine whether the peak pixel seen at the candidate location is indeed merely a cosmic-ray hit or is the actual peak of a stellar point-spread function, we employ a deep-learning model (C.X. et al., manuscript in preparation) based on the results from DeepCR¹⁵. We find that no pixels in the vicinity of the candidate progenitor have a model score higher than 5.1×10^{-5} . If we use this score as a threshold, the model has a completeness of 99.93% based on the test data taken with the same instrument. We therefore conclude that progenitor candidate is a real point-spread function with $>3\sigma$ confidence. If the object was not actually detected, we find that the upper limit at 3σ to detection in F814W is >26.3 mag.

Inserting and recovering an artificial star of varying brightness at the exact SN position with Dolphot in both F225W and F658N led to estimates of the upper limits to detection (at 3σ) of >23.6 mag and >24.1 mag, respectively. In addition, note that we measured a brightness of the SN itself in the 2019 HST observations of $m_{\rm F555W} = 21.53 \pm 0.01$ mag and $m_{\rm F814W} = 20.33 \pm 0.01$ mag.

The SN site also can be found in pre-explosion Spitzer data both from the cryogenic and so-called warm (post-cryogenic) missions, from 3.6 μm to 24 μm . The data are from observations with the Infrared Array Camera (IRAC46) in channels 1 (3.6 μm) and 2 (4.5 μm ; the SN site sits in a gap of spatial coverage in channels 3 and 4 at 5.8 μm and 8 μm , respectively) on 2004 March 8 (programme 59, principal investigator G. Rieke) and on 2007 October 16 (programme 40410, principal investigator G. Rieke) in channels 2 and 4; from observations with the Multiband Imaging Photometer for Spitzer (MIPS47) at 24 μm on 2004 March 16 (programme 59, principal investigator G. Rieke; the sensitivity and resolution of the data at 70 μm and 160 μm are not sufficient to hope to detect the progenitor and were not considered further); and from observations with IRAC in channels 1 and 2 on 2011 November 15 (programme 80089, principal investigator D. Sanders). We show the 2011 November 15 IRAC observation in channel 1 in Extended Data Fig. 1.

Observations with IRAC of the SN itself were obtained on 2019 January 24 (programme 14098, principal investigator O. Fox); however, we did not analyse these data, other than to extract an absolute position for the SN of $\alpha=6\,h\,18\,\text{min}\,03.43\,\text{s}$, $\delta=78^\circ\,22'\,01.4''$ (J2000; $\pm0.3''$ in each coordinate). Using MOPEX⁴⁵, we constructed mosaics from all of the useful pre-SN imaging data, and with APEX within MOPEX⁴⁹ we inserted into the images an artificial star of varying brightness at this absolute position. From this, we estimated upper limits to detection of the progenitor (at 3σ) of >19.0 mag and >18.1 mag in channels 1 and 2 (respectively) from the 2004 March 8 data; >18.1 mag and >14.5 mag in channels 2 and 4 (respectively) from 2007 October 16; and >19.0 mag and >18.4 mag in channels 1 and 2 (respectively) from 2011 November 15 (we have assumed the zeropoints from the IRAC Instrument Handbook). We also estimated >10.2 mag at 24 μ m from the 2004 March 16 observation (we have assumed the zeropoint from the MIPS Instrument Handbook).

We show the resulting spectral energy distribution (SED), or limits thereon, for the SN 2018zd progenitor in Extended Data Fig. 2. The distance $(9.6\pm1.0\,\mathrm{Mpc})$ and extinction $(A_\mathrm{V}=0.52\pm0.10\,\mathrm{mag})$ to the SN were adopted ('Luminosity distance' and 'Extinction' sections), assuming that the latter also applied to the progenitor as well. We have further assumed a reddening law³s with $R_\mathrm{V}=3.1$ and extended it into the mid-infrared⁵s. For comparison, we also show single-star SAGB and RSG (with respective initial masses $M_\mathrm{init}=8\,M_\odot$ and $15\,M_\odot$) models from BPASS v2.2³1 with metallicities $Z\!=\!0.020$ (solar) and $Z\!=\!0.010$ (subsolar; as discussed in Supplementary Information, the SN site metallicity is probably subsolar). We have further included for comparison the observed SED for the candidate SAGB star MSX SMC 055 (IRAS 00483-7347)³² as well as the SED for the progenitor of the low-luminosity type II-P SN 2005cs⁵3.54

We note that the SEDs for the BPASS RSG models with $M_{\rm init} = 15\,M_{\odot}$ are probably not realistic, since they are merely bare photospheres, whereas we would expect such a star to possess a dusty CSM, as was the case for the progenitor of SN 2017eaw³⁷. The same could also potentially be said for the SAGB models, given the dusty nature of MSX SMC 055. Again, these BPASS model SEDs are bare photospheres and do not include CSM, for the presence of which we have strong evidence (given here) in the case of the SN 2018zd progenitor; this merits further development of the SED models including the effect of dusty CSM.

