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A luminous, blue progenitor system for the type Iax supernova 2012Z

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Type Iax supernovae are stellar explosions that are spectroscopically similar to some type Ia supernovae at the time of maximum light emission, except with lower ejecta velocities[1,2]. They are also distinguished by lower luminosities. At late times, their spectroscopic properties diverge from those of other supernovae[3–6], but their composition (dominated by iron-group and intermediate-mass elements[1,7]) suggests a physical connection to normal type Ia supernovae. Supernovae of type Iax are not rare; they occur at a rate between 5 and 30 per cent of the normal type Ia rate[1]. The leading models for type Iax supernovae are thermonuclear explosions of accreting carbon–oxygen white dwarfs that do not completely unbind the star[8–10], implying that they are 'less successful' versions of normal type Ia supernovae, where complete stellar disruption is observed. Here we report the detection of the luminous, blue progenitor system of the type Iax SN 2012Z in deep pre-explosion imaging. The progenitor system's luminosity, colours, environment and similarity to the progenitor of the Galactic helium nova V445 Puppis[11–13] suggest that SN 2012Z was the explosion of a white dwarf accreting material from a helium-star companion. Observations over the next few years, after SN 2012Z has faded, will either confirm this hypothesis or perhaps show that this supernova was actually the explosive death of a massive star[14,15].

SN 2012Z was discovered[16] in the Lick Observatory Supernova Search on 2012 January 29.15 UT. It had an optical spectrum similar to the type Iax (previously called SN 2002cx-like) SN 2005hk[3–5] (see Extended Data Fig. 1). The similarities between type Iax and normal type Ia supernovae make understanding the progenitors of the former important, especially because no progenitor of the latter has been identified. Like core-collapse supernovae (but also slowly declining, luminous type Ia supernovae), type Iax supernovae are found preferentially in young, star-forming galaxies[17,18]. A single type Iax supernova, SN 2008ge, was in a relatively old (S0) galaxy with no indication of current star formation to deep limits[19]. Non-detection of the progenitor of SN 2008ge in Hubble Space Telescope (HST) pre-explosion imaging restricts its initial mass to $\lesssim 12\ M_\odot$ (where $M_\odot$ is the solar mass), and combined with the lack of hydrogen or helium in the SN 2008ge spectrum, favours a white dwarf progenitor[19].

Deep observations of NGC 1309, the host galaxy of SN 2012Z, were obtained with HST in 2005–06 and 2010, serendipitously including the location of the supernova before its explosion. To pinpoint the position of SN 2012Z with high precision, we obtained follow-up HST data in 2013. Colour-composite images made from these observations before and after the supernova are shown in Fig. 1, and photometry of stellar

