

# The electron-capture origin of supernova 2018zd

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There are two well-understood regimes of stellar death, although the transition has remained unresolved for 40 years. Stars up to about 8 solar masses lose their outer layers and leave behind a degenerate core – a white dwarf. More massive stars (above  $\sim 10$  solar masses) produce an iron core, which collapse to a neutron star or black hole in a core-collapse supernova. Theoretically, stars in between ( $\sim 8$ – $10$  solar masses) are expected to produce an electron-capture supernova when the degenerate O+Ne+Mg core of a super-asymptotic giant branch star collapses as a result of electron capture onto Ne and Mg nuclei<sup>1, 2, 3</sup>. However, until now 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: progenitor identification, circumstellar material, chemical composition<sup>4, 5, 6</sup>, explosion energy, light curve, and nucleosynthesis<sup>7, 8, 9, 10, 11</sup>. SN 2018zd is the only supernova having strong evidence for or consistent with all six. These new data cast the decades-long debate about SN 1054 in a new light, which has some of these characteristics, but suffers from thousand year old observations and the difficulty of making inferences from evolved supernova remnants.

On 2018 Mar. 2.49 (UT dates are used throughout), we discovered AT 2018zd<sup>12</sup> at an unfiltered optical magnitude of 17.8 in the outskirts of NGC 2146 (redshift  $z = 0.002979$ <sup>13</sup>), where pre-explosion *Hubble Space Telescope* (*HST*) and *Spitzer Space Telescope* images yield a faint progenitor candidate (Extended Data Figs. 1 & 2, and Methods). Combined with our pre-discovery detection at 18.1 mag on 2018 Mar. 1.54, we estimate an explosion epoch of 2018 Mar.  $1.4 \pm 0.1$  ( $\sim 3$  hr before the first detection; Extended Data Fig. 3 and Methods) and use it as a reference

epoch for all phases. At 4.9 days post explosion, we classified AT 2018zd as a young Type II (hydrogen-rich) supernova (SN), designating it SN 2018zd<sup>14</sup>. Over time, SN 2018zd developed a plateau and broad Balmer-series P-Cygni lines in the optical light curve and spectra, respectively, further classifying it as a Type II-P (plateau) SN (Extended Data Figs. 3 & 4). The luminosity distance of NGC 2146 is uncertain, ranging from 11 to 18 Mpc in the literature<sup>15</sup>. Thus, we apply the standard candle method and adopt a distance of  $9.6 \pm 1.0$  Mpc (see 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 realised 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 <sup>56</sup>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<sup>7, 8, 10</sup>, but are consistent within the lowest-mass Fe CCSNe (see Methods). 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 ( $\sim 4$  mag) from the plateau to the radioactive decay tail, due to the low <sup>56</sup>Ni production<sup>9</sup>.

Among a sample of well-observed Type II SN light curves<sup>16</sup> (Fig. 1), SN 2018zd fits in the Type II-P morphology and displays the largest plateau drop ( $\sim 3.8$  mag). Even among a sample of low-luminosity Type II-P SNe<sup>17</sup> that often show larger plateau drops than other Type II subclasses (Fig. 1), SN 2018zd is comparable to SNe 1999eu and 2006ov with the largest drops

ever observed, which indicates an intrinsically low  $^{56}\text{Ni}$  production. For SNe 1999eu and 2006ov, the lack of additional data prevents the investigations of other ECSN indicators, and 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  $^{56}\text{Co}$  heating rate, and an estimated  $^{56}\text{Ni}$  mass is  $(8.6 \pm 0.5) \times 10^{-3} M_{\odot}$  at the assumed luminosity distance of 9.6 Mpc (Extended Data Fig. 3). This is larger than the canonical  $^{56}\text{Ni}$  yield for ECSNe, but still within the upper limit (see also Methods for the effect of distance uncertainty).

As SAGB stars are thought to have mass-loss rates ( $\dot{M} \approx 10^{-4} M_{\odot} \text{ yr}^{-1}$ ) a few orders of magnitude higher than those of RSG stars of similar initial mass<sup>4</sup>, the circumstellar material (CSM) density is expected to be a few orders of magnitude higher, as it scales as  $\rho_{\text{CSM}} \propto \dot{M}/v_{\text{wind}}$ , assuming constant wind mass loss with similar SAGB and RSG wind velocities<sup>18</sup>  $v_{\text{wind}}$ . Compared to 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/out that bring the partial H- and He-burning products to the stellar surface<sup>5,6</sup>.

In a sample of Type II SN ultraviolet (UV) colours<sup>16</sup>, SN 2018zd stands out, reaching the minimum in  $U - V$  colour (i.e., becoming bluer until)  $\sim 5$  d after the explosion (Fig. 2), which suggests a possible delayed shock-breakout through dense CSM<sup>19</sup>. In such a case, a photosphere initially forms inside the unshocked optically-thick CSM<sup>20</sup>; 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 (see Methods and Extended Data Fig. 6) show that  $\dot{M} \approx 0.01 M_{\odot} \text{ yr}^{-1}$  for the last  $\sim 10$  yr before the explosion is required to reproduce the early-time  $U - V$  colour of SN 2018zd, assuming a typical constant<sup>18</sup>  $v_{\text{wind}} = 20 \text{ km s}^{-1}$  (Fig. 2). Since the estimated mass loss is a few orders of magnitude greater than that expected from SAGB or RSG wind, it is likely dominated by eruptive events<sup>4,5</sup>.

Consistent with the possible delayed shock breakout seen in the early UV colour, SN 2018zd exhibits unusually persistent ( $\gtrsim 9$  d) flash features, reaching the highest ionisation states at  $\sim 5$  d after the explosion (Fig. 3). The strengths of flash features depend on the photospheric temperature, CSM density, and CSM abundance<sup>21,22,23</sup>. 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 atmospheres<sup>22</sup> (Fig. 3; note that the line ratios are not well reproduced by either solar-abundance or He-rich models alone<sup>23</sup>, and a mixture of both with higher density needs to be modeled for a more detailed abundance analysis). Based on the model comparisons, we estimate He-, C-, and N-rich, but O-poor CSM mass fractions of  $X_{\text{He}} \approx 0.3\text{--}0.8$ ,  $X_{\text{C}} \approx 3 \times 10^{-3}$ ,  $X_{\text{N}} \approx 8 \times 10^{-3}$ , and  $X_{\text{O}} \approx 10^{-4}$ , which is more consistent with an SAGB than an RSG atmosphere<sup>5,6</sup>.

Since the core composition and explosion nucleosynthesis are different from Fe CCSNe (but see Methods 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  $^{58}\text{Ni}$  yield than radioactive  $^{56}\text{Ni}$  (a

parent nuclide of  $^{56}\text{Fe}$ ) from the innermost neutron-rich ejecta (electron fraction  $Y_e \lesssim 0.49$ )<sup>10, 11</sup>; weak O, Mg, and Fe lines owing to the thin ( $\sim 0.01 M_\odot$ ) O+C shell which is further burned to Fe-group elements<sup>7, 8</sup>; and weak C lines because of the efficient dredge-up/out reducing most of the He-rich layer before the explosion<sup>4, 5, 6</sup> (N lines are hard to be constrained in Type II-P SNe, as [N II]  $\lambda\lambda 6548, 6583$  are hidden by strong  $H\alpha$ )<sup>24</sup>. For low-mass progenitors ( $\lesssim 12 M_\odot$ ), a low line ratio of [O I]/[Ca II] is expected due to the low O-core mass<sup>25, 26, 24</sup>.

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 model<sup>11</sup>, which we call the “approximate ECSN” model. Comparison of the nebular spectra of SN 2018zd with the  $9 M_\odot$  models<sup>11</sup> 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]  $\lambda\lambda 6300, 6364$ /[Ca II]  $\lambda\lambda 7291, 7323 < 1$  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 region<sup>25</sup>. In ECSN models<sup>10</sup>, 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 ejecta<sup>26, 24</sup> – 1.3–3.0 in the ECSN models<sup>10</sup>. 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 ratio<sup>27</sup>, but we leave a detailed theoretical study to future works.

SN 1054, whose remnant is the Crab Nebula, has been suggested as an ECSN candidate<sup>28, 29, 9, 18</sup>. It shows He-, C-, and Ni-rich ejecta, but O- and Fe-poor abundances<sup>27, 30</sup>, small ejecta mass ( $4.6 \pm 1.8 M_{\odot}$ )<sup>31</sup>, and low kinetic energy ( $\sim 10^{49}$  erg)<sup>29</sup>, although the observed relatively high neutron star kick velocity ( $\sim 160 \text{ km s}^{-1}$ ) compared to those theoretically predicted for ECSNe ( $< 10 \text{ km s}^{-1}$ )<sup>32</sup> is somewhat questionable. The slowly expanding filaments ( $\sim 1,200 \text{ km s}^{-1}$ ) without a blast wave outside likely indicate the presence of CSM decelerating the SN ejecta<sup>31, 29</sup>, and the historical light curve of SN 1054 may be similar to that of ECSNe<sup>29, 9, 18</sup>. If both SNe 1054 and 2018zd are ECSNe, the differences may help us understand the diversity of the class, whilst the similarities may help us understand some of the properties of SN 1054 that remain unknown (see Methods and Extended Data Table 1 for other previously suggested ECSN candidates).

SN 2018zd fulfills the expected characteristics and is strong evidence for the existence of ECSNe and their progenitor SAGB stars, which puts constraints on many fields of physics and astrophysics (see Methods and Extended Data Fig. 9 for a rough ECSN rate calculation). 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<sup>6, 5</sup>, giving a variety of expected mass windows at different metallicities (e.g.,  $\Delta M_{\text{SAGB}} \sim 0.2\text{--}1.4 M_{\odot}$  at solar metallicity<sup>4</sup>). Their final fate may vary from core-collapse to thermonuclear ECSNe depending on the electron-capture rates

and oxygen flame speed in the degenerate core<sup>33,34</sup>, resulting in different nucleosynthetic yields and galactic chemical evolution<sup>35</sup>. The core-collapse ECSNe are expected to leave low mass, spin, and kick-velocity neutron stars<sup>32</sup>, forming a low-mass peak ( $\sim 1.25 M_{\odot}$ ) in neutron star mass distribution<sup>36</sup> and low-eccentricity ( $\sim 0.2$ ) gravitational wave source population<sup>37</sup>. Therefore, using SN 2018zd as an ECSN template, future statistical studies with large surveys will be able to further reveal the true nature, rate, and implications of ECSNe for stellar evolution, core-collapse physics, supernova remnants, cosmic nucleosynthesis, the neutron star mass distribution, and the gravitational wave source population.