It is difficult to infer much about the nature of the SN 2018zd progenitor, based on a probable detection in one band and upper limits in the others. However, its inferred SED does appear to be less consistent with that of an $M_{\rm init} \gtrsim 8\,M_{\odot}$ RSG star, as well as the SN 2005cs progenitor, and more consistent with a potentially dusty SAGB star, such as MSX SMC 055. If there were circumstellar dust around the SN 2018zd progenitor, it was destroyed as the SN shock progressed through.

We should revisit this site either with HST or the James Webb Space Telescope in a bandpass similar to F814W, when the SN has sufficiently faded, to confirm that the candidate object was indeed the progenitor. Again, we cannot entirely

rule out that the source detected in the pre-SN image at the precise SN position is not related to a cosmic-ray hit; however, all of the indications suggest that this is a real detected star, which should have vanished when the SN site is observed at a sufficiently late time.

MESA + STELLA progenitor and light-curve models. Recent work *1,55-57 has highlighted the non-uniqueness of bolometric light-curve modelling for extracting explosion characteristics (ejecta mass $M_{\rm ej}$, explosion energy $E_{\rm exp}$ and progenitor radius R) from plateau features (in particular, luminosity at day 50, $L_{\rm 50}$, and plateau duration, $t_{\rm p}$) without an independent prior on one of $M_{\rm ej}$, $E_{\rm exp}$ or R. Owing to the presumed presence of dense CSM and its potential influence on the early light curves and velocities, shock-cooling modelling and early expansion velocities cannot simply lift this degeneracy.

To allow light-curve analysis to be agnostic to the progenitor mass, three different explosion models were created with equally good by-eye matches to the bolometric light curve and expansion-velocity data on the plateau. The progenitor models were selected from a pre-existing grid of MESA MESA Progenitor models with expected ejecta masses and radii within the family of explosions consistent with the L_{50} , $t_{\rm p}$ and $M_{\rm Ni}$ of SN 2018zd (Extended Data Fig. 6; see Supplementary Information for the model details).

The explosion energies for each model were then chosen and adjusted to match the light curve of SN 2018zd with the respective progenitor model radii using the degeneracy relations⁴³

$$\begin{split} \log{(E_{51})} &= -0.728 + 2.148 \log{(L_{\rm p,42})} - 0.280 \log{(M_{\rm Ni})} \\ &+ 2.091 \log{(t_{\rm p,2})} - 1.632 \log{(R_{\rm 500})}, \\ \log{(M_{10})} &= -0.947 + 1.474 \log{(L_{\rm p,42})} - 0.518 \log{(M_{\rm Ni})} \\ &+ 3.867 \log{(t_{\rm p,2})} - 1.120 \log{(R_{\rm 500})}, \end{split} \label{eq:eq:energy}$$

where $E_{51} = E_{\rm exp}/10^{51}\,{\rm erg}$, $M_{10} = M_{\rm ej}/10\,M_{\odot}$, $M_{\rm Ni}$ is in units of M_{\odot} , $L_{\rm p,42} = L_{\rm 50}/10^{42}\,{\rm erg}\,{\rm s}^{-1}$, $t_{\rm p,2} = t_{\rm p}/100\,{\rm d}$, and $R_{\rm 500} = R/500\,R_{\odot}$. Plugging in $L_{\rm 50} = 8.6 \times 10^{41}\,{\rm erg}\,{\rm s}^{-1}$ from the bolometric light curve at day 50, $t_{\rm p} = 125.4\,{\rm d}$ determined by fitting the drop from the plateau¹⁷, and observed $M_{\rm Ni} = 0.0086\,M_{\odot}$, these relations describe the possible explosion parameter space (Extended Data Fig. 6). They are intended for Ni-rich $(M_{\rm Ni} > 0.03\,M_{\odot})$ type II-P SNe of RSG progenitors with no fallback, but nonetheless provide a heuristic estimate for the degeneracy between explosion energy, progenitor radius and ejected mass.

This degeneracy motivates the set of progenitor models and explosion energies that we use to reproduce the light-curve properties, and reveals low recovered $E_{\rm exp}$ that overlaps substantially with the expected parameter space of ECSNe. The mapping between $M_{\rm el}$ recovered for Fe CCSNe and ECSNe is less robust, as differences in mixing extent and H/He abundances could account for differences in the recovered $M_{\rm el}$ from explosions of different stellar progenitors 42,43,61 . As seen in Extended Data Fig. 6, even though SN 2018zd is not particularly dim, low-energy explosions of radially extended progenitors can match the plateau luminosity. A slightly lower- $M_{\rm el}$ progenitor with a radius of $1,400\,R_{\odot}$, for example, could even produce this luminosity with an explosion energy of $\sim 1.5 \times 10^{50}\,{\rm erg}$.

The explosions were carried out using MESA until near shock breakout. The models were then handed off to STELLA 62-64 to produce synthetic bolometric light curves and expansion velocities (Extended Data Fig. 6; see Supplementary Information for the modelling details). We see good agreement between all three models and observations (varying by at least 50% in $M_{\rm ep}$, $E_{\rm exp}$ and R), with deviations at early times that can be attributed to the extended stellar atmosphere and potential interaction with the circumstellar environment.