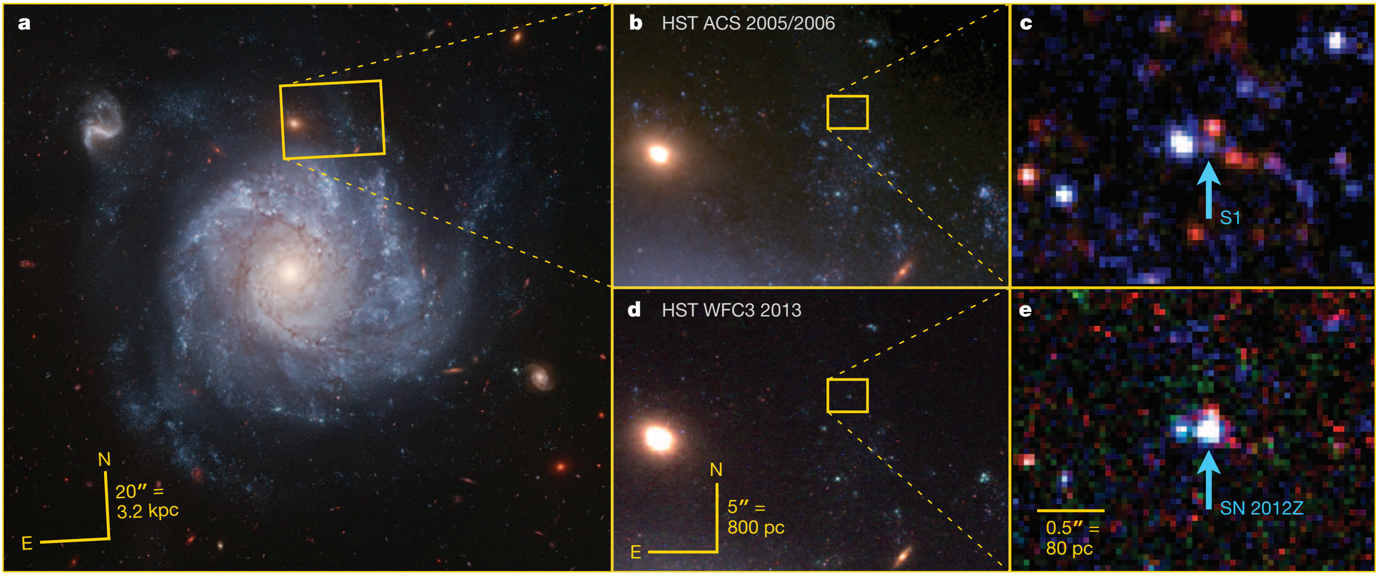

Figure 1 | HST colour images before and after supernova 2012Z. **a**, Hubble Heritage image of NGC 1309 (http://heritage.stsci.edu/2006/07); panels **b** and **c** zoom in on the progenitor system S1 in the deep, pre-explosion data. **d**, **e**, Shallower post-explosion images of SN 2012Z on the same scale as **b** and **c**, respectively. The source data for these images are available as Supplementary Information.

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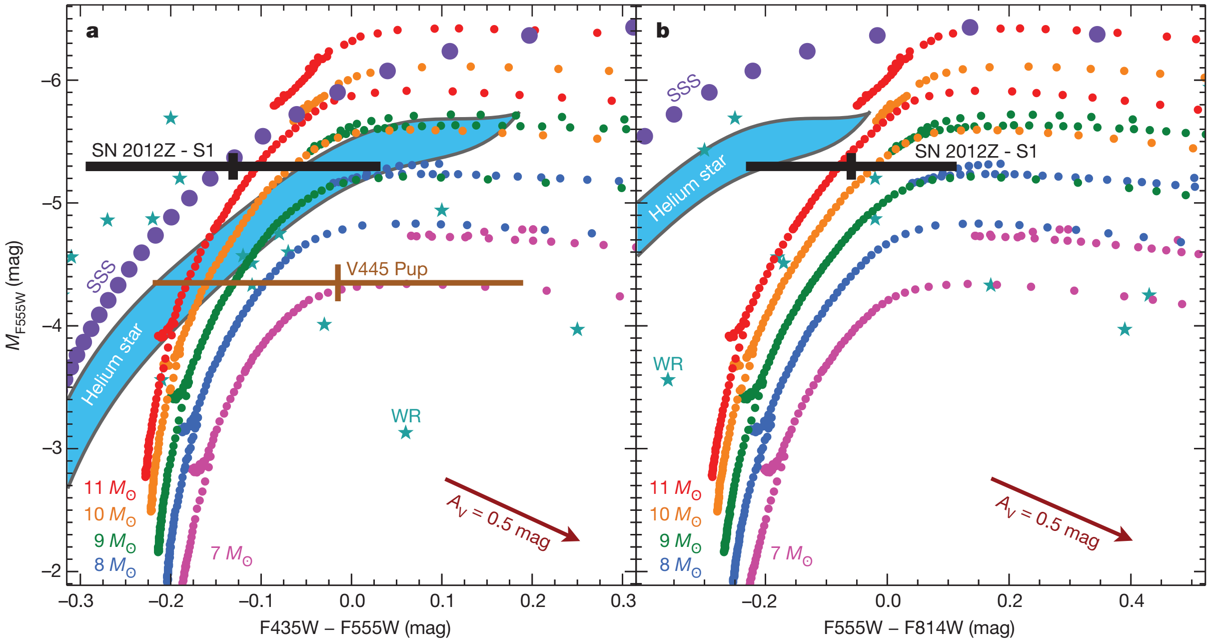

Figure 2 | Colour–magnitude diagrams of the SN 2012Z progenitor S1 and comparison models. **a**, The F435W − F555W colour (roughly $B-V$), **b**, the F555W − F814W colour (roughly $V-I$), both plotted against the F555W (V) absolute magnitude. Black and brown crosses represent the progenitor systems for SN 2012Z and V445 Pup[12], respectively, with 1σ photometric uncertainties. Other comparisons plotted include evolutionary tracks[24] for single stars (coloured dotted curves, with initial mass ranging from 7 to 11 $M_\odot$ as indicated), thermal models for Eddington-luminosity super-soft sources (SSS; purple dots), candidate Wolf–Rayet stars[26] (WR; blue-grey stars), and models for helium-star donors to 1.2 $M_\odot$ initial mass carbon–oxygen white dwarfs[29] (shaded blue regions). The effect of interstellar extinction with $A_V = 0.5$ mag is also shown (magenta arrow).

sources in the pre-explosion images near the supernova location is reported in Extended Data Table 1. We detect a source, called S1, coincident with the supernova at a formal separation of 0.0082″ ± 0.0103″ (equal to 1.3 ± 1.6 pc at 33 Mpc, the distance to NGC 1309; refs 20, 21). The pre-explosion data reach a 3σ limiting magnitude of $M_V \approx -3.5$ mag, quite deep for typical extragalactic supernova progenitor searches[22], but certainly the possibility exists that the progenitor system of SN 2012Z was of lower luminosity and would be undetected in our data (as has been the case for all normal type Ia supernova progenitor searches to date[23]). However, the locations of SN 2012Z and S1 are identical to within 0.8σ, and we estimate only a 0.24% (2.1%) probability that a random position near SN 2012Z would be within 1σ (3σ) of any detected star, making a chance alignment unlikely (see Methods, and Extended Data Fig. 2). We also observe evidence for variability in S1 (plausible for a pre-supernova system; Extended Data Table 2), at a level exhibited by only 4% of objects of similar brightness. We thus conclude there is a high likelihood that S1 is the progenitor system of SN 2012Z.