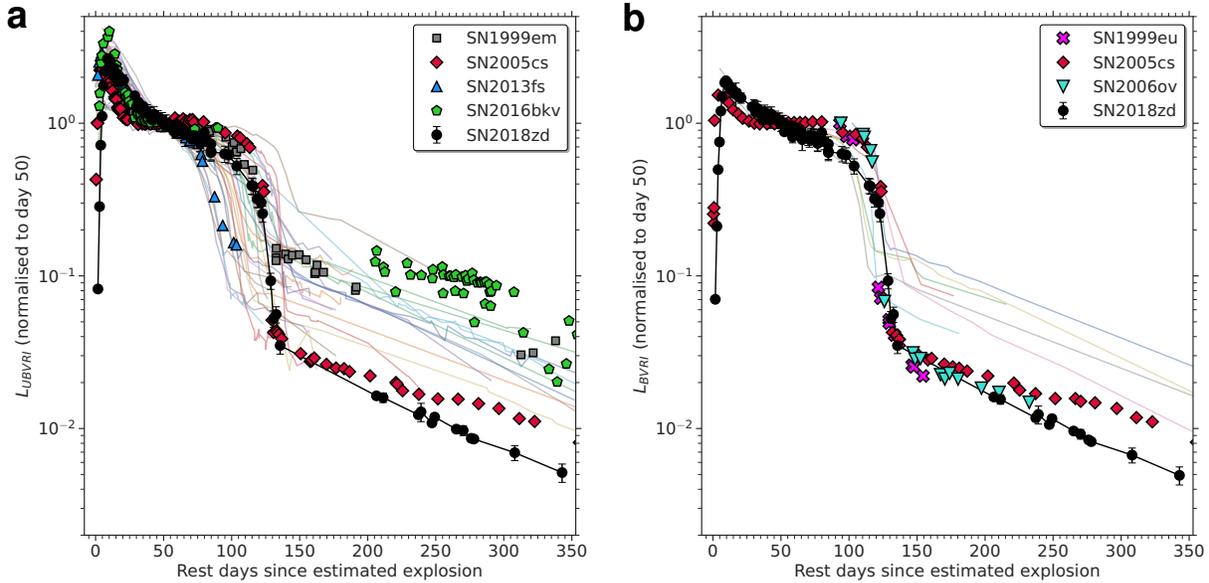
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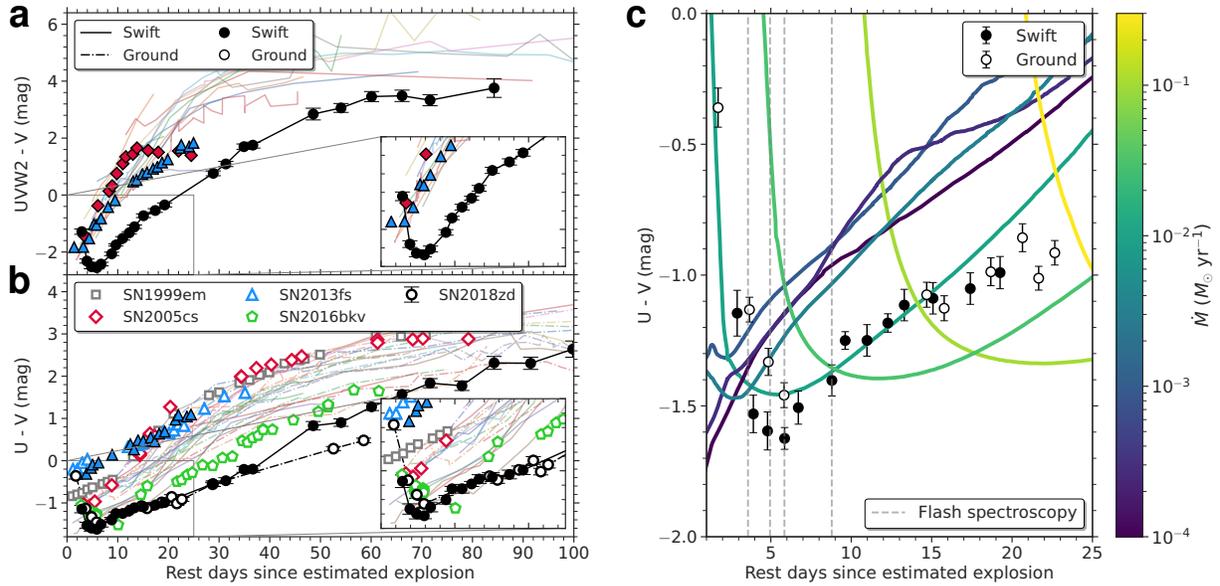
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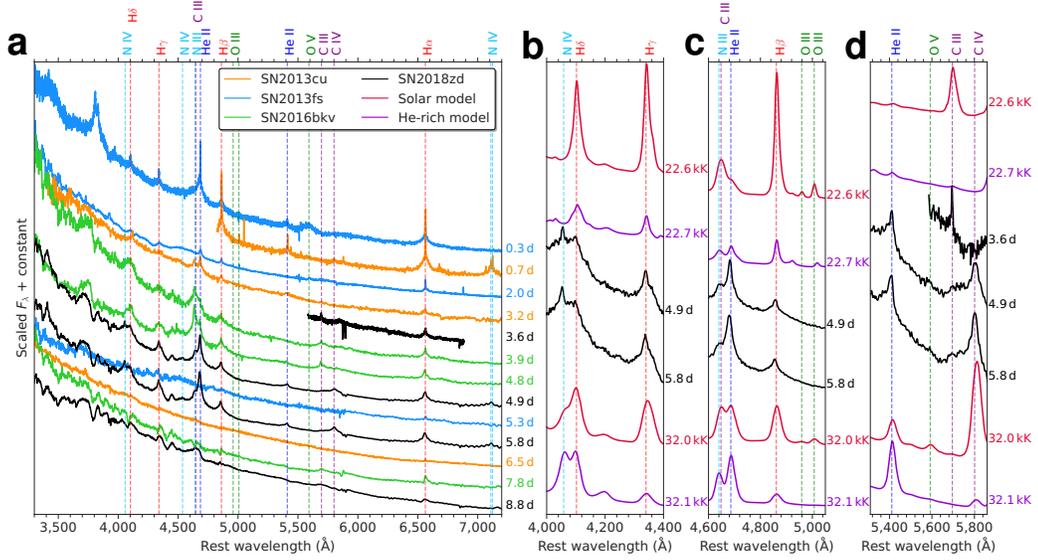
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**Figure 1 Normalised pseudobolometric light curves.** (a) Comparison of the normalised pseudobolometric ( $UBVR$ ; see Methods) light curve of SN 2018zd with a well-observed Type II SN sample<sup>16</sup> (transparent lines), including archetypal SN 1999em, low-luminosity SN 2005cs, and early-flash SN 2013fs, along with low-luminosity and early-flash SN 2016bkv<sup>38</sup>. (b) Comparison of the normalised pseudobolometric ( $BVRI$ ) light curve of SN 2018zd with a low-luminosity Type II-P SN sample<sup>17</sup>, including SNe 1999eu and 2006ov with the largest plateau drops ever to our knowledge. Error bars denote  $1\sigma$  uncertainties. Because of the distance uncertainty of SN 2018zd, we normalise each light curve to day 50 and make the comparisons distance independent. SN 2018zd shows the largest plateau drop that is comparable to SNe 1999eu and 2006ov, indicating an intrinsically low  $^{56}\text{Ni}$  production.

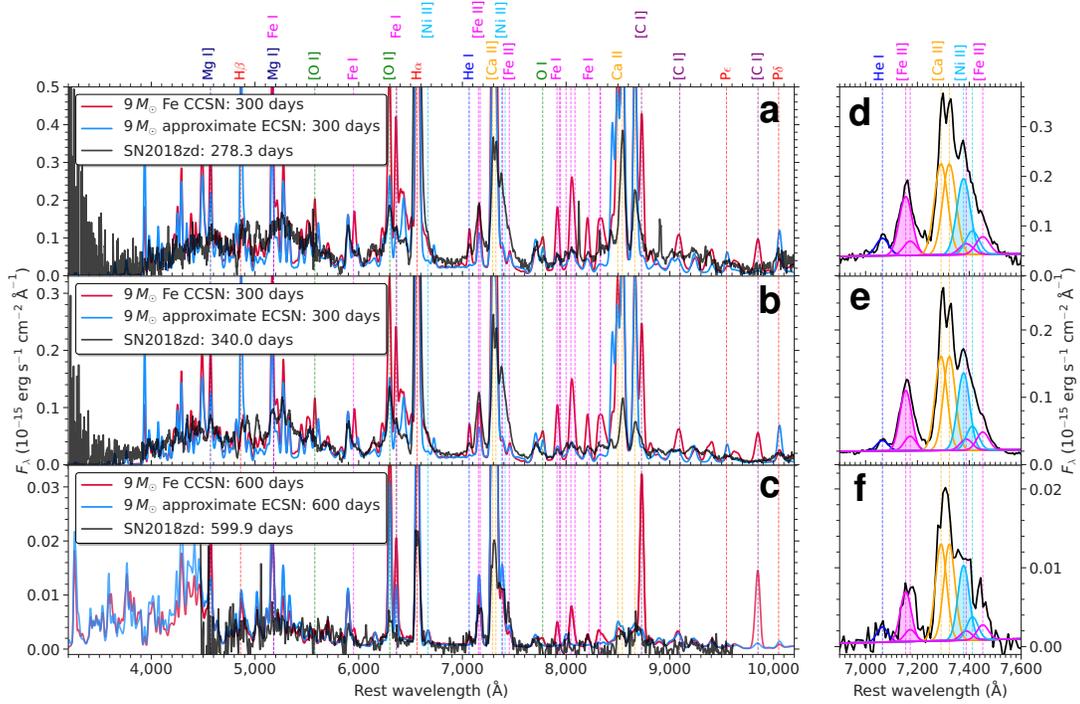


**Figure 2 UV colour light curves. (a, b)** Comparison of the UV colours of SN 2018zd with the sample as in Fig. 1a. Error bars denote  $1\sigma$  uncertainties. Note the pronounced sharp blueward colour evolution of SN 2018zd over the first  $\sim 5$  d, shown in the insets, suggesting a possible delayed shock-breakout through dense CSM. **(c)** Comparison of the  $U-V$  colour of SN 2018zd with our MESA+STELLA CSM models (see Methods and Extended Data Fig. 6) assuming a typical constant wind velocity of  $20 \text{ km s}^{-1}$  (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  $\sim 10$  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.



**Figure 3 Flash spectral time series.** (a) Comparison of the flash spectral time series of SN 2018zd with well-sampled Type II-P SNe 2013fs<sup>21</sup> and 2016bkv<sup>38</sup>, and Type IIb (mostly stripped H-rich envelope) SN 2013cu<sup>39</sup>. SN 2018zd exhibits the persistent flash features ( $\gtrsim 9$  d), whilst most of the flash features in the other SNe disappear within  $\sim 5$  d after the explosion. (b, c, d) Comparison of SN 2018zd with the scaled and resampled flash spectral models of solar abundance ( $X_{\text{H}} = 0.70$ ,  $X_{\text{He}} = 0.28$ ,  $X_{\text{C}} = 3.02 \times 10^{-3}$ ,  $X_{\text{N}} = 1.18 \times 10^{-3}$ ,  $X_{\text{O}} = 9.63 \times 10^{-3}$ ) and He-rich ( $X_{\text{H}} = 0.18$ ,  $X_{\text{He}} = 0.80$ ,  $X_{\text{C}} = 5.58 \times 10^{-5}$ ,  $X_{\text{N}} = 8.17 \times 10^{-3}$ ,  $X_{\text{O}} = 1.312 \times 10^{-4}$ ) atmosphere with  $\dot{M}_{\text{mod}} = 3 \times 10^{-3} M_{\odot} \text{yr}^{-1}$  and  $v_{\text{mod}} = 150 \text{ km s}^{-1}$  (the densest CSM with the finest temperature grid spacing)<sup>22</sup>. The temperatures are constrained to be within  $\sim 20,000$  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  $\rho_{\text{obs}}/\rho_{\text{mod}} = (\dot{M}_{\text{obs}}/v_{\text{obs}})/(\dot{M}_{\text{mod}}/v_{\text{mod}}) = 25$  with  $\dot{M}_{\text{obs}} = 0.01 M_{\odot} \text{ yr}^{-1}$  from the UV colours and assuming  $v_{\text{obs}} = 20 \text{ km s}^{-1}$  (the wind P-Cygni components of SN 2018zd are not resolved, only giving an upper-limit  $v_{\text{obs}} < 76.3 \text{ km s}^{-1}$  from the highest spectral resolution of C III  $\lambda 5696$  at 3.6 d). Based on the model comparisons, the line ratios of N IV/H $\delta > 1$  (b) and He II/H $\beta > 1$  (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.