To account for the early deviations, we affix a wind-density profile with $\rho_{\rm wind}(r) = \dot{M}_{\rm wind}/4\pi r^2 v_{\rm wind}$, where r is the radial extent, $\dot{M}_{\rm wind}$ is a constant wind mass-loss rate, and $v_{\rm wind}$ is the wind velocity for time $t_{\rm wind}$ (that is, $M_{\rm wind} = \dot{M}_{\rm wind} t_{\rm wind}$), onto the MESA model at handoff to STELLA. We construct a grid of CSM models by varying the following parameters:

$$\dot{M}_{\text{wind}} = \left\{ 10^{-4}, \ 3 \times 10^{-4}, \ 10^{-3}, \ 3 \times 10^{-3}, \ 10^{-2}, \ 3 \times 10^{-2}, \ 10^{-1}, \ 3 \times 10^{-1} \right\} \ M_{\odot} \ \text{yr}^{-1}$$

and $t_{\rm wind} = \{1,3,10,30\}$ yr for each MESA model, assuming a typical wind velocity!9 $\nu_{\rm wind} = 20\,{\rm km\,s^{-1}}$. Then we perform χ^2 fitting on the observed bolometric light curve over the full temporal evolution and find the best-fit parameters $\dot{M}_{\rm wind} = 0.01\,M_{\odot}~{\rm yr}^{-1}$ and $t_{\rm wind} = 10\,{\rm yr}$.

Remarkably, the best-fit parameters are the same for all three degenerate models, and also reproduce the early blueward UV-colour evolution (Extended Data Fig. 6). Thus, we choose model M8.3_R1035_E0.23 (Supplementary Information) as being representative and present it for the UV-colour plot in Fig. 2. In addition to matching the early-time luminosity excess, a dense wind profile suppresses the early photospheric and Fe line velocities 20 . The kink seen in the modelled Fe line velocity with Sobolev optical depth $\tau_{\rm Sob}=1$ in the STELLA models can be attributed to numerics at the boundary between the CSM profile and the surface of the stellar ejecta (Extended Data Fig. 6). Overall, the models still yield general agreement between the calculated velocity evolution and the data.

We note that at $3-10\,d$ after the explosion, the blackbody temperatures ($\sim\!20,000-25,000\,K$) may be underestimated (Supplementary Information), which could affect the luminosity around the peak, and so the CSM models as well. For the flash spectral model comparisons in Fig. 3, we use a conservative temperature constraint of $\sim\!20,000-30,000\,K$.

The rate of ECSNe. Among other previously suggested ECSN candidates (Supplementary Information and Extended Data Fig. 7), type IIn-P SNe share similar properties to SN 2018zd. Thus, the type IIn-P SN rate may be related to the ECSN rate. As there is no rate estimation for type IIn-P SNe in the literature to our knowledge, we put a rough lower limit using publicly announced type IIn SNe on the Weizmann Interactive Supernova Data Repository (WISeREP)65 and/ or the Transient Name Server (TNS) by cross-checking with the literature and the Open Supernova Catalog66, and also cross-correlating the public spectra to SN spectral libraries Superfit⁶⁷ and SNID⁶⁸ when available. There are 528 objects classified as type IIn SNe on WISeREP and/or TNS (as of 2020 March 11). We exclude 73 objects as misclassified early-flash type II SNe, type Ia-CSM SNe, type Ibn SNe, SN imposters or active galactic nuclei. Although 241 objects do not have enough public and/or published spectra and/or light curves to secure the type IIn classifications and/or to be identified as type IIn-P SNe, we include them in the further analysis so as not to overestimate the lower limit when taking a number ratio of type IIn-P to type IIn SNe (see below and Supplementary Fig. 1).

To identify type IIn-P SN candidates from the 455 objects, we apply two light-curve criteria based on the known type IIn-P SN characteristics: (1) the V, r/R or i/I-band decline of less than 2 mag in the first 50 d after the explosion; and (2) the V, r/R or i/I-band drop of more than 2 mag in 30 d within 100–150 d after the explosion. This yields four type IIn-P SN candidates: SNe 2005cl (z=0.025878)⁶⁹, 2005bb (z=0.015124)⁶⁹, 2006bb (z=0.0153)⁷⁰ and 2011A (z=0.008916)⁷¹. In addition, there are three known type IIn-P SNe: 1994W (z=0.004116)⁷², 2009kn (z=0.015798)⁷³ and 2011ht (z=0.003646)⁷⁴ (Supplementary Fig. 1).

To compare with the volume-limited (\leq 60 Mpc) Lick Observatory Supernova Search (LOSS) sample⁷⁵, we apply the same distance cut, leaving 42 type IIn SNe (17 and 25 with sufficient and insufficient data, respectively) and 3 type IIn-P SNe (SNe 1994W, 2011A and 2011ht). As these SNe were discovered by different surveys with different strategies, we have no handle on the incompleteness (but also see Supplementary Fig. 1). Thus, we neglect the incompleteness and take the number ratio of type IIn-P to type IIn SNe within 60 Mpc multiplied by the LOSS type IIn SN rate⁷⁵, $3/42 \times 8.8\% = 0.63\%$ of all CCSNe, as a rough lower limit of the type IIn-P SN rate.