The colour–magnitude diagram (CMD) presented in Fig. 2 shows S1 to be luminous and blue, yet in an odd place on the diagram for a star about to explode. If its light is dominated by a single star, S1 is moderately consistent with an ~18.5 $M_\odot$ main-sequence star[24], an ~11 $M_\odot$ blue supergiant early in its evolution off the main sequence, or perhaps an ~7.5 $M_\odot$ (initial mass) blue supergiant later in its evolution (with core helium-burning in a blue loop, where models are quite sensitive to metallicity and rotation[25]). None of these stars are expected to explode in standard stellar evolution theory, particularly without any signature of hydrogen in the supernova[22].

The SN 2012Z progenitor system S1 is in a similar region in the CMD to some Wolf–Rayet stars[26]: these are highly evolved, massive stars that are expected to undergo core collapse and may produce a supernova. If S1 were a single Wolf–Rayet star, its photometry is most consistent with the WN subtype and an initial mass of ~30–40 $M_\odot$; such Wolf–Rayet stars are thought perhaps to explode with a helium-dominated outer layer as a type Ib supernova[27], and to be unlikely to produce the structure and composition of ejecta seen in type Iax supernovae[1,3,6,7]. Moreover, isochrones[24] fitted to the neighbouring stars (Extended Data Fig. 3) yield an age range of ~10–42 Myr, longer than the 5–8 Myr lifetime of such a massive Wolf–Rayet star.

S1 may be dominated by accretion luminosity; its brightness in B and V bands is not far from the predicted thermal emission of an Eddington-luminosity Chandrasekhar-mass white dwarf (a super-soft source, SSS in Fig. 2). However, its $V-I$ and $V-H$ colours are too red for a SSS model. A composite scenario, with accretion power dominating the blue flux, and another source providing the redder light (perhaps a fainter, red donor star) may be plausible.

The leading models of type Iax supernovae[8–10] are based on explosions of carbon–oxygen white dwarfs, so S1 may be the companion star to an accreting white dwarf. Although there are a variety of potential progenitor systems (including main-sequence and red-giant donors, which are inconsistent with S1 if they dominate the system's luminosity), in standard scenarios no companion star can have an initial mass greater than ~7 $M_\odot$; otherwise, there would not be enough time to form the primary carbon–oxygen white dwarf that explodes. Thus, the photometry of S1 suggests that if it is the companion to a carbon–oxygen white dwarf, recent binary mass transfer must have played a role in its evolution. One model for a luminous, blue companion star is a relatively massive (~2 $M_\odot$ when observed) helium star[11,28,29], formed after binary mass transfer and a common envelope phase (for example, a close binary with initial masses of ~7 and ~4 $M_\odot$). Although the model parameter space has not been fully explored, the predicted region in the CMD for helium star donors in a binary system with a 1.2 $M_\odot$ initial-mass accreting carbon–oxygen white dwarf[29] is shown in Fig. 2, and S1 is consistent with being in this region. The evolutionary timescale for such a model is also well matched to the ages of nearby stars (Extended Data Fig. 3).

SN 2012Z and the star S1 have an interesting analogue in our own Milky Way, namely, the helium nova V445 Puppis[11–13], thought to be the surface explosion of a near-Chandrasekhar-mass helium-accreting white dwarf. Though S1 is somewhat brighter than the pre-explosion observations of V445 Pup, their consistent colours, similar variability amplitude[13], and the physical connection between V445 Pup and likely progenitors of type Iax supernovae[8–10] is highly suggestive. Indeed, two type Iax supernovae (though not SN 2012Z itself) have shown evidence for helium in the system[1,17]. In this model, a low helium accretion rate could lead to a helium nova (like V445 Pup), whereas a higher mass-transfer rate could result in stable helium burning on the carbon–oxygen white dwarf, allowing it to grow in mass before the supernova. The accretion is expected to begin as the helium star starts to evolve and grow in radius; indeed, S1 photometry is consistent with the evolutionary track of a helium star with a mass (after losing its hydrogen envelope) of $\sim 2\ M_\odot$, on its way to becoming a red giant[11].