**Figure 4 Nebular spectral time series.** (a, b, c) Comparison of the nebular spectral time series of SN 2018zd with the scaled (by  $^{56}\text{Ni}$  mass and phase) and resampled  $9 M_{\odot}$  Fe CCSN and “approximate ECSN” (excluding the He-core composition from the Fe CCSN) models<sup>11</sup>. The large number of narrow lines at  $\lesssim 5500 \text{ \AA}$  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]  $\lambda 4571$ , Mg I]  $\lambda 5180$  + Fe I  $\lambda 5180$ , [O I]  $\lambda 5577$ , Fe I  $\lambda 5950$ , [O I]  $\lambda\lambda 6300, 6364$  + Fe I  $\lambda 6364$ , O I  $\lambda 7774$ , Fe I cluster  $7900\text{--}8500 \text{ \AA}$ , [C I]  $\lambda 8727$ , [C I]  $\lambda 9100$ , and [C I]  $\lambda 9850$ , as well as the low line ratio of [O I]  $\lambda\lambda 6300, 6364$ /[Ca II]

$\lambda\lambda 7291, 7323 < 1$  observed in SN 2018zd. He I  $\lambda 7065$  is weaker in the approximate ECSN model than in the observed spectra; the emission from the dredged-up/out elements (e.g., He and N) in the H-rich envelope may be underestimated by the model. **(d, e, f)** Simultaneous Gaussian fits to He I  $\lambda 7065$ , [Fe II]  $\lambda 7155$ , [Fe II]  $\lambda 7172$ , [Ca II]  $\lambda 7291$ , [Ca II]  $\lambda 7323$ , [Ni II]  $\lambda 7378$ , [Fe II]  $\lambda 7388$ , [Ni II]  $\lambda 7412$ , and [Fe II]  $\lambda 7452$  (see Methods). Note the stronger [Ni II]  $\lambda 7378$  (the blue shaded region) than [Fe II]  $\lambda 7155$  (the pink shaded region), yielding  $[\text{Ni II}]/[\text{Fe II}] = 1.3\text{--}1.6$ . 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.

## Methods

**Follow-up imaging.** Follow-up imaging was obtained with the Las Cumbres Observatory network of 0.4 m, 1 m, and 2 m telescopes<sup>40</sup> through the Global Supernova Project, the Neil Gehrels *Swift* Observatory Ultraviolet/Optical Telescope (UVOT), the Noguchi Astronomical Observatory (Chiba, Japan) 0.26 m telescope, and the Itagaki Astronomical Observatory (Okayama and Tochigi, Japan) 0.35 m and 0.5 m telescopes. For the Las Cumbres photometry, point-spread-function (PSF) fitting was performed using `lcogtsnpipe`<sup>16</sup>, a PyRAF-based photometric reduction pipeline. *UBV*- and *gri*-band data were calibrated to Vega<sup>41</sup> and AB<sup>42</sup> magnitudes, respectively, using standard fields observed on the same night by the same telescope as the SN. The *Swift* UVOT photometry was done using the pipeline for the *Swift* Optical Ultraviolet Supernova Archive (SOUSA)<sup>43</sup>, including the updated sensitivity corrections and zeropoints<sup>44</sup> and the subtraction of the underlying host-galaxy count rates using images from October/November 2019. The unfiltered optical Itagaki (KAF-1001E CCD) and Noguchi (ML0261E CCD) photometry was extracted using `Astrometrica`<sup>45</sup> and calibrated to the Fourth US Naval Observatory CCD Astrograph Catalog (UCAC4)<sup>46</sup>. All photometry will be available for download via the Weizmann Interactive Supernova Data Repository (WiSeREP)<sup>47</sup> and the Open Supernova Catalog<sup>48</sup>. We correct all photometry for the Milky Way (MW) and host-galaxy extinction (see Section Extinction and Extended Data Fig. 3).

We estimate an explosion epoch by fitting a quadratic function  $F_1(t - t_0)^2$  to the unfiltered Itagaki and first three Noguchi points with similar CCD spectral responses ( $\lambda_{\text{eff}} = 6500\text{--}6700 \text{ \AA}$ ), where the effect of CSM interaction is less prominent than in the UV bands (Extended Data Fig. 3). This

yields an explosion epoch  $t_0 = \text{MJD } 58178.4 \pm 0.1$ , where the uncertainty is estimated from the difference between the explosion epoch and the first Itagaki detection. Even if we use the most conservative explosion epoch of the last nondetection on MJD 58175.5, the difference is only 2.9 rest-frame days, not affecting the main results of this paper.

We fit a blackbody spectral energy distribution (SED) to every epoch of the Las Cumbres and *Swift* photometry containing at least three filters (excluding the  $r$  band owing to strong  $\text{H}\alpha$  contamination) obtained within 0.3 d of each other to estimate the blackbody temperature and radius at the assumed luminosity distance (note that the observed SED peaks are bluer than the Swift wavelength coverage between 3–10 d after the explosion, potentially underestimating the blackbody temperatures<sup>16</sup>). Then we integrate the fitted blackbody SED to obtain bolometric (and pseudobolometric) luminosity at each epoch. Since we only have the unfiltered Noguchi photometry during the plateau drop owing to the Sun constraint, we estimate a bolometric (and pseudobolometric) correction by finding the offset of the Noguchi photometry to the Las Cumbres and *Swift* integrated bolometric (and pseudobolometric) luminosity during the plateau phase (50–80 d) where most of the SED ( $\sim 80\%$ ) is in the spectral response range of the unfiltered CCD. Then we apply the bolometric (and pseudobolometric) correction to the Noguchi photometry and include it in the bolometric (and pseudobolometric) light curve during the plateau drop (Fig. 1). This procedure is also justified by the good agreement with the tail bolometric (and pseudobolometric) luminosity obtained from the Las Cumbres multiband photometry after the Sun constraint.

**Follow-up spectroscopy.** Follow-up spectroscopy was obtained with the FLOYDS spectrograph mounted on the Las Cumbres Observatory 2 m Faulkes Telescope North (FTN)<sup>40</sup> through the

Global Supernova Project, the Boller & Chivens (B&C) spectrograph mounted on the 2.3 m Bok telescope, the Blue Channel (BC) spectrograph mounted on the 6.5 m MMT, and the Low Resolution Imaging Spectrometer (LRIS)<sup>49, 50, 51</sup> and the DEep Imaging Multi-Object Spectrograph (DEIMOS)<sup>52</sup> mounted on the 10 m Keck-I and Keck-II telescopes, respectively. For the FLOYDS observations, a 2'' slit was placed on the target at the parallactic angle<sup>53</sup> (to minimise the effects of atmospheric dispersion). One-dimensional spectra were extracted, reduced, and calibrated following standard procedures using the FLOYDS pipeline<sup>54</sup>. The Bok low-resolution optical spectra were taken with the 300 lines  $\text{mm}^{-1}$  grating using a 1.5'' slit width, and the MMT moderate-resolution spectra were obtained using a 1.0'' slit width. The spectra were reduced using standard techniques in IRAF, including bias subtraction, flat-fielding, and sky subtraction. Flux calibration was done with spectrophotometric standard star observations taken on the same night at similar airmass. The Keck LRIS spectra were reduced using the `Lpipe` pipeline<sup>55</sup> with the default parameters and standard spectroscopic reduction techniques. The Keck DEIMOS spectrum was reduced with a custom-made Python pipeline that performs flat-field correction, sky subtraction, optimal extraction<sup>56</sup>, and flux calibration using a standard star observed on the same night as the SN. All spectra will be available for download via WISeREP and the Open Supernova Catalog. We correct all spectra for the MW and host-galaxy extinction and calibrate the flux using the photometry (Extended Data Fig. 4).

We measure expansion velocities of  $\text{H}\alpha$ ,  $\text{H}\beta$ , and  $\text{Fe II } \lambda 5169$  from the absorption minimum by fitting a P-Cygni profile to each line. Then we translate the difference between the observed minimum and the rest wavelength of the line to an expansion velocity using the relativistic Doppler

formula (Extended Data Fig. 5). We estimate the velocity uncertainties by randomly varying the background region by  $\pm 5 \text{ \AA}$ .

We simultaneously fit Gaussian functions to He I  $\lambda 7065$ , [Fe II]  $\lambda 7155$ , [Fe II]  $\lambda 7172$ , [Ca II]  $\lambda 7291$ , [Ca II]  $\lambda 7323$ , [Ni II]  $\lambda 7378$ , [Fe II]  $\lambda 7388$ , [Ni II]  $\lambda 7412$ , and [Fe II]  $\lambda 7452$  in the nebular spectra assuming a single full width at half-maximum (FWHM) velocity for all lines and the theoretically expected line ratios for the [Ca II], [Fe II], and [Ni II] lines<sup>57</sup> (Fig. 4). The resultant [Ni II]  $\lambda 7378$ /[Fe II]  $\lambda 7155$  ratios and FWHM velocities are 1.3–1.6 and 2,500–2,100  $\text{km s}^{-1}$ , respectively, from 278–600 d after the explosion.

**Follow-up spectropolarimetry.** Follow-up spectropolarimetric observations of SN 2018zd were obtained using the CCD Imaging/Spectropolarimeter (SPOL<sup>58</sup>) on the 6.5 m MMT telescope using a 2.8'' slit on 2018 April 23 (53 d after the explosion). We used a 964 lines  $\text{mm}^{-1}$  grating with a typical wavelength coverage of 4050–7200  $\text{\AA}$  and a resolution of  $\sim 29 \text{ \AA}$ . We used a rotatable semi-achromatic half-wave plate to modulate incident polarization and a Wollaston prism in the collimated beam to separate the orthogonally polarized spectra onto a thinned, anti-reflection-coated  $800 \times 1200$  pixel SiTe CCD. The efficiency of the wave plate as a function of wavelength was measured and corrected for by inserting a fully-polarizing Nicol prism into the beam above the slit. A series of four separate exposures that sample 16 orientations of the wave plate yield two independent, background-subtracted measures of each of the normalised linear Stokes parameters,  $Q$  and  $U$ . Two such sequences were acquired and combined to increase the signal-to-noise ratio.

Our spectropolarimetric analysis is performed primarily using the linear Stokes parameters,  $q = Q/I$  and  $u = U/I$ , which are rotated  $45^\circ$  with respect to each other, allowing us to decompose the polarization signal into orthogonal components in position-angle space. We use the debiased polarization level,  $p_{\text{db}} = \sqrt{|(q^2 + u^2) - \frac{1}{2}(\sigma_q^2 + \sigma_u^2)|}$ , in favour of the standard polarization level,  $p = \sqrt{q^2 + u^2}$ , because the standard polarization level is a positive-definite quantity that measures the distance from the origin in a  $q$  vs.  $u$  plane. When the signal-to-noise ratio is low, this positive-definite quantity can be misleading, whereas the debiased polarization value accounts for large uncertainty in measurements of  $q$  and  $u$ .

SN 2018zd exhibits a mean polarization of 0.9% across the continuum at 5100–5700 Å and 0.8% across the continuum at 6000–6300 Å. However, the polarization does not vary much across the entire spectrum, even across absorption and emission-line features. Typically, a polarized continuum would become depolarized across emission-line features due to dilution with unpolarized light from the emission line. Since SN 2018zd does not exhibit any such changes across any of its emission-line features, we suggest that the majority of the polarization signal arises in the interstellar medium rather than in the SN itself. The Serkowski relation<sup>59</sup> suggests that  $p_{\text{max}} < 9 E(B - V)$ . If all 0.9% of the continuum peak polarization in SN 2018zd were due to the interstellar medium, then we could estimate the extinction to be  $E(B - V) > p_{\text{max}}/9 = 0.1$  mag and a reddening of at least  $A_V = 3.1 E(B - V) = 0.31$  mag.

**Extinction.** We obtained the MW extinction<sup>60</sup> of  $A_{V,\text{MW}} = 0.258$  mag via the NASA/IPAC Infrared Science Archive<sup>61</sup>. We measure the total Na I D EW of each host and MW component using the MMT BC spectra (moderate resolution of 1.45 Å) taken between 3.6–53.4 d after the explo-

sion. Since the ratio of the total Na I D EW of the host to MW varies between 1.07 and 1.25, we estimate  $A_{V,\text{host}} \gtrsim A_{V,\text{MW}}$ . As a cross-check, we transform the *gri* magnitudes of SN 2018zd to *VRI* magnitudes<sup>62</sup> and compare the *V-I* colour to that of well-observed, low-extinction Type II-P SNe 1999em<sup>63</sup>, 1999gi<sup>64</sup>, 2012aw<sup>65</sup>, and 2017eaw<sup>66</sup> by assuming  $A_{V,\text{host}} = A_{V,\text{MW}}$  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  $A_{V,\text{host}} = A_{V,\text{MW}}$  and assume a reddening<sup>67</sup> law with  $R_V = 3.1$ , consistent with the lower limit obtained from the spectropolarimetry. 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  $\pm 0.10$  mag.