The identification of SN 2018zd-like SNe from type II-P SNe (48.2% of all CCSNe) requires not only the light-curve morphology, but also the early UV colours and the flash and nebular spectroscopy, all of which combined are rarely available on WISeREP, TNS and/or the Open Supernova Catalog. This current sample limitation may indicate that many SN 2018zd-like SNe have been overlooked as normal type II-P SNe. Given the limitation, we simply take the lowest possible limit of >0% with the one identification of SN 2018zd as an ECSN.

By combining the estimated type IIn-P and SN 2018zd-like lower limits, we obtain a type IIn-P + SN 2018zd-like lower limit of >0.6% of all CCSNe. From the nucleosynthetic point of view, ECSNe are expected to constitute \lesssim 8.5% of all CCSNe. $^{\circ}$. With the above estimates, the ECSN rate can be roughly constrained within 0.6–8.5% of all CCSNe, which corresponds to a narrow SAGB progenitor mass window of $\Delta M_{\rm SAGB}\approx 0.06-0.69\,M_{\odot}$ assuming maximum and minimum SAGB masses of 9.25 M_{\odot} and 9.25 $M_{\odot}-\Delta M_{\rm SAGB}$ (respectively) at solar metallicity (Extended Data Fig. 8). We note that the type IIn-P and SN 2018zd-like rates are probably metallicity dependent (as is the SAGB mass window), but we defer more detailed analysis with a homogeneous sample in the future when one becomes publicly available.

Data availability

The data that support the plots within this paper and other findings of this study are available from the Open Supernova Catalog (https://sne.space/) and the Weizmann Interactive Supernova Data Repository (https://wiserep.weizmann.ac.il/), or from the corresponding author upon reasonable request.

Code availability

MESA is publicly available at http://mesa.sourceforge.net/.

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Author contributions

D.H. initiated the study, triggered follow-up observations, reduced the Las Cumbres data, produced the light-curve models, performed the analysis and wrote the manuscript. D.A.H. is the principal investigator of the Las Cumbres Observatory Global Supernova Project through which all of the Las Cumbres data were obtained; he also assisted with data interpretation and the manuscript. S.D.V.D. is the principal investigator of the HST programme 'The Stellar Origins of Supernovae' (GO-15151) through which the post-explosion HST data were obtained; he also found the progenitor candidate in the pre-explosion HST F814W image, calculated the upper limits in the pre-explosion HST and Spitzer images, and assisted with data interpretation and the manuscript. J.A.G. produced the progenitor and light-curve models and assisted with their interpretation and the manuscript, K.M. assisted with theoretical nebular spectral model interpretation and the manuscript. T.J.M. and N.T. assisted with theoretical SAGB progenitor and ECSN light-curve model interpretations and the manuscript. K.N. assisted with theoretical SAGB progenitor and ECSN explosion model interpretation and the manuscript. G.H. assisted in obtaining the Las Cumbres data, reduced the FLOYDS spectra and contributed comments to the manuscript. I.A., C.M. and J.B. assisted in obtaining the Las Cumbres data; I.A. and C.M. also contributed comments to the manuscript. K.A.B. obtained the Keck LRIS and DEIMOS spectra, reduced the LRIS spectra and contributed comments to the manuscript. S.V. is the principal investigator of the Keck proposals (2018B, project code U009; 2019A, project code U019; 2019B, project code U034) under which the nebular spectra were obtained; he also built the Las Cumbres photometric and spectroscopic reduction pipelines, reduced the Keck DEIMOS spectrum and contributed comments to the manuscript. Y.D. assisted in obtaining the Keck LRIS and DEIMOS spectra. P.J.B. obtained and reduced the Swift UVOT data. J.E.A. obtained and reduced the MMT and Bok spectra. C.B. reduced and analysed the MMT SPOL spectropolarimetry. G.G.W. is the principal investigator of the Supernova Spectropolarimetry (SNSPOL) project. P.S.S. is the principal investigator of the SPOL instrument. G.G.W. and P.S.S. collected the spectropolarimetric data with the SPOL instrument at the MMT Observatory. N.S. is the principal investigator of the MMT and Bok programmes; he also contributed comments to the manuscript. D.J.S. co-leads the University of Arizona team that obtained the MMT and Bok spectra; he also contributed comments to the manuscript. G.S.A. reduced and analysed the archival HST WFC3/IR data (GO-12206) of the host galaxy NGC 2146. C.X. and C.M. analysed and rejected the cosmic rays in the pre-explosion HST F814W image. A.V.F., M.C.B., G.F. and P.L.K. are co-investigators of the HST programme (GO-15151); they also contributed comments to the manuscript (which A.V.F. edited in detail). T.N. monitored the supernova and provided his photometry. K.I. is the discoverer of the supernova; he also monitored the supernova and provided his photometry.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41550-021-01384-2.