Although the scenario of a helium-star donor to an exploding carbon-oxygen white dwarf is a promising model for the progenitor and supernova observations, we cannot yet rule out the possibility that S1 is a single star that itself exploded. Fortunately, by late 2015, SN 2012Z will have faded below the brightness of S1, and HST imaging will allow us to distinguish between these models. Our favoured interpretation of S1 as the companion star predicts that it will still be detected (though perhaps modified by the impact of its exploding neighbour, a reduction in accretion luminosity, or a cessation of variability). On the other hand, if S1 has completely disappeared, it will be a strong challenge to models of type Iax supernovae, and will perhaps blur the line between thermonuclear white-dwarf supernovae and massive-star core-collapse supernovae, with important impacts on our understanding of stellar evolution and chemical enrichment.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Supplementary Information is available in the online version of the paper.

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Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to S.W.J. (saurabh@physics.rutgers.edu).

METHODS

Observations and reduction. SN 2012Z provides a unique opportunity to search for a type Iax supernova progenitor, because of deep, pre-explosion HST observations. Its face-on spiral host galaxy NGC 1309 was also the site of the nearby, normal type Ia SN 2002fk, and as such was targeted in 2005 and 2006 with the HST Advanced Camera for Surveys (ACS) and in 2010 with the HST Wide-Field Camera 3 (WFC3) optical (UVIS) and infrared (IR) channels, to observe Cepheid variable stars in order to anchor the type Ia supernova distance scale (HST programs GO-10497, GO-10802, GO-11570, GO/DD-10711). To measure the location of SN 2012Z with high precision, we used HST WFC3/UVIS images of NGC 1309 (fortuitously including SN 2012Z) taken on 2013 January 04 UT (program GO-12880), as well as targeted HST WFC3/UVIS images of SN 2012Z taken on 2013 June 30 UT (GO-12913).

The 2005–06 ACS images include 2 visits totalling 9,600 s of exposure time in the F435W filter (similar to Johnson *B*), 14 visits for a total exposure of 61,760 s in F555W (close to Johnson *V*) and 5 visits for 24,000 s in F814W (analogous to Cousins *I*). These are showing the blue, green, and red channels, respectively, of Fig. 1a–c. We re-reduced the archived data, combining the multiple exposures (including sub-sampling and cosmic ray rejection) using the AstroDrizzle software from the DrizzlePac package[30], with the results shown in Fig. 1b and c. Figure 1d and e shows our combined HST WFC3/UVIS F555W (blue; 1,836 s) + F625W (green; 562 s) + F814W (red; 1,836 s) images from January and June 2013, with SN 2012Z visible.

We used the DrizzlePac TweakReg routine to register all of the individual flat-fielded frames to the WFC3/UVIS F555W image taken on 2013 January 04 UT. The typical root-mean-square (r.m.s.) residual of individual stars from the relative astrometric solution was 0.009″, corresponding to 0.18 pixels in ACS and 0.23 pixels in WFC3/UVIS. We drizzle the ACS images to the native scale of UVIS, 0.04″ per pixel (20% smaller than the native 0.05″ ACS pixels) and subsample the ACS point-spread function (PSF) correspondingly with a pixel fraction parameter of 0.8.

Photometry and astrometry. In Extended Data Table 1, we present photometry of sources in the region based on the HST ACS images from 2005–06 (F435W, F555W, and F814W), as well as WFC3/IR F160W data (6,991 s of total exposure time) from 2010. The stars are sorted by their proximity to the supernova position, and their astrometry is referenced to SDSS images of the field, with an absolute astrometric uncertainty of 0.080″ (but this is irrelevant for the much more precise relative astrometry of SN 2012Z and S1). We performed photometry on the HST images using the PSF-fitting software DolPhot, an extension of HSTPhot[31]. We combined individual flatfielded frames taken during the same HST visit at the same position, and then used DolPhot to measure photometry using recommended parameters for ACS and WFC3.

The WFC3/UVIS images of SN 2012Z from January and June 2013 provide a precise position for the supernova of RA = 3 h 22 min 05.39641 s, dec. = $-15^\circ\,23'\,14.9390''$ (J2000) with a registration uncertainty of 0.0090″ (plus an absolute astrometric uncertainty of 0.08″, irrelevant to the relative astrometry). As shown in Fig. 1 we detect a stellar source (called S1) in the pre-explosion images coincident with the position of the supernova with a formal separation, including centroid uncertainties, of $0.0082'' \pm 0.0103''$, indicating an excellent match and strong evidence for S1 being the progenitor system of SN 2012Z.

Chance alignment probability. To estimate the probability of a chance alignment, we use the observed density of sources detected with signal-to-noise ratio $S/N > 3.0$ (in any filter) and $S/N > 3.5$ (in all bands combined, via DolPhot) in a 200×200 pixel ($8'' \times 8''$) box centred on SN 2012Z (452 sources), and find only a 0.24% (2.1%) chance that a random position would be consistent with a detected star at 1σ (3σ). Moreover, only 171 of these stars are as bright as S1, so *a posteriori* there was only a 0.09% (0.80%) chance of a 1σ (3σ) alignment with such a bright object. As shown in Extended Data Fig. 2, these results are not especially sensitive to the size of the region used to estimate the density of sources, at least down to 50×50 pixels ($2'' \times 2''$) around SN 2012Z. Nearer than this, the density of sources increases by a factor of a few, though with substantially larger uncertainty given the low number of sources (including S1 itself). We base our fiducial chance alignment probability on the larger region where the density of sources stabilizes with good statistics, but our qualitative results do not depend on this choice.