**Luminosity distance.** We apply the expanding photosphere method (EPM)<sup>64, 68</sup> and the standard candle method (SCM)<sup>69</sup> using the measured Fe II  $\lambda 5169$  velocities and transforming the *gri* to *VRI* magnitudes<sup>62</sup>, which yields  $6.5 \pm 0.7$  and  $9.6 \pm 1.0$  Mpc, respectively. The EPM is best used at early times ( $\lesssim 30$  d) when SN emission can be approximated as a diluted blackbody in free expansion<sup>68</sup>. 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<sup>70, 71, 72</sup> at day 50 when the CSM interaction is negligible, which is well reproduced by our MESA+STELLA models (see Section MESA+STELLA progenitor and light-curve modeling and Extended Data Fig. 6). Thus, we favour the SCM over the EPM.

It has been suggested that NGC 2146 may be further than the SCM estimate. There is a claim of a preliminary tip of the red giant branch (TRGB) distance obtained from archival *HST* WFC3/IR data (program GO-12206, PI: M. Westmoquette) that places the galaxy out at  $\sim 18$  Mpc<sup>15</sup>. We

have independently reduced and analysed this same data and find that the single orbit of observations available (split between F110W & F160W) do 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 due 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<sup>73</sup> (e.g., 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 Section Alternative scenarios.

**Host galaxy.** NGC 2146 is an edge-on spiral galaxy with several tidal streams that were likely ejected during a galaxy merger event  $\sim 800$  Myr ago<sup>74</sup> (Extended Data Fig. 1). The presence of a starburst-driven superwind from the bulge is revealed across the electromagnetic spectrum from  $\gamma$ -rays to infrared<sup>75, 76, 74, 77</sup>, indicating an ongoing high star formation rate<sup>78</sup> ( $\text{SFR} \approx 10 M_{\odot} \text{ yr}^{-1}$ ). Based on radio observations of the bulge<sup>79</sup>, there are many more dense H II regions (each containing up to 1,000 type O6 stars) than supernova remnants, suggesting a relatively young phase of the starburst. The bulge has a high dust content and roughly solar metallicity ( $12 + \log_{10}[\text{O}/\text{H}] = 8.68 \pm 0.10$ )<sup>78, 80</sup>. Since SN 2018zd is at a relatively large separation from the nucleus of  $1'83$  north-west ( $36''.1$  north,  $103''.7$  west; Extended Data Fig. 1), and the galactic radius parameter  $R_{25} = 1'.78$  (via NASA/IPAC Extragalactic Database<sup>81</sup>), if we reasonably assume that there is an abundance gradient for the galaxy, the metallicity at the SN site is likely subsolar; this merits future investigations once the SN fades.

***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 ACS/WFC instrument on 2004 April 10 (program GO-9788, PI L. Ho, with total exposure times of 120 s and 700 s, respectively; the F814W image consists of a single exposure), as well as in F225W with WFC3/UVIS on 2013 March 7 (program GO-13007, PI L. Armus; total exposure time of 1500 s). Other *HST* data have been obtained of the host galaxy in other bands with other instruments, but these do not contain the SN site. We initially matched the F814W image with a Las Cumbres *V*-band image of fair quality (seeing 1''8) obtained at the McDonald Observatory facility on 2018 March 5.11, using 8 stars in common between the ground-based and *HST* data, with a root-mean-square (RMS) uncertainty in the astrometric solution of 1.99 ACS/WFC pixels. On visual inspection we found the site to be quite sparse, but we were able to identify a potential candidate progenitor in the ACS image within the  $1\sigma$  positional uncertainty.

We confirmed the candidate more precisely by obtaining images of the SN itself on 2019 May 19 in F555W and F814W with WFC3/UVIS, as part of program GO-15151 (PI S. Van Dyk). We were able to astrometrically register the 2019 F814W image mosaic to the 2004 one using 23 stars in common, with an RMS 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 Figure 1.

We extracted photometry from all of the *HST* images using the package Dolphot<sup>82</sup>. We applied Dolphot to the individual FLC frames. We found that Dolphot detected and measured a source

at the position of the progenitor candidate with  $m_{F814W} = 25.05 \pm 0.15$  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, whilst constructing an image mosaic from the single frame, as would normally be the case for two or more dithered exposures. Additionally, we note that the flux measurement with Dolphot may also 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 PSF, we employ a deep learning model (Xu et. al., in preparation) based on the results from DeepCR<sup>83</sup>. We find that no pixels in the vicinity of the candidate progenitor have a model score higher than  $5.1 \times 10^{-5}$ . 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 PSF with  $> 3\sigma$  confidence. If the object was not actually detected, we find that the upper limit at  $3\sigma$  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  $3\sigma$ ) of  $> 23.6$  and  $> 24.1$  mag, respectively. We also note that we measured a brightness of the SN itself in the 2019 *HST* observations of  $m_{F555W} = 21.53 \pm 0.01$  and  $m_{F814W} = 20.33 \pm 0.01$  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 to 24  $\mu\text{m}$ . The data are from observations with

the Infrared Array Camera (IRAC<sup>84</sup>) in channels 1 (3.6  $\mu\text{m}$ ) and 2 (4.5  $\mu\text{m}$ ; the SN site sits in a gap of spatial coverage in channels 3 and 4 at 5.8 and 8.0  $\mu\text{m}$ , respectively) on 2004 March 8 (program 59, PI G. Rieke) and on 2007 October 16 (program 40410, PI G. Rieke) in channels 2 and 4; from observations with the Multiband Imaging Photometer for Spitzer (MIPS<sup>85</sup>) at 24  $\mu\text{m}$  on 2004 March 16 (program 59, PI G. Rieke; the sensitivity and resolution of the data at 70 and 160  $\mu\text{m}$  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 (program 80089, PI D. Sanders). We show the 2011 November 15 IRAC observation in ch1 in Extended Data Figure 1.

Observations with IRAC of the SN itself were obtained on 2019 January 24 (program 14098, PI O. Fox); however, we did not analyse these data, other than to extract an absolute position for the SN of  $\alpha = 6^{\text{hr}}18^{\text{m}}03.43^{\text{s}}$ ,  $\delta = +78^{\circ}22'01''.4$  (J2000;  $\pm 0''.3$  in each coordinate). Using MOPEX<sup>86</sup> we constructed mosaics from all of the useful pre-SN imaging data, and with APEX within MOPEX<sup>87</sup> 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  $3\sigma$ ) of  $> 19.0$  and  $> 18.1$  mag in ch1 and ch2 (respectively) from the 2004 March 8 data;  $> 18.1$  and  $> 14.5$  mag in ch2 and ch4 (respectively) from 2007 October 16; and  $> 19.0$  and  $> 18.4$  mag in ch1 and ch2 (respectively) from 2011 November 15 (we have assumed the zeropoints from the IRAC Instrument Handbook<sup>88</sup>). We also estimated  $> 10.2$  mag at 24  $\mu\text{m}$  from the 2004 March 16 observation (we have assumed the zeropoint from the MIPS Instrument Handbook<sup>89</sup>).

We show the resulting SED, or limits thereon, for the SN 2018zd progenitor in Extended Data Figure 2. The distance ( $9.6 \pm 1.0$  Mpc) and extinction ( $A_V = 0.52 \pm 0.10$  mag) to the SN dis-

cussed in Sections Luminosity distance and Extinction were adopted, assuming that the latter also applied to the progenitor as well. We have further assumed a reddening<sup>67</sup> law with  $R_V = 3.1$  and extend it into the mid-infrared<sup>90</sup>. For comparison we also show single-star models from BPASS v2.2<sup>91</sup>, specifically those for SAGB stars (i.e., those in the initial mass range  $M_{\text{init}} = 6\text{--}8 M_{\odot}$  with bolometric luminosities  $L \approx 10^5 L_{\odot}$  in the last model timestep) and RSG stars with  $M_{\text{init}} = 8 M_{\odot}$  and  $M_{\text{init}} = 15 M_{\odot}$ . Here we considered the models with metallicities  $Z = 0.020$  (solar) and  $Z = 0.010$  (subsolar; as discussed in Section Host galaxy, the SN site metallicity is likely subsolar). We have extrapolated the SEDs of the BPASS models into the mid-infrared via MARCS<sup>92</sup> 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 IRAC and MIPS Instrument Handbooks. We have further included for comparison the observed SED for the candidate SAGB star MSX SMC 055 (IRAS 00483–7347)<sup>93</sup>, assuming Galactic foreground extinction and adjusted to a Small Magellanic Cloud distance modulus of  $\mu = 18.90$  mag (Extragalactic Distance Database<sup>94</sup>), as well as the SED for the progenitor of the low-luminosity Type II-P SN 2005cs<sup>95, 96</sup>, assuming the total reddening from the two studies of that progenitor and adjusted to a recent accurate distance for M51<sup>97</sup>. Note that the SEDs for the BPASS RSG models with  $M_{\text{init}} = 15 M_{\odot}$  are likely 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 2017eaw<sup>66</sup>. 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, of which we have strong evidence (given here) for the presence 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  $M_{\text{init}} \gtrsim 8 M_{\odot}$  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 are 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 modeling.** Recent work<sup>72, 98, 99, 100</sup> highlights the nonuniqueness of bolometric light-curve modeling for extracting explosion characteristics (ejecta mass  $M_{\text{ej}}$ , explosion energy  $E_{\text{exp}}$ , and progenitor radius  $R$ ) from plateau features (in particular, luminosity at day 50,  $L_{50}$ , and plateau duration,  $t_p$ ) without an independent prior on one of  $M_{\text{ej}}$ ,  $E_{\text{exp}}$ , or  $R$ . Due to the presumed presence of a dense CSM and its potential influence on the early light curves and velocities, shock-cooling modeling 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<sup>101</sup> of MESA<sup>102, 103, 104, 105, 106</sup> RSG progenitor models with expected ejecta masses and radii within the family of explosions consistent with the  $L_{50}$ ,  $t_p$ , and  $M_{\text{Ni}}$  of SN 2018zd (Extended Data Fig. 6). All models began at solar metallicity ( $Z = 0.02$ ), and the naming scheme gives explosion properties (M[ $M_{\text{ej}}/M_{\odot}$ ]-R[ $R/R_{\odot}$ ]-E[ $E_{\text{exp}}/10^{51}$  erg]). The high-ejecta-mass model, M17.2\_R718\_E0.48, is  $18.8 M_{\odot}$  at core collapse ( $20 M_{\odot}$  at Zero Age Main Sequence (ZAMS)) with no rotation, no exponential overshooting ( $f_{\text{ov}} = f_{0,\text{ov}} = 0.0$ ), mixing length  $\alpha_{\text{env}} = 2.0$  in the H-rich envelope, and a wind efficiency factor  $\eta_{\text{wind}} = 0.4$ . The moderate model, M14.5\_R864\_E0.37, is  $16.3 M_{\odot}$  at core collapse ( $17 M_{\odot}$  at ZAMS) with modest initial rotation  $\Omega/\Omega_{\text{crit}} = 0.2$ , no exponential overshooting,  $\alpha_{\text{env}} = 2.0$ , and  $\eta_{\text{wind}} = 0.2$ . The low-ejecta-mass and large-radius model, M8.3\_R1035\_E0.23, is  $11.8 M_{\odot}$  at core collapse ( $15 M_{\odot}$  at ZAMS) with modest rotation  $\Omega/\Omega_{\text{crit}} = 0.2$ , moderately high exponential overshooting ( $f_{\text{ov}} = 0.018, f_{0,\text{ov}} = 0.006$ ),  $\alpha_{\text{env}} = 2.0$ , and  $\eta_{\text{wind}} = 0.9$ . Despite the ZAMS mass typical of a red supergiant, this model sufficiently captures the relevant explosion properties for the SAGB explosion scenario, as the mass of the H-rich ejecta, explosion energy, and progenitor radius determine the plateau properties of Type II-P SNe, not the ZAMS mass.