 $\label{thm:continuous} \textbf{Supplementary information} \ The online version contains supplementary material available at $$https://doi.org/10.1038/s41550-021-01384-2.$

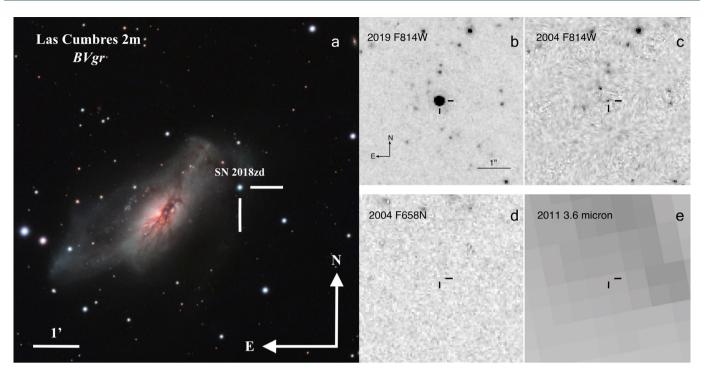
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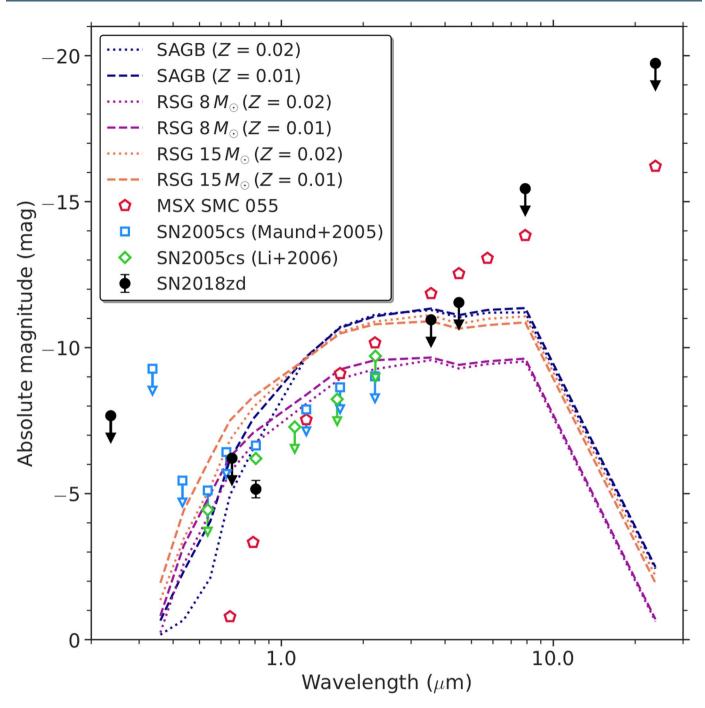
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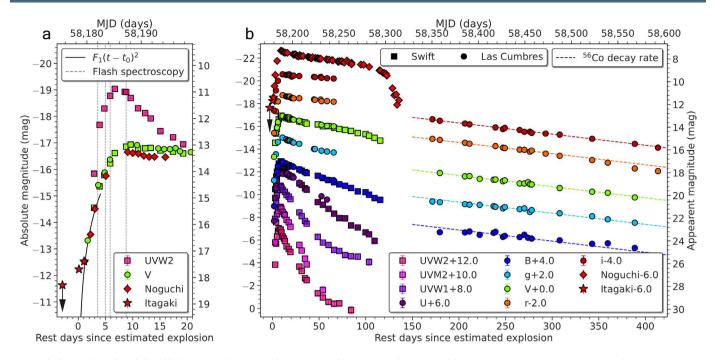
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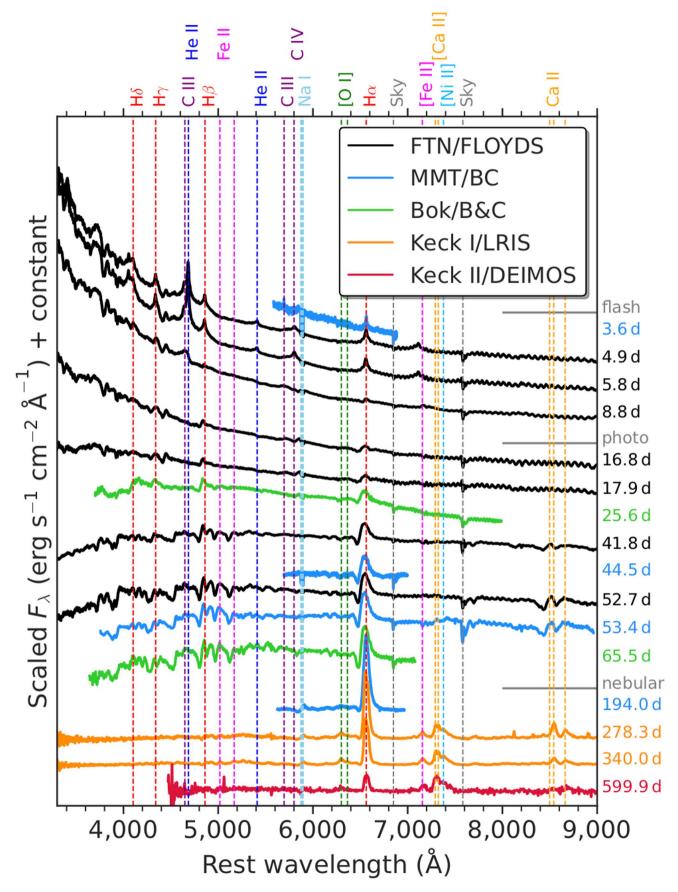
Extended Data Fig. 1 | The host galaxy and post- and pre-explosion images of SN 2018zd. a, Las Cumbres 2 m BVgr-composite image of SN 2018zd and the host starburst galaxy NGC 2146 (Supplementary Information), courtesy of Peter Iláš. At the assumed luminosity distance of 9.6 Mpc, 1' corresponds to 2.8 kpc. SN 2018zd is on a tidal stream which was likely ejected during a galaxy merger event. **b**, Portion of an HST WFC3/UVIS F814W mosaic obtained on 2019 May 19, 443.7 d after the explosion of SN 2018zd (indicated by the tick marks). **c**, Portion of an HST ACS/WFC F814W mosaic from 2004 April 10; the SN site is similarly indicated by tick marks. This mosaic consists of a single exposure, so to remove a number of cosmic-ray hits in the image, we use a masked mean filter to smooth any pixels that have a score of 0.001 or higher from our deep-learning model (Methods). The pixels associated with the progenitor candidate had scores $< 4 \times 10^{-5}$, so are not affected. **d**, Same as panel (**c**), but with F658N on the same epoch. **e**, Portion of a *Spitzer* IRAC 3.6 μ m mosaic obtained on 2011 November 15, with the SN site again indicated by tick marks. All panels (**b**)-(**e**) are shown to the same scale and orientation, with north up and east to the left. The progenitor candidate is identified only in the single HST ACS/WFC F814W image (**c**).