Given the surface brightness of NGC 1309, we crudely estimate $\sim 160\,M_\odot$ in stars projected within an area corresponding to our 1σ error circle ($\sim 8\,\mathrm{pc}^2$). These should be roughly uniformly distributed throughout this small region, so our chance alignment probability should accurately quantify the probability that SN 2012Z originated from an undetected progenitor that was only coincidentally near a detected source like S1.

The pre-explosion data for SN 2012Z are the deepest so far for a type Iax supernova, reaching $M_V \approx -3.5$; the next best limits come from SN 2008ge[19], which yielded no progenitor detection down to $M_V \approx -7$. The star S1, at $M_V \approx -5.3$, would not have been detected in any previous search for type Iax supernova progenitors. This implies that our chance alignment probability calculation can be taken at face value; there have not been previous, unsuccessful 'trials' that would reduce the unlikelihood of a chance coincidence. Viewed in the context of progenitor searches for normal type Ia supernovae, in only two cases (SN 2011fe[23] and SN 2014J[32]) would a star of the luminosity of S1 have been clearly detected in pre-explosion data. Other normal type Ia supernovae, like SN 2006dd[33], have progenitor detection limits in pre-explosion observations just near, or above, the luminosity of S1.

Variability of S1. NGC 1309 was imaged over 14 epochs in F555W with ACS before SN 2012Z exploded. Examining these individually, we find some evidence for variability in S1; the photometry is presented in Extended Data Table 2. Formally, these data rule out the null hypothesis of no variability at 99.95% (3.5σ), with $\chi^2 = 36.658$ in 13 degrees of freedom. However, most of the signal is driven by one data point (MJD 53600.0; a 4.2σ outlier); excluding this data point (though we find no independent reason to do so) reduces the significance of the variability to just 91.1% (1.7σ). To empirically assess the likelihood of variability, we looked to see how often stars with the same brightness as S1 (within 0.5 mag) doubled in brightness relative to their median like S1 in one or more of the 14 epochs; we find that just 4% do so (4 of the nearest 100, 9 of the nearest 200, and 20 of nearest 500 such stars). As variability might be expected in a supernova progenitor before explosion (from non-uniform accretion, for example), combining this with the chance alignment probability strengthens the identification of S1 as the progenitor system of SN 2012Z. It also disfavours the possibility that S1 is a compact, unresolved star cluster.

Properties of S1 and nearby stars. In Fig. 2 we present CMDs of S1 and other objects for comparison. In the figure, S1 has been corrected for Milky Way reddening ($E(B-V)_{\mathrm{MW}} = 0.035$ mag, corresponding to $A_{\mathrm{F435W}} = 0.14$ mag, $A_{\mathrm{F555W}} = 0.11$ mag, $A_{\mathrm{F814W}} = 0.06$ mag), and host reddening ($E(B-V)_{\mathrm{host}} = 0.07$ mag; $A_{\mathrm{F435W}} = 0.28$ mag, $A_{\mathrm{F555W}} = 0.22$ mag, $A_{\mathrm{F814W}} = 0.12$ mag) based on narrow, interstellar absorption lines in high-resolution spectroscopy of SN 2012Z itself (M.D.S. *et al.*, manuscript in preparation). This low extinction is consistent with the photometry and spectroscopy of SN 2012Z, as well as its location in the outskirts of a face-on spiral host. For the potential Galactic analogue V445 Pup progenitor, we correct its photometry for Galactic and circumstellar reddening[12].

Figure 2 also shows stellar evolution tracks[24] for stars with initial masses of 7, 8, 9, 10, and 11 $M_\odot$, adopting a metallicity of 0.87 solar, based on the H II region metallicity gradient[20] for NGC 1309 interpolated to the supernova radial location. The Eddington-luminosity accreting Chandrasekhar-mass white dwarfs are shown as the large purple dots, with each subsequent dot representing a change in temperature of 1,000 K. These 'super-soft' sources are fainter in F555W for higher temperatures (and bluer F435W − F555W colours) as the fixed (Eddington-limited) bolometric luminosity emerges in the ultraviolet for hotter systems. The shaded blue region represents the range of helium-star donors for carbon–oxygen white dwarf supernova progenitor models starting with a $1.2\,M_\odot$ white dwarf[29]. We converted the model temperatures and luminosities to our observed bands assuming a blackbody spectrum. The expected temperature and luminosity for this class of models is expected to vary with white dwarf mass, and, therefore, we regard this region as approximate; its shape, size, and location is subject to change.