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 relations<sup>72</sup>

$$\begin{aligned}\log(E_{51}) &= -0.728 + 2.148 \log(L_{p,42}) - 0.280 \log(M_{\text{Ni}}) + 2.091 \log(t_{p,2}) - 1.632 \log(R_{500}), \\ \log(M_{10}) &= -0.947 + 1.474 \log(L_{p,42}) - 0.518 \log(M_{\text{Ni}}) + 3.867 \log(t_{p,2}) - 1.120 \log(R_{500}),\end{aligned}\tag{1}$$

where  $E_{51} = E_{\text{exp}}/10^{51}$  erg,  $M_{10} = M_{\text{ej}}/10 M_{\odot}$ ,  $M_{\text{Ni}}$  is in units of  $M_{\odot}$ ,  $L_{p,42} = L_{50}/10^{42}$  erg s<sup>-1</sup>,  $t_{p,2} = t_p/100$  d, and  $R_{500} = R/500 R_{\odot}$ . Plugging in  $L_{50} = 8.6 \times 10^{41}$  erg s<sup>-1</sup> from the bolometric light curve at day 50,  $t_p = 125.4$  d determined by fitting the drop from the plateau<sup>16</sup>, and observed  $M_{\text{Ni}} = 0.0086 M_{\odot}$ , these relations describe the possible explosion parameter space (Extended Data Fig. 6). These relations are intended for Ni-rich ( $M_{\text{Ni}} > 0.03 M_{\odot}$ ) 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 which we use to reproduce the light-curve properties, and reveals low recovered  $E_{\text{exp}}$  which overlap significantly with the expected parameter space of ECSNe. The mapping between  $M_{\text{ej}}$  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  $M_{\text{ej}}$  from explosions of different stellar progenitors<sup>71, 107, 72</sup>. 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- $M_{\text{ej}}$  progenitor with a radius of  $1400 R_{\odot}$ , for example, could even produce this luminosity with an explosion energy of  $\approx 1.5 \times 10^{50}$  erg.

The explosions were carried out using MESA revision 12115, making use of the updated prescription for removing material falling back onto the inner boundary<sup>106, 72</sup>, which can be relevant at the low explosion energies required here. Of the three explosions, only M8.3\_R1035\_E0.23 undergoes significant late-time fallback, totaling  $2 M_{\odot}$ , which is excised from the model with no extra heating and negligible change in the total explosion energy. A thermal bomb was injected in the innermost  $0.1 M_{\odot}$  of each model, heating the star to the desired total final energy  $E_{\text{exp}}$ . The evolution of the shock was modeled in MESA with the ‘‘Duffell RTI’’ prescription for mixing via the Rayleigh-Taylor instability<sup>108, 105</sup>, terminating near shock breakout, when the shock reaches a mass coordinate of  $0.04 M_{\odot}$  below the outer boundary of each model. The  $^{56}\text{Ni}$  distribution in each model was then scaled to match the observed value of  $0.0086 M_{\odot}$ .

These models near shock breakout were then handed off to STELLA<sup>109, 110, 111</sup> to produce synthetic observables. Bolometric light curves and expansion velocities were produced using 600 spatial zones and 100 frequency bins, without any additional material outside the stellar photosphere (Extended Data Fig. 6). We see good agreement between all three models and observations (varying by at least 50% in  $M_{\text{ej}}$ ,  $E_{\text{exp}}$ , and  $R$ ), with deviations at early times which can be attributed to the extended stellar atmosphere and potential interaction with the circumstellar environment.

In order to account for the early deviations, we affix a wind density profile with  $\rho_{\text{wind}}(r) = \dot{M}_{\text{wind}}/4\pi r^2 v_{\text{wind}}$ , where  $\dot{M}_{\text{wind}}$  is a constant wind mass-loss rate, and  $v_{\text{wind}}$  is the wind velocity for time  $t_{\text{wind}}$  (i.e.,  $M_{\text{wind}} = \dot{M}_{\text{wind}} t_{\text{wind}}$ ), onto the MESA model at handoff to STELLA. For models with CSM, 600 zones are used in STELLA, including 400 zones for the original ejecta, and 200 additional zones for the wind model. We construct a grid of CSM models by varying the following

parameters:  $\dot{M}_{\text{wind}} = \{10^{-4}, 3 \times 10^{-4}, 10^{-3}, 3 \times 10^{-3}, 10^{-2}, 3 \times 10^{-2}, 10^{-1}, 3 \times 10^{-1}\} M_{\odot} \text{ yr}^{-1}$  and  $t_{\text{wind}} = \{1, 3, 10, 30\} \text{ yr}$  for each MESA model, assuming a typical wind velocity<sup>18</sup>  $v_{\text{wind}} = 20 \text{ km s}^{-1}$ . Then we perform  $\chi^2$  fitting on the observed bolometric light curve over the full temporal evolution and find the best-fit parameters  $\dot{M}_{\text{wind}} = 0.01 M_{\odot} \text{ yr}^{-1}$  and  $t_{\text{wind}} = 10 \text{ yr}$ .

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 M8.3\_R1035\_E0.23 as a representative model and present it for the UV-colour plot in Figure 2. In addition to matching the early-time luminosity excess, a dense wind profile suppresses the early photospheric and Fe line velocities<sup>20</sup>. The kink seen in the modeled Fe line velocity with Sobolev optical depth  $\tau_{\text{Sob}} = 1$  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 between 3–10 d after the explosion, the blackbody temperatures ( $\sim 20,000\text{--}25,000 \text{ K}$ ) may be underestimated (see Section Follow-up imaging), which could affect the luminosity around the peak, and so the CSM models. For the flash spectral model comparisons in Figure 3, we use a conservative temperature constraint of  $\sim 20,000\text{--}30,000 \text{ K}$ .

**Alternative scenarios.** A low-mass ( $\lesssim 9.6 M_{\odot}$ ) Fe CCSN is a possible alternative for SN 2018zd, as similar explosion energy ( $\sim 10^{50} \text{ erg}$ )<sup>112</sup> and nucleosynthesis<sup>113</sup> to ECSNe may be expected because of a similar steep density gradient outside the degenerate core. For a low-mass RSG star, however, no high constant ( $\gtrsim 10^{-5} M_{\odot} \text{ yr}^{-1}$ )<sup>114, 115, 116</sup> and/or eruptive<sup>117, 118</sup> mass loss is expected

to produce dense confined He-, C-, and N-rich, but O-poor CSM (but note that the mass loss is quite sensitive to the model treatments of, e.g., convection and off-center nuclear burning<sup>119</sup>). In addition, a low-mass RSG has Si-, O-, and He-rich layers<sup>5</sup> which are expected to produce additional Si, S, Ca, Mg, O, C, and He lines in nebular spectra<sup>11</sup>. Thus, a low-mass Fe CCSN may be able to explain the light-curve morphology, but likely not the early-time CSM interaction and nebular spectra observed for SN 2018zd.

On the other side of the progenitor mass spectrum, another possible alternative for SN 2018zd is a high-mass ( $\gtrsim 25 M_{\odot}$ ) Fe CCSN, as small kinetic energy ( $\sim 10^{50}$  erg) and ejected radioactive  $^{56}\text{Ni}$  mass ( $\lesssim 10^{-3} M_{\odot}$ ) may be expected owing to fallback accretion onto the central remnant<sup>120, 121</sup>. For such high fallback accretion, however, extra luminosity ( $L \propto t^{-5/3}$ ) at late times ( $t \gtrsim 200$  d) is expected<sup>122, 123</sup>. Also, no ejected stable  $^{58}\text{Ni}$  should be observed, as produced in the innermost neutron-rich layer<sup>10</sup>. Thus, a high-mass Fe CCSN may be able to explain the photospheric light curve, but not the late-time exponential tail and nebular spectra of SN 2018zd.

If the luminosity distance to NGC 2146 were larger than 12 Mpc, it would be quite unlikely that SN 2018zd is an ECSN, since  $M_{\text{Ni}} > 0.01 M_{\odot}$ ,  $E_{\text{exp}} > 4 \times 10^{50}$  erg, and  $M_{\text{ej}} > 10 M_{\odot}$  in a reasonable progenitor radius range of 400–1400  $R_{\odot}$  according to the light-curve scaling (Eq. 1). Then SN 2018zd would become a real challenge to stellar evolution and SN explosion theories to reconcile all of the observational ECSN indicators with a higher  $M_{\text{Ni}}$ ,  $E_{\text{exp}}$ ,  $M_{\text{ej}}$ , and  $M_{\text{ZAMS}}$  for the progenitor. If the luminosity distance were 18 Mpc, the progenitor candidate detection of SN 2018zd in *HST* F814W would become as bright as that of the SN 2005cs progenitor (Extended Data Fig. 2), but still on the faint end of Type II SN progenitors<sup>117, 124</sup> despite the expected higher

$M_{\text{ej}}$  and  $M_{\text{ZAMS}}$  from the light-curve scaling.

**Other ECSN candidates.** In addition to SN 1054, other previously suggested ECSN candidates can be divided into three types: intermediate-luminosity red transients (ILRTs; e.g., SN 2008S and AT 2017be)<sup>125, 126, 127, 128, 129, 130</sup>; low-luminosity Type II-P SNe<sup>7, 8, 17, 38</sup>; and Type IIn-P SNe (e.g., SNe 2009kn and 2011ht)<sup>131, 132, 18, 29</sup> (Extended Data Table 1).

ILRTs are the luminosity gap transients between novae and supernovae, whose origin has been debated as either a massive star outburst<sup>133, 134, 135, 136</sup> or terminal ECSN explosion<sup>125, 126, 127, 128, 129, 130</sup>. Their progenitors are surrounded by dusty, optically thick shells, resulting in CSM-dominated transients<sup>125, 126, 127, 133, 134, 128</sup>. However, their faint light-curve morphology with CSM interaction requires extremely low explosion energy ( $\lesssim 10^{48}$  erg) that is unexpected for ECSNe<sup>9, 18, 137</sup>, and their chemical composition and nucleosynthesis are unclear owing to the lack of nebular-phase spectra.

Low-luminosity Type II-P SNe typically yield low  $^{56}\text{Ni}$  mass ( $\lesssim 10^{-2} M_{\odot}$ )<sup>17</sup> with ECSN-like light-curve morphology (Fig. 1), but their chemical composition and nucleosynthesis are inconsistent with ECSNe<sup>11</sup> (Extended Data Fig. 7), and their CSM density is generally low compared to that expected from ECSNe<sup>4, 18</sup> (except for SN 2016bkv<sup>38</sup>). Low-mass RSG progenitors have been directly identified for SNe 2003gd<sup>138</sup>, 2005cs<sup>139, 138</sup>, 2008bk<sup>140</sup>, excluding SAGB stars – the progenitors of ECSNe.

Type IIn-P SNe show Type IIn-like narrow CSM emission lines in spectra and Type II-P-like light-curve morphology with large plateau drops similar to ECSNe<sup>131, 132, 29, 18</sup> (Extended Data

Fig. 8), although the SN signatures (e.g., chemical abundance) are mostly hidden below the CSM interaction. Whilst no Type IIn-P SN progenitors have been directly identified, a pre-explosion outburst has been observed for SN 2011ht<sup>141</sup>. The true nature of Type IIn-P SNe is yet to be revealed.

**The rate of ECSNe.** Since Type IIn-P SNe share similar properties as SN 2018zd, 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 WISEREP and/or the Transient Name Server (TNS<sup>142</sup>) by cross-checking with the literature and the Open Supernova Catalog and cross-correlating the public spectra to SN spectral libraries Superfit<sup>143</sup> and SNID<sup>144</sup> when available. There are 528 objects classified as Type IIn SNe on WISEREP and/or TNS (as of 2020 Mar. 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 that we do not overestimate the lower limit (Extended Data Fig. 8).

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 ( $z = 0.025878$ )<sup>145</sup>; 2005db ( $z = 0.015124$ )<sup>145</sup>; 2006bo ( $z = 0.0153$ )<sup>146</sup>; and 2011A ( $z = 0.008916$ )<sup>147</sup>, in addition to three known Type IIn-P SNe 1994W ( $z = 0.004116$ )<sup>148</sup>, 2009kn

( $z = 0.015798$ )<sup>131</sup>, and 2011ht ( $z = 0.003646$ )<sup>132</sup> (Extended Data Fig. 8).