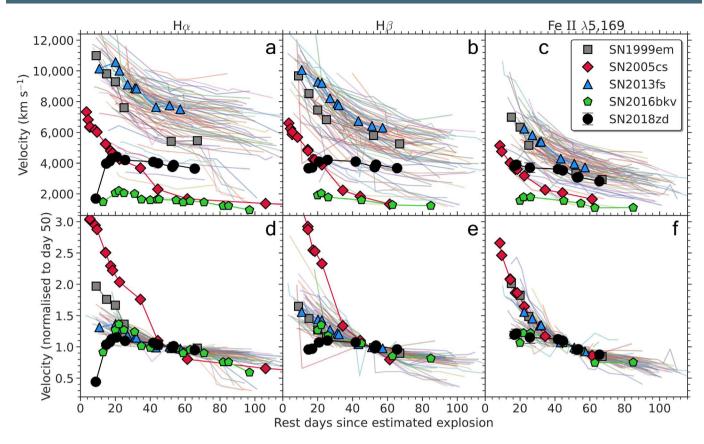
Extended Data Fig. 2 | SN progenitor and SAGB candidate SEDs. The SED for the SN 2018zd progenitor candidate resulting from pre-explosion *HST* and *Spitzer* archival data (Methods; black solid circles). For comparison we show model SEDs from BPASS v2.2⁵¹ for SAGB stars (in the initial mass range $M_{\rm init} = 6 - 8\,M_{\odot}$ with bolometric luminosities $L \approx 10^5\,L_{\odot}$ in the last model timestep; navy curves) and RSG stars at $M_{\rm init} = 8\,M_{\odot}$ (purple curves) and $M_{\rm init} = 15\,M_{\odot}$ (orange curves), at metallicities Z = 0.02 (solar; short-dashed line) and Z = 0.01 (subsolar; long-dashed line). The SEDs of the BPASS models are extrapolated into the mid-infrared via MARCS⁷⁹ model stellar atmospheres of similar temperatures as the last BPASS model timesteps, deriving synthetic photometry from those atmosphere models using the bandpass throughputs provided in the *Spitzer* IRAC and MIPS Instrument Handbooks. Also shown for comparison are the SEDs for the SAGB candidate MSX SMC 055 (assuming Galactic foreground extinction and adjusted to a Small Magellanic Cloud distance modulus of $\mu = 18.90$ mag from the Extragalactic Distance Database⁸⁰; red open pentagons⁵²) and for the progenitor of the low-luminosity Type II-P SN 2005cs (assuming the total reddening from the two studies^{53,54} and adjusted to a recent accurate distance for M51⁸¹; blue open squares⁵³, green open diamonds⁵⁴). The luminosity of the *HST* ACS/WFC F814W detection of the SN 2018zd progenitor candidate lies between MSX SMC 055 and the SN 2005cs progenitor.