S1 is inconsistent with all confirmed progenitors of core-collapse supernovae (exclusively type II supernovae), which are mostly red supergiants[22]. The blue supergiant progenitor of, for example, SN 1987A, was more luminous and probably more massive than S1[34]. However, we caution that our theoretical expectations for massive stars could be modified if S1 is in a close binary system where mass transfer has occurred.

The stars detected in the vicinity of S1 provide clues to the nature of recent star formation in the region. They include red supergiants (like S2 and S3 from Extended Data Table 1) as well as objects bluer and more luminous than S1 (like S5). We show CMDs including these stars in Extended Data Fig. 3; the stars plotted have a signal-to-noise ratio $S/N > 3.5$ in the displayed filters, and were required to be no closer than 3 pixels to a brighter source to avoid photometric uncertainties from crowding. Model isochrones[24] imply that these stars span an age range of ~10–42 Myr. These tracks favour an initial mass for S1 of ~ 7–$8\,M_\odot$ (neglecting mass transfer) if it is roughly coeval with its neighbours. In other words, if S1 were a 30–40 $M_\odot$ initial-mass Wolf–Rayet star with a predicted lifetime of only 5–8 Myr (ref. 27), it would be the youngest star in the region.

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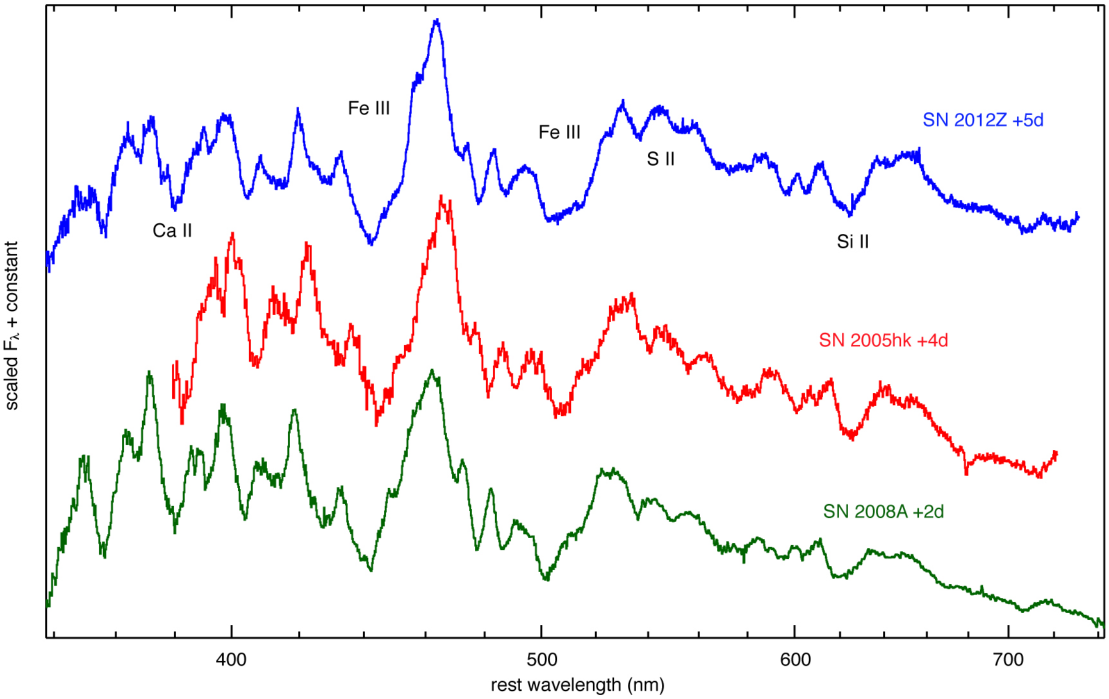
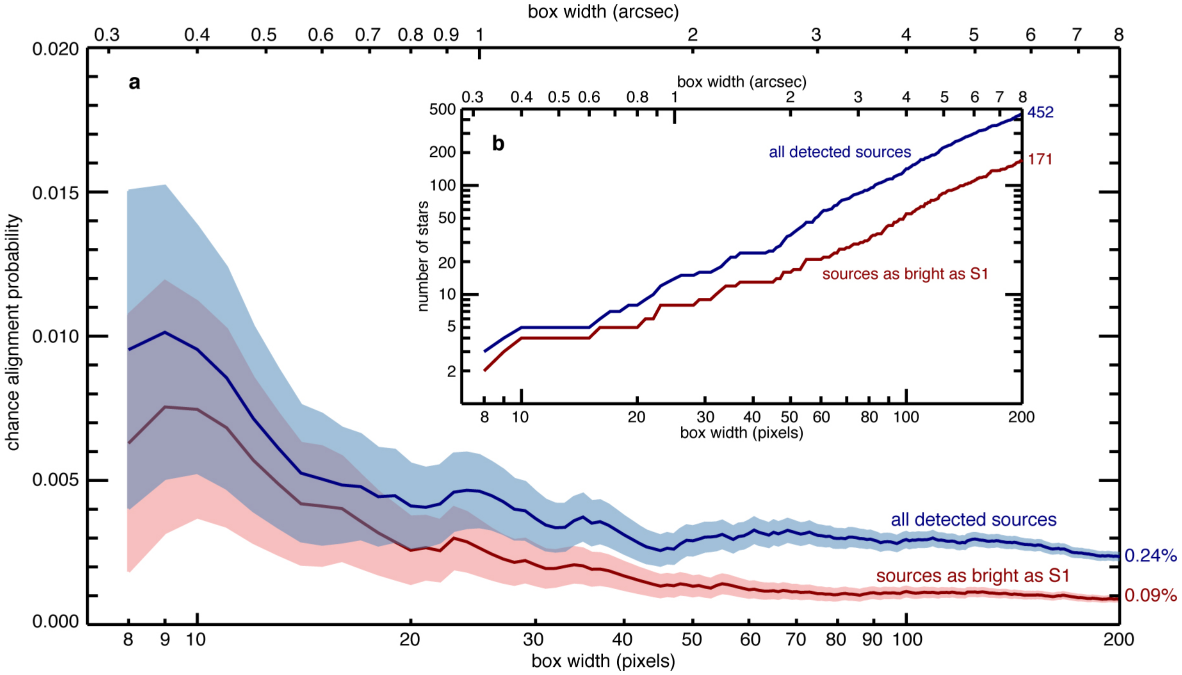
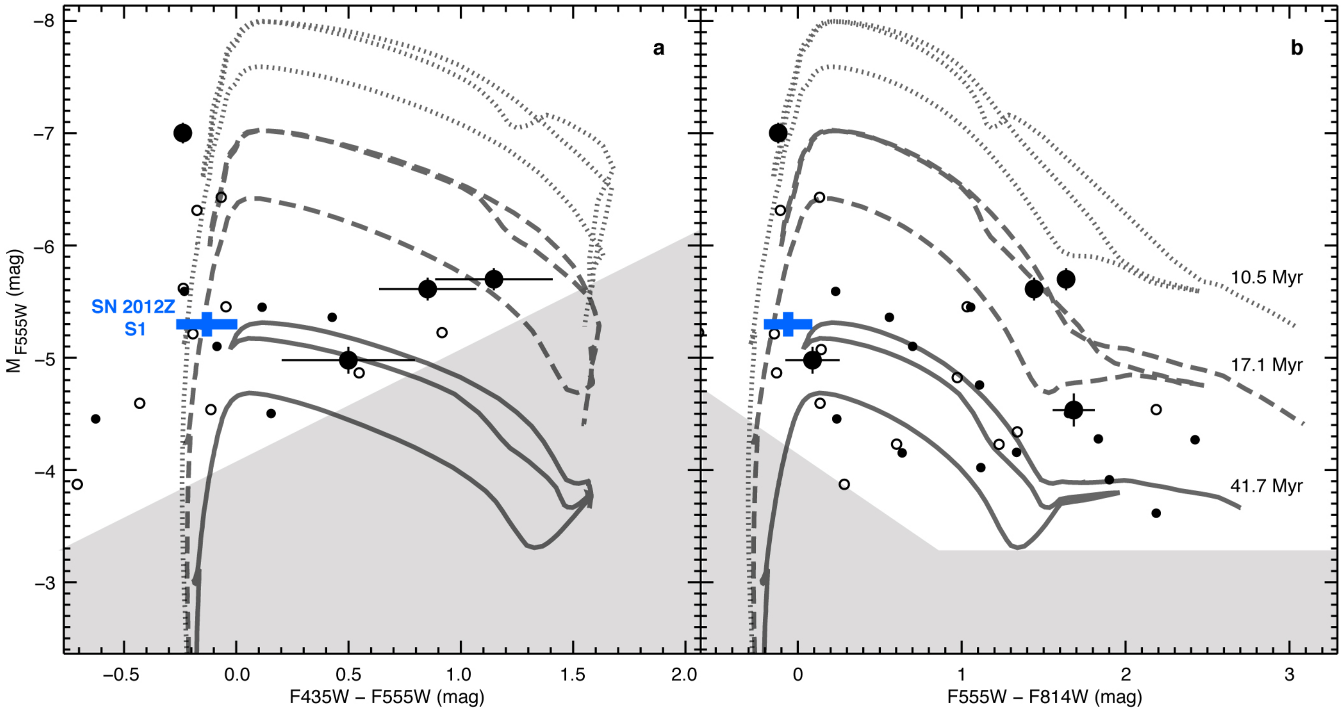


Extended Data Figure 1 | Spectra of type Iax supernovae near maximum light. SN 2012Z[1] is similar to SN 2005hk[4] and SN 2008A[6], all classified as type Iax supernovae. The SN 2012Z spectrum was taken on 2012 February 16 UT with the Whipple Observatory 1.5 m telescope (+FAST spectrograph) with a total exposure time of 1,800 s. Each flux density (F_λ) spectrum is labelled by its rest-frame phase past maximum light in B band. Prominent features due to intermediate-mass and iron-group elements are indicated; these features are also observed in luminous, slowly declining type Ia supernova spectra at maximum light, though with higher expansion velocities.