To compare with the volume-limited ( $\leq 60$  Mpc) Lick Observatory Supernova Search (LOSS) sample<sup>149, 150</sup>, we apply the same distance cut, leaving 42 Type II<sub>n</sub> SNe (17 and 25 with sufficient and insufficient data, respectively) and 3 Type II<sub>n</sub>-P SNe 1994W, 2011A, and 2011ht. As these SNe were discovered by different surveys with different strategies, we have no handle on the incompleteness (but see Extended Data Fig. 8). Thus, we neglect the incompleteness and take the number ratio of Type II<sub>n</sub>-P to Type II<sub>n</sub> SNe within 60 Mpc multiplied by the LOSS Type II<sub>n</sub> SN rate<sup>150</sup>,  $3/42 \times 8.8\% = 0.63\%$  of all CCSNe, as a rough lower limit of the Type II<sub>n</sub>-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 at least one identification of SN 2018zd as an ECSN.

By combining the estimated Type II<sub>n</sub>-P and SN 2018zd-like lower limits, we obtain a Type II<sub>n</sub>-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<sup>113</sup>. 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  $\Delta M_{\text{SAGB}} \approx 0.06\text{--}0.69 M_{\odot}$  assuming maximum and minimum SAGB masses of  $9.25 M_{\odot}$  and  $9.25 M_{\odot} - \Delta M_{\text{SAGB}}$  (respectively) at solar metallicity<sup>4</sup> (Extended

Data Fig. 9). We note that Type II<sub>n</sub>-P and SN 2018zd-like rates are likely 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, potentially putting stringent constraints on many fields of physics and astrophysics.

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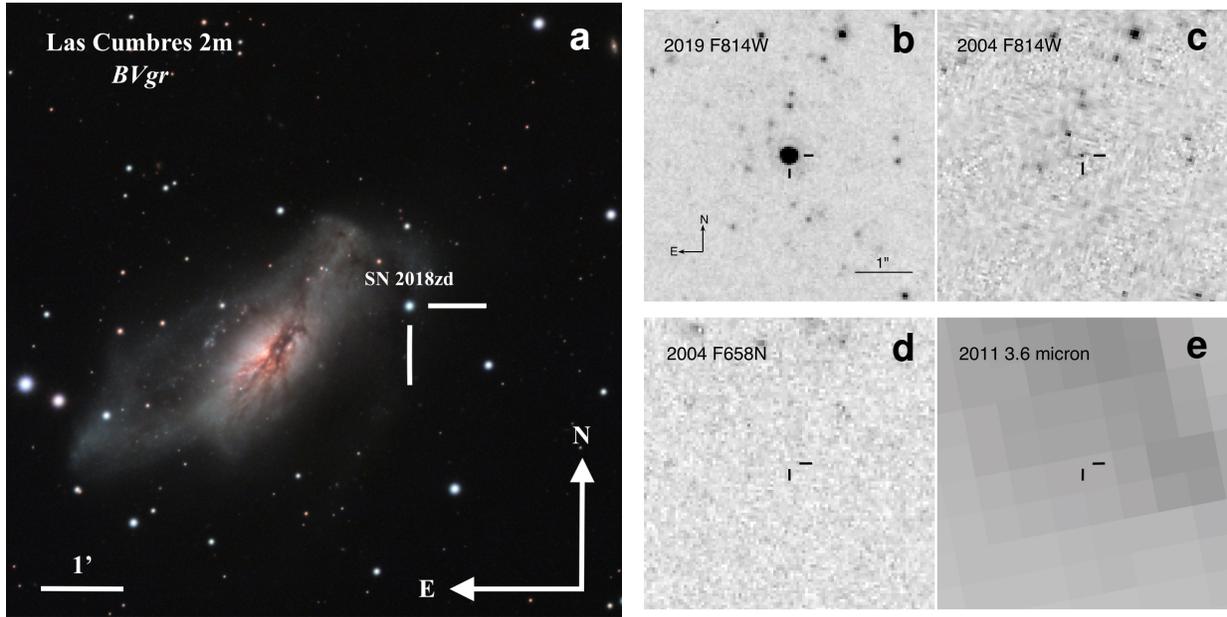
**Author Contributions** D. Hiramatsu initiated the study, triggered follow-up observations, reduced the Las Cumbres data, produced the light-curve models, performed the analysis, and wrote the manuscript. D.A.H. is the PI of the Las Cumbres Observatory Global Supernova Project through which all of the Las Cumbres data were obtained; he also assisted with data interpretations and the manuscript. S.D.V.D. is the PI of the *HST* program “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 interpretations and the manuscript. J.A.G. produced the progenitor and light-curve models and assisted with their interpretations and the manuscript. K.M. assisted with theoretical nebular spectral model interpretations 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 interpretations 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 PI 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 PI of the Supernova Spectropolarimetry (SNSPOL) project. P.S.S. is the PI 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 PI of the MMT and Bok programs; 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-Is of the *HST* program (GO-15151); they also contributed comments to the manuscript. 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.

**Author Information** Reprints and permissions information is available at [www.nature.com/reprints](http://www.nature.com/reprints). The authors declare that they have no competing financial interests. Correspondence and requests for materials should be addressed to D. Hiramatsu ([dhiramatsu@lco.global](mailto:dhiramatsu@lco.global)).

**Data Availability** The photometric and spectroscopic data that support the findings of this study will be available on the Open Supernova Catalog at <https://sne.space/> and WISeREP at <https://wiserep.weizmann.ac.il/>. Source Data for Figs. 1 & 2, and for Extended Data Figs. 2, 5, & 6 will be provided with the online version of the paper.

### Extended Data

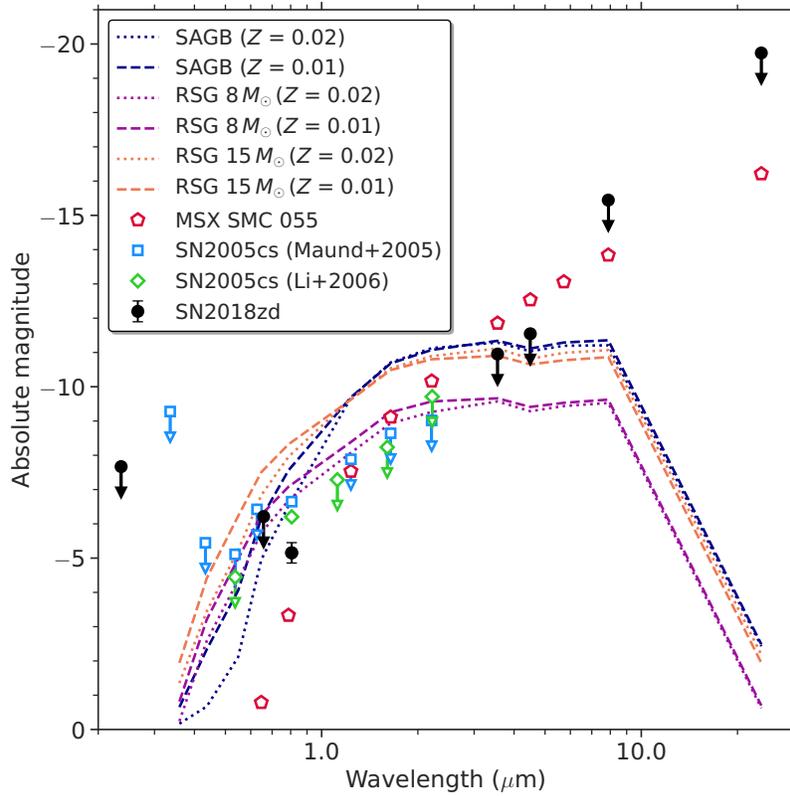


#### Extended Data Figure 1 The host galaxy and post- and pre-explosion images of SN 2018zd.

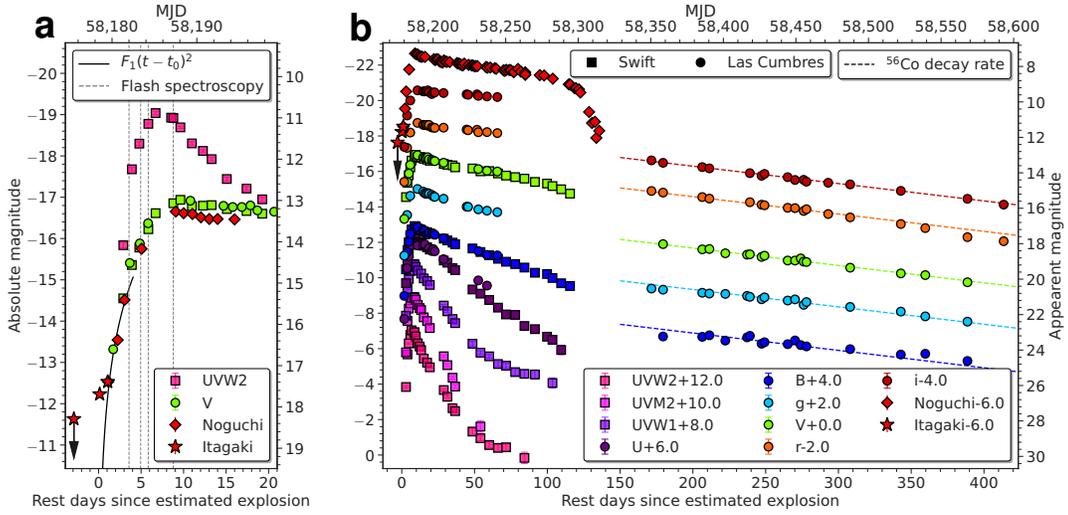
**(a)** Las Cumbres 2 m *BVgr*-composite image of SN 2018zd and the host starburst galaxy NGC 2146, courtesy of Peter Iláš. At the assumed luminosity distance of 9.6 Mpc, 1' corresponds to 2.8 kpc. SN 2018zd is on a tidal stream which was likely ejected during a galaxy merger event<sup>74</sup>.

**(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 (see 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  $\mu\text{m}$  mosaic obtained on 2011 November 15, with the SN site again indicated by tick marks. All

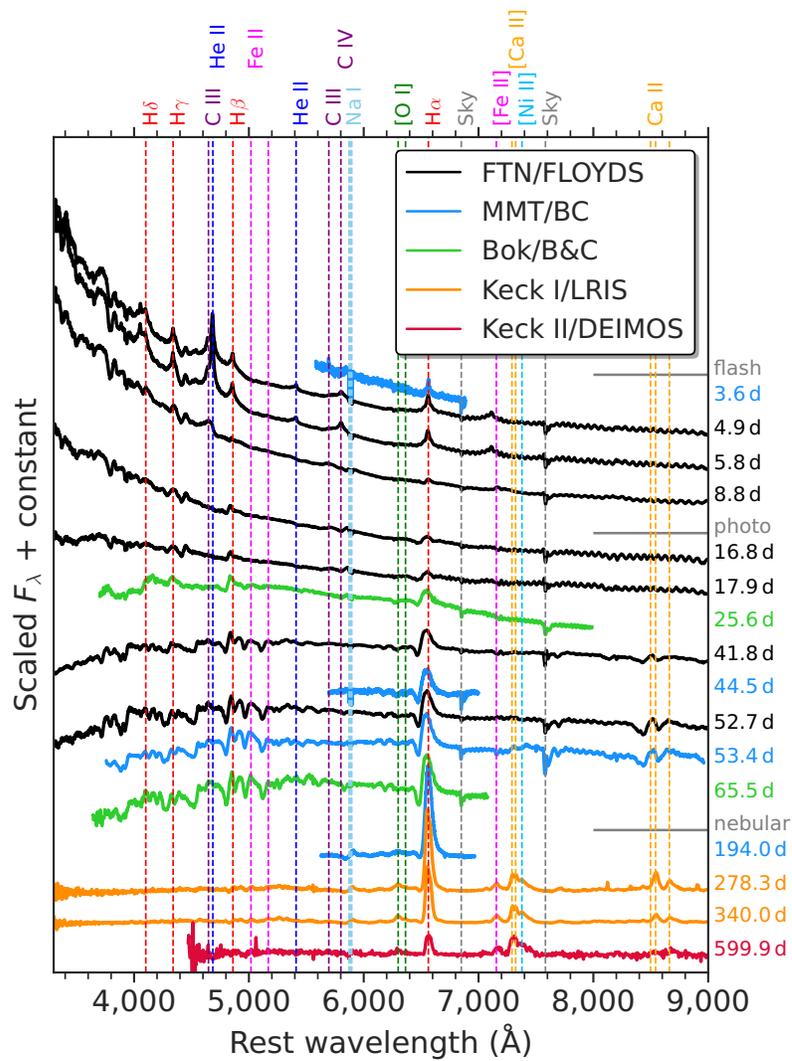
panels (b)–(e) are shown to the same scale and orientation, with north up and east to the left. The progenitor candidate is identified only in the single *HST* ACS/WFC F814W image (c).