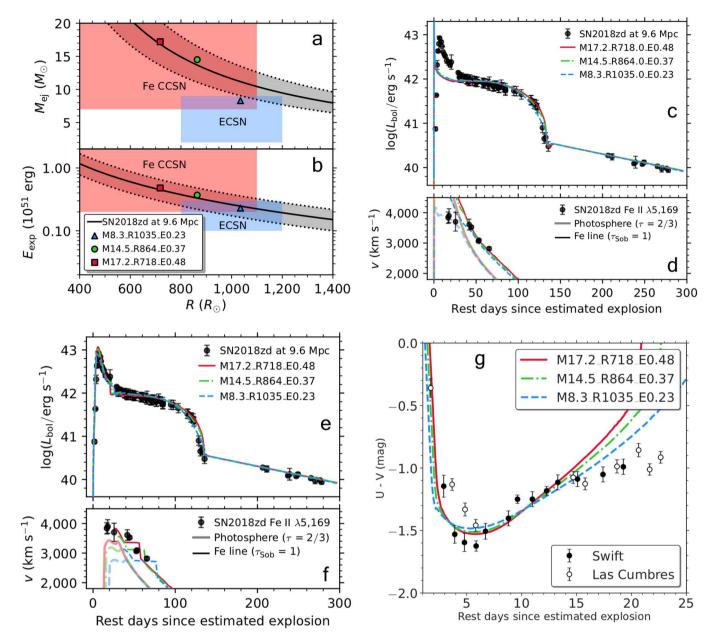
Extended Data Fig. 3 | Multiband light curve of SN 2018zd. a, Multiband light curve of SN 2018zd focusing on the early rise. A quadratic function $F_1(t-t_0)^2$ is fitted to the unfiltered optical Itagaki and the first three Noguchi points to estimate an explosion epoch t_0 = MJD 58178.4 \pm 0.1 (Supplementary Information). The observed flash-spectroscopy epochs (Extended Data Fig. 4) are marked by the vertical dashed lines. Note the sharper rise in the *Swift UVW*2 than in the *V* and unfiltered photometry during the flash-spectroscopy epochs. **b**, Multiband light curve of SN 2018zd up to the ⁵⁶Co decay tail. The data gap is due to the Sun constraint. Error bars denote 1σ uncertainties and are sometimes smaller than the marker size. The light-curve shape resembles that of a typical Type II-P SN. Comparing the luminosity on the tail to that of SN 1987A⁸², we estimate a ⁵⁶Ni mass of $(8.6 \pm 0.5) \times 10^{-3} \, \text{M}_{\odot}$ at the assumed luminosity distance of 9.6 Mpc.



Extended Data Fig. 4 | Optical spectral time series of SN 2018zd. The flash features (for example, He II, C III, and C IV) persist up to > 8.8 d and disappear before 16.8 d. Then the broad Balmer-series P Cygni lines appear, typical of the photospheric phase of a Type II-P SN. After ~ 200 d, the nebular emission lines (for example, H α , [Ca II], and [NI II]) dominate over the relatively flat continuum.



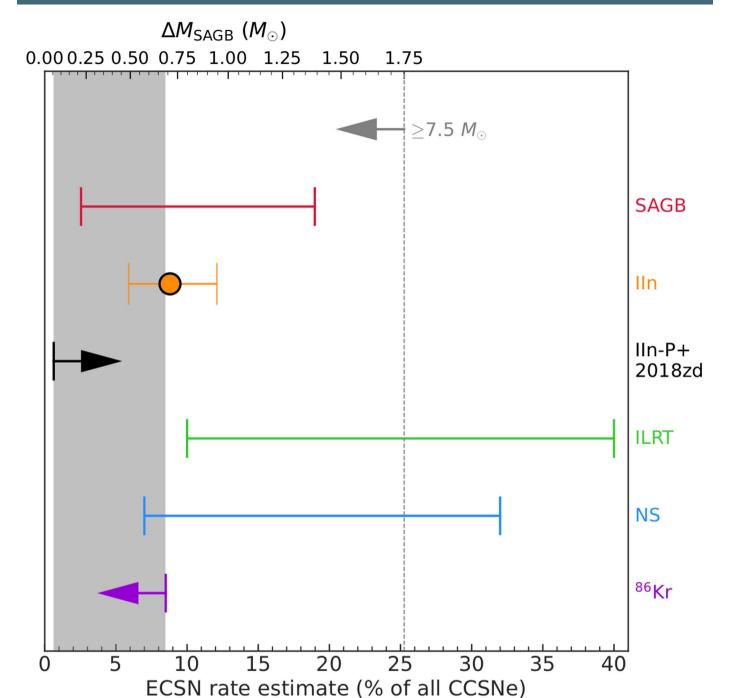
Extended Data Fig. 5 | Expansion velocities as a function of time. Comparison of the unnormalised (**a, b, c**) and normalized (to day 50; **d, e, f**) H α , H β , and Fe II λ 5169 expansion velocities of SN 2018zd (Supplementary Information) with a Type II SN sample⁸³ (transparent lines), including archetypal SN 1999em, along with low-luminosity SN 2005cs⁸⁴, early-flash SN 2013fs²¹, and low-luminosity and early-flash SN 2016bkv^{77,85}. Error bars denote 1 σ uncertainties and are sometimes smaller than the marker size. Note the pronounced early H α and H β rises and the relatively flat velocity evolution (up to ~30 d) of SN 2018zd, indicating shock propagation inside the dense, optically-thick CSM.



Extended Data Fig. 6 | MESA+STELLA progenitor and degenerate light-curve models. **a**, **b**, Ejecta mass $M_{\rm ej}$ and explosion energy $E_{\rm exp}$ inferred from Eq. (1) (Methods) as a function of progenitor radius R consistent with the bolometric light curve of SN 2018zd at the assumed luminosity distance of 9.6±1.0 Mpc, along with the properties of the three degenerate explosion models. The blue and red shaded regions show explosion parameters expected for ECSNe^{6,710} and typical of Fe CCSNe⁸⁶, respectively. **c**, **d**, Three degenerate MESA+STELLA explosion models providing good fits to the light curve and velocities inferred from the Fe II λ 5169 line during the plateau phase. Models are labelled by $M[M_{\rm ej,\odot}]_{\rm em}[R_{\odot}]_{\rm em}[E_{\rm exp,51}]$. Error bars denote 1 σ uncertainties. Note the observed early-time excess luminosity and suppressed velocity of SN 2018zd. This light-curve degeneracy highlights the inability to distinguish ECSNe from Fe CCSNe solely based on their light curves, suggesting that many ECSNe might have been overlooked owing to the lack of additional observations. **e**, **f**, Same as panels (**c**, **d**), but adding a dense wind profile ($\dot{M}_{\rm wind} = 0.01 \, {\rm M}_{\odot} {\rm yr}^{-1}$, $v_{\rm wind} = 20 \, {\rm km \, s}^{-1}$, and $t_{\rm wind} = 10 \, {\rm yr}$) to the three degenerate MESA models before handoff to STELLA. **g**, Comparison of the UV-colour models with the same wind CSM parameters as in panels (**e**, **f**). Error bars denote 1 σ uncertainties. All three models with the same wind CSM parameters are able to reproduce the early-time luminosity excess and blueward UV-colour evolution almost identically, suggesting the insensitivity of a particular model choice. Despite a possible artificial velocity kink when the Fe line-forming region transitions from the CSM to the stellar ejecta, the velocity evolution with the early suppression is also reproduced.

ECSN	Progenitor			Explosion		
Candidate	Identification	CSM	Chemical Composition	Energy	Light Curve	Nucleosynthesis
SN 2018zd	√?	\checkmark	\checkmark	√?	✓	✓
SN 1054 (Crab)	_	√?	\checkmark	✓	√?	✓
ILRT	√?	\checkmark	?	×	×	?
Low-Lum. II-P	×	?	×	√?	\checkmark	×
IIn-P	?	\checkmark	?	√?	✓	√?

Extended Data Fig. 7 | ECSN candidate checklist. Check marks, check+question marks, and cross marks (respectively) indicate observations consistent, perhaps consistent, and inconsistent with theoretical expectations. Dashed lines indicate the lack of observational constraints, and lone question marks indicate unknowns (Supplementary Information). For SN 2018zd, we identify a faint progenitor candidate that may be consistent with an SAGB star (Extended Data Figs. 1 & 2), and the explosion energy is consistent within the light-curve degeneracy (Extended Data Fig. 6).



Extended Data Fig. 8 | ECSN rate estimators. Comparison of the ECSN rate estimates: 'SAGB' is the SAGB mass window from stellar evolutionary calculations at solar metallicity⁵; 'Iln' is the observed Type IIn SN rate from a volume-limited (\leq 60 Mpc) sample⁷⁵; 'Iln-P+2018zd' is a rough lower limit of the Type IIn-P SN rate within 60 Mpc combined with SN 2018zd (Methods); 'ILRT' is a rough estimate from ILRTs within 30 Mpc⁸⁷; 'NS' is an estimated rate from the bimodality in the neutron star mass distribution³¹ assuming that the low-mass and high-mass peaks originate from ECSNe and Fe CCSNe, respectively; and '⁸⁶Kr' is an upper limit from the ECSN nucleosynthesis calculation⁷⁶ assuming that ECSNe are the dominant production source of ⁸⁶Kr. The conversion between the fraction of all CCSNe and the SAGB mass window is performed assuming the Salpeter initial mass function with lower and upper CCSN mass limits of 7.5 M_{$_{\odot}$} and 120 M_{$_{\odot}$} (respectively) and maximum and minimum SAGB masses of 9.25 M_{$_{\odot}$} and 9.25 M_{$_{\odot}$}. The grey shaded region shows a rough ECSN rate constraint by the IIn-P+2018zd lower limit and the nucleosynthesis upper limit.