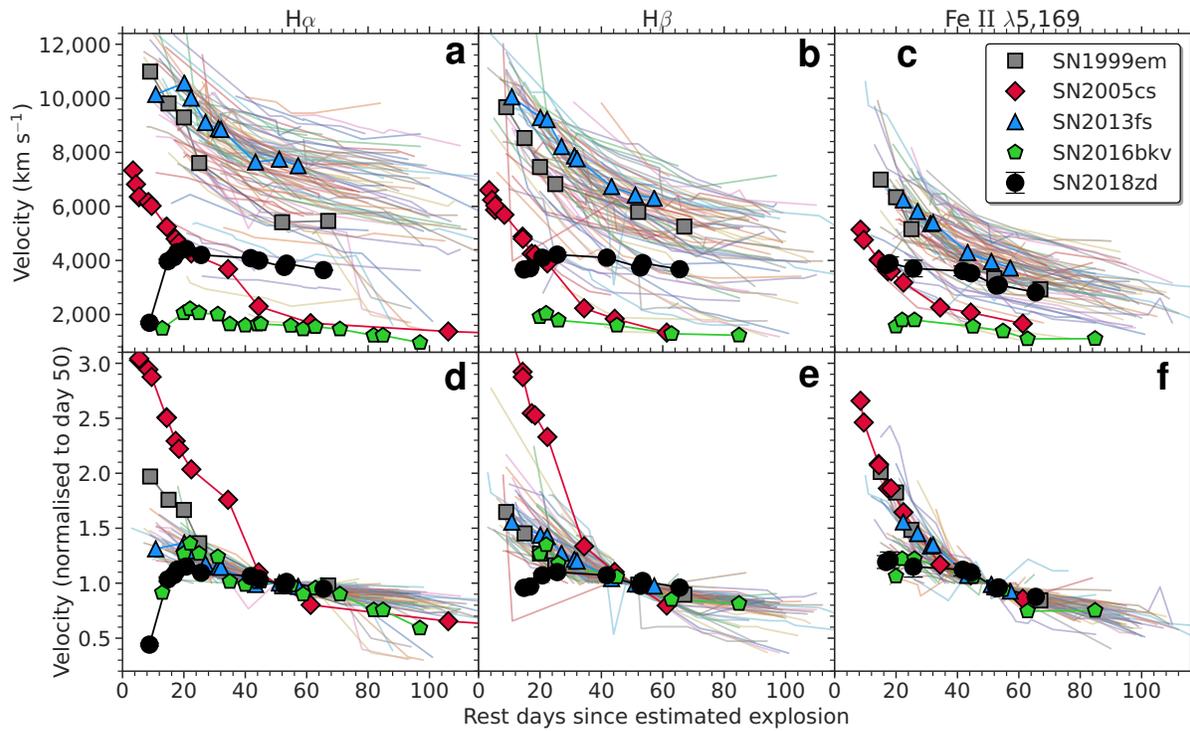
**Extended Data Figure 2 SN progenitor and SAGB candidate SEDs.** The SED for the SN 2018zd progenitor candidate resulting from pre-explosion *HST* and *Spitzer* archival data (black solid circles). For comparison we show model SEDs from BPASS v2.2<sup>91</sup> for SAGB stars (navy curves), RSG stars at  $M_{\text{init}} = 8 M_{\odot}$  (purple curves), and RSG stars at  $M_{\text{init}} = 15 M_{\odot}$  (orange curves), at metallicities  $Z = 0.02$  (short-dashed line) and  $Z = 0.01$  (long-dashed line). Also shown for comparison is the SED for the SAGB candidate MSX SMC 055 (red open pentagons<sup>93</sup>) and for the progenitor of the low-luminosity Type II-P SN 2005cs in M51 (blue open squares<sup>95</sup>, green open diamonds<sup>96</sup>). 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.



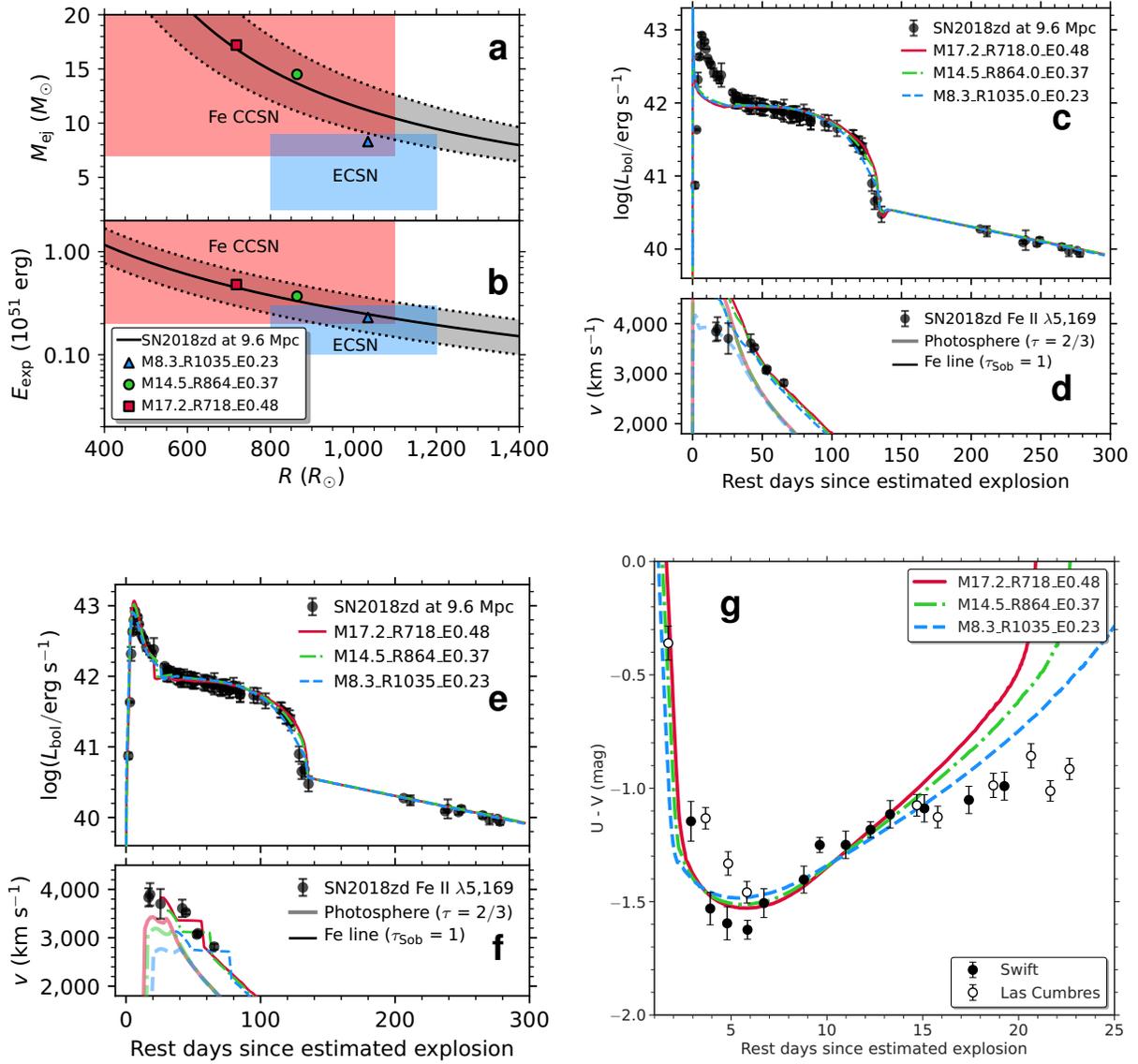
**Extended Data Figure 3 Multiband light curve of SN 2018zd.** (a) Multiband light curve of SN 2018zd focusing on the early rise. A quadratic function  $F_1(t - t_0)^2$  is fitted to the unfiltered optical Itagaki and the first three Noguchi points to estimate an explosion epoch  $t_0 = \text{MJD } 58178.4 \pm 0.1$ . The observed flash spectroscopy epochs (Extended Data Fig. 4) are marked by the vertical dashed lines. Note the sharper rise in the *Swift* *UVW2* than in the *V* and unfiltered photometry during the flash-spectroscopy epochs. (b) Multiband light curve of SN 2018zd up to the  $^{56}\text{Co}$  decay tail. The data gap is due to the Sun constraint. Error bars denote  $1\sigma$  uncertainties and are sometimes smaller than the marker size. The light-curve shape resembles a typical Type II-P SN<sup>151</sup>. Comparing the luminosity on the tail to that of SN 1987A<sup>152</sup>, we estimate a  $^{56}\text{Ni}$  mass of  $(8.6 \pm 0.5) \times 10^{-3} M_{\odot}$  at the assumed luminosity distance of 9.6 Mpc.



**Extended Data Figure 4 Optical spectral time series of SN 2018zd.** The flash features (e.g., 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<sup>151</sup>. After ~ 200 d, the nebular emission lines (e.g., H $\alpha$ , [Ca II], and [Ni II]) dominate over the relatively flat continuum.

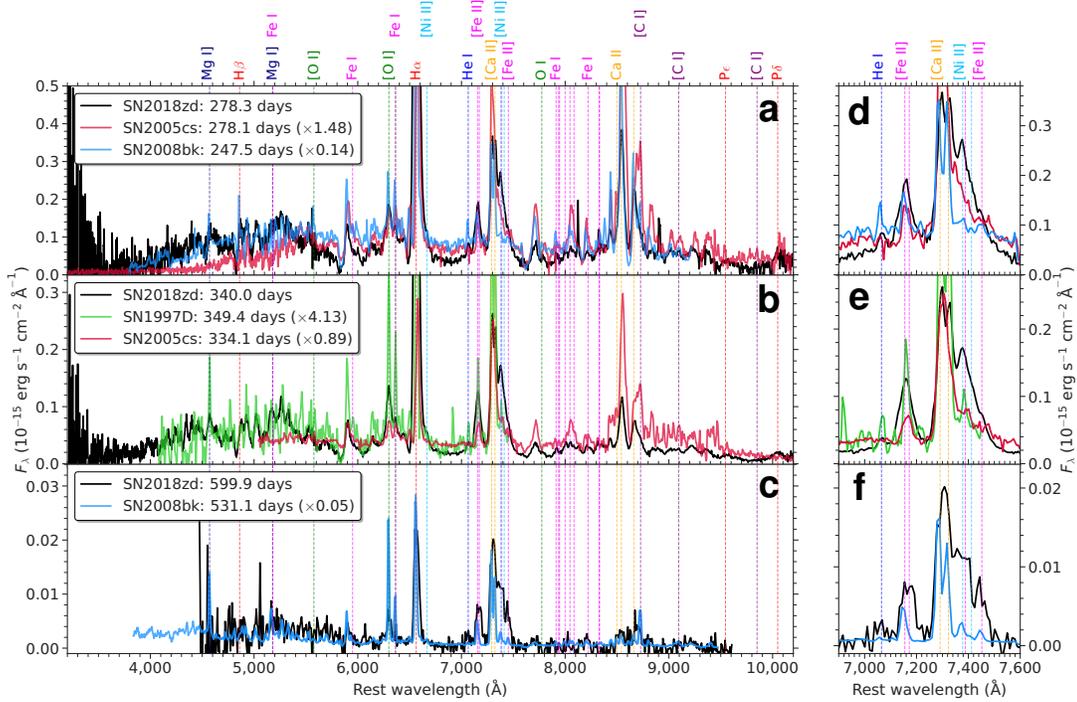


**Extended Data Figure 5 Expansion velocities as a function of time.** Comparison of the unnormalised (**a, b, c**) and normalised (to day 50; **d, e, f**)  $H\alpha$ ,  $H\beta$ , and  $\text{Fe II } \lambda 5169$  expansion velocities of SN 2018zd with a Type II SN sample<sup>153</sup> (transparent lines), including archetypal SN 1999em, along with low-luminosity SN 2005cs<sup>154</sup>, early-flash SN 2013fs<sup>21</sup>, and low-luminosity and early-flash SN 2016bkv<sup>38, 155</sup>. Error bars denote  $1\sigma$  uncertainties and are sometimes smaller than the marker size. Note the pronounced early  $H\alpha$  and  $H\beta$  rises and the relatively flat velocity evolution (up to  $\sim 30$  d) of SN 2018zd, indicating shock propagation inside the dense, optically-thick CSM.

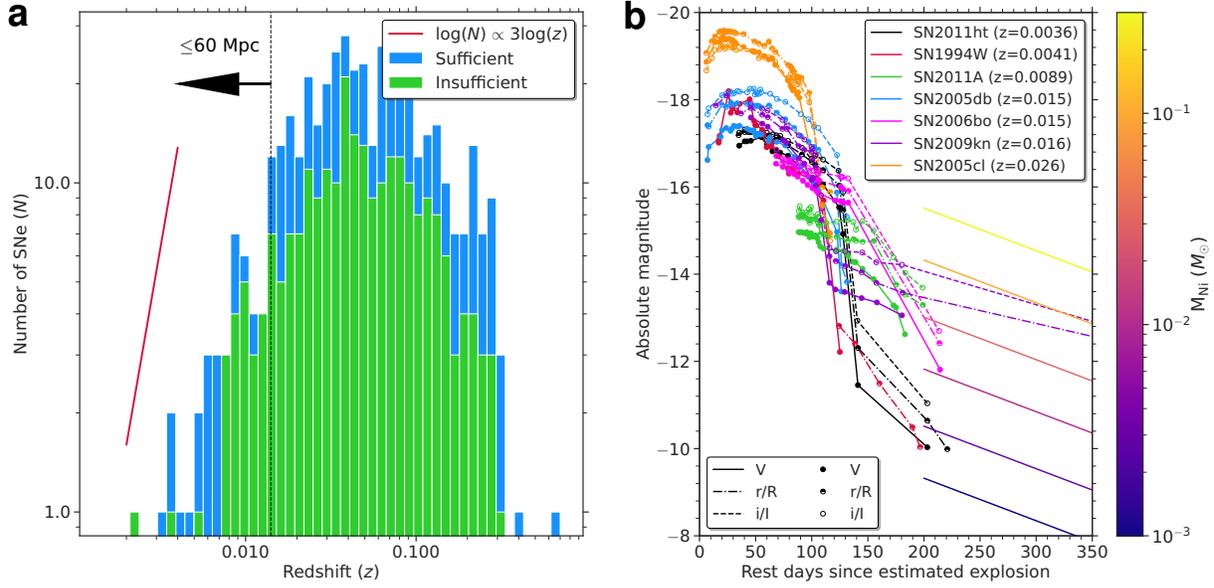


**Extended Data Figure 6 MESA+STELLA progenitor and degenerate light-curve models. (a, b)** Ejecta mass  $M_{ej}$  and explosion energy  $E_{exp}$  inferred from Eq. 1 as a function of progenitor radius  $R$  consistent with the bolometric light curve of SN 2018zd at the assumed luminosity distance of  $9.6 \pm 1.0$  Mpc, along with the properties of the three degenerate explosion models. The blue and red shaded regions show explosion parameters expected for ECSNe<sup>9, 5, 6</sup> and typical of Fe CCSNe<sup>156</sup>, respectively. **(c, d)** Three degenerate MESA+STELLA explosion models providing good

fits to the light curve and velocities inferred from the Fe II  $\lambda 5169$  line during the plateau phase. Models are labeled by  $M[M_{\text{ej},\odot}]$ - $R[R_{\odot}]$ - $E[E_{\text{exp},51}]$ . Error bars denote  $1\sigma$  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 ( $\dot{M}_{\text{wind}} = 0.01 M_{\odot} \text{ yr}^{-1}$ ,  $v_{\text{wind}} = 20 \text{ km s}^{-1}$ , and  $t_{\text{wind}} = 10 \text{ yr}$ ) 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  $1\sigma$  uncertainties. All three models with 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.

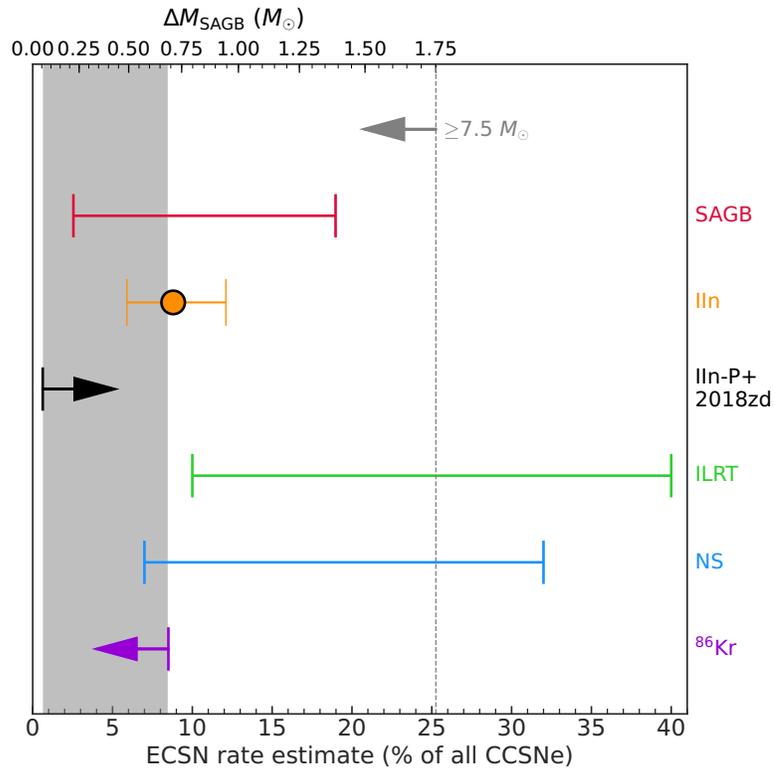


**Extended Data Figure 7 Nebular spectral time series of low-luminosity Type II-P SNe. (a, b, c)** Comparison of the nebular spectral time series of SN 2018zd with the scaled (by integrated flux as in the legend) and resampled low-luminosity Type II-P SNe 1997D<sup>157</sup>, 2005cs<sup>154</sup>, and 2008bk<sup>158, 159, 153</sup>. In ascending order of wavelength, note the distinct Mg I]  $\lambda$ 4571 and [O I]  $\lambda$ 6300, 6364 + Fe I  $\lambda$ 6364 observed in SN 1997D; Fe I cluster 7900–8500 Å, [C I]  $\lambda$ 8727, and [C I]  $\lambda$ 9100 observed in SN 2005cs; and Mg I]  $\lambda$ 4571, [O I]  $\lambda$ 6300, 6364 + Fe I  $\lambda$ 6364, Fe I cluster 7900–8500 Å, and [C I]  $\lambda$ 8727 observed in SN 2008bk. **(d, e, f)** Same as panels (a, b, c), but zoomed into the wavelength range of interest (as in Fig. 4). Note the line intensity ratios of [Ni II]  $\lambda$ 7378/[Fe II]  $\lambda$ 7155 < 1 observed in SNe 1997D, 2005cs, and 2008bk. The strong C, O, Mg, and/or Fe lines combined with the weak Ni lines observed in SNe 1997D, 2005cs, and 2008bk are inconsistent with the ECSN chemical composition and nucleosynthesis.



**Extended Data Figure 8 Public Type IIIn and IIIn-P SN samples.** **(a)** Redshift distribution of the 455 public Type IIIn SNe retrieved from WISerEP and/or TNS. 241 objects have insufficient public spectra and/or light curves to secure the Type IIIn classifications and/or to be identified as Type IIIn-P SNe, but are included in the sample so as not to overestimate the lower limit. The red line is the number density slope by assuming the volume term with the standard cosmology ( $H_0 = 71.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_{\Lambda_0} = 0.7$ , and  $\Omega_{m_0} = 0.3$ , giving  $d_L \propto z$  for  $z < 0.1$ ). The black dotted line is the distance cut ( $\leq 60 \text{ Mpc}$ ) we apply to compare with the LOSS sample<sup>149, 150</sup>. By comparing the number density slope to the sample histogram as a first-order estimation, the sample does not seem to suffer significantly from incompleteness within 60 Mpc. **(b)** Comparison of the identified Type IIIn-P SN candidates by applying the two light-curve criteria. The explosion epochs of SNe 2006bo and 2011A are not well constrained and can shift up to  $\pm 64 \text{ d}$  and  $\pm 85 \text{ d}$ , respectively<sup>146, 147</sup>. The colour-coded tails at 200–350 d are the expected  $V$ -band tails from the

fully trapped radioactive heating for a given  $^{56}\text{Ni}$  mass<sup>152</sup>. The observed Ni-mass upper limits are within  $10^{-3}$ – $3 \times 10^{-2} M_{\odot}$  assuming that the tails are purely powered by the radioactive heating.



**Extended Data Figure 9 ECSN rate estimators.** Comparison of the ECSN rate estimates: “SAGB” is the SAGB mass window from stellar evolutionary calculations at solar metallicity<sup>4</sup>; “IIn” is the observed Type IIn SN rate from a volume-limited ( $\leq 60$  Mpc) sample<sup>150</sup>; “IIn-P+2018zd” is a rough lower limit of the Type IIn-P SN rate within 60 Mpc combined with SN 2018zd (see Methods); “ILRT” is a rough estimate from ILRTs within 30 Mpc<sup>127</sup>; “NS” is an estimated rate from the bimodality in the neutron star mass distribution<sup>36</sup> assuming that the low-mass and high-mass peaks originate from ECSNe and Fe CCSNe, respectively; and “<sup>86</sup>Kr” is an upper limit from the ECSN nucleosynthesis calculation<sup>113</sup> assuming that ECSNe are the dominant production source of <sup>86</sup>Kr. 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

$7.5 M_{\odot}^{124}$  and  $120 M_{\odot}^{156}$ (respectively) and maximum and minimum SAGB masses of  $9.25 M_{\odot}$  and  $9.25 M_{\odot} - \Delta M_{\text{SAGB}}$  (respectively) at solar metallicity<sup>4</sup>. The grey vertical dotted line is where the minimum SAGB mass equals the assumed lower CCSN mass limit of  $7.5 M_{\odot}$ . The grey shaded region shows a rough ECSN rate constraint by the IIn-P+2018zd lower limit and the nucleosynthesis upper limit.

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

**Extended Data Table 1 ECSN candidate checklist.** Check marks, check+question marks, and cross marks (respectively) indicate observations consistent, maybe consistent, and inconsistent with theoretical expectations. Dashed lines indicate the lack of observational constraints, and lone question marks indicate unknowns. 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). For low-luminosity Type II-P SNe and Type IIn-P SNe, the overall light-curve morphology can be reproduced within the expected explosion energy range<sup>7, 8, 18, 120</sup>. For Type IIn-P SN 2011ht<sup>160</sup>, we measure  $[\text{Ni II}] \lambda 7378 / [\text{Fe II}] \lambda 7155 = 3.8$  at 155 d after the explosion, which may indicate ECSN-like nucleosynthesis, although the spectrum may not be fully nebular given the relatively early phase.