Extended Data Figure 2 | Chance alignment probability calculation. **a**, Chance alignment probability between a random position and a detected source within a square box of the given width (top axis, in arcsec; bottom axis, in pixels) centred at the position of SN 2012Z. This calculation is based on a 1σ position coincidence (0.0103″ = 0.2575 WFC3/UVIS pixels); a 3σ position coincidence gives probabilities approximately 9 times higher. The offset between SN 2012Z and S1 is 0.8σ. The shaded regions show a naive Poisson-like uncertainty estimate with a fractional error given by $1/\sqrt{N_{\mathrm{sources}}}$. **b**, Number of detected sources (including S1) as a function of the box size. The lines show results for all stellar sources (>3σ detection in any band; blue) and just those as bright as S1 (red).



Extended Data Figure 3 | Stars in the neighbourhood of the SN 2012Z progenitor. The SN 2012Z progenitor system S1 (blue) is shown along with nearby stars (all with 1σ photometric uncertainties), with three isochrones[24] with ages of 10.5 (dotted), 17.0 (dashed), and 41.7 Myr (solid). **a**, The F435W − F555W colour (roughly $B - V$), **b**, the F555W − F814W colour (roughly $V - I$), both plotted against the F555W (roughly V) absolute magnitude. The large, filled circles correspond to stars within 10 WFC3/UVIS pixels (0.4″) of the supernova location, small filled circles are within 20 pixels (0.8″), and the small open circles are within 30 pixels (1.2″). Objects in the grey shaded regions would not be detected given the depth of the combined images.

Extended Data Table 1 | Pre-explosion photometry of SN 2012Z progenitor system S1 and nearby stars

Star	R.A. (J2000)	Decl. (J2000)	F435W (mag)	F555W (mag)	F814W (mag)	F160W (mag)
S1	$3^{h}22^{m}05^{s}.39591$	$-15^{\circ}23'14''.9350$	27.589 (0.122)	27.622 (0.060)	27.532 (0.135)	26.443 (0.321)
S2	$3^{h}22^{m}05^{s}.40280$	$-15^{\circ}23'14''.9402$	>29.221	28.551 (0.116)	27.463 (0.093)	26.032 (0.238)
S3	$3^{h}22^{m}05^{s}.39483$	$-15^{\circ}23'14''.8102$	28.466 (0.258)	27.221 (0.041)	25.435 (0.022)	23.699 (0.027)
S4	$3^{h}22^{m}05^{s}.38460$	$-15^{\circ}23'15''.0314$	28.258 (0.211)	27.308 (0.046)	25.717 (0.028)	23.887 (0.033)
S5	$3^{h}22^{m}05^{s}.41013$	$-15^{\circ}23'14''.9362$	25.778 (0.029)	25.918 (0.014)	25.888 (0.030)	25.435 (0.136)
S6	$3^{h}22^{m}05^{s}.37564$	$-15^{\circ}23'15''.0702$	>28.807	28.386 (0.116)	26.553 (0.055)	24.986 (0.085)
S7	$3^{h}22^{m}05^{s}.41970$	$-15^{\circ}23'14''.8454$	28.539 (0.286)	27.942 (0.078)	27.703 (0.146)	26.436 (0.322)
S8	$3^{h}22^{m}05^{s}.37049$	$-15^{\circ}23'14''.6690$	>28.847	28.763 (0.164)	27.279 (0.101)	25.032 (0.092)
S9	$3^{h}22^{m}05^{s}.36477$	$-15^{\circ}23'15''.0634$	27.683 (0.127)	27.470 (0.050)	26.266 (0.042)	24.753 (0.069)
S10	$3^{h}22^{m}05^{s}.39605$	$-15^{\circ}23'15''.4062$	>28.912	29.305 (0.273)	26.969 (0.077)	25.214 (0.102)
S11	$3^{h}22^{m}05^{s}.37904$	$-15^{\circ}23'14''.5218$	27.196 (0.083)	27.329 (0.045)	26.949 (0.076)	>26.614
S12	$3^{h}22^{m}05^{s}.37556$	$-15^{\circ}23'14''.4202$	>28.897	28.302 (0.109)	27.095 (0.085)	25.381 (0.131)
S13	$3^{h}22^{m}05^{s}.36527$	$-15^{\circ}23'14''.5054$	28.085 (0.181)	27.560 (0.055)	26.852 (0.069)	25.740 (0.171)
S14	$3^{h}22^{m}05^{s}.40432$	$-15^{\circ}23'15''.5778$	>29.360	28.651 (0.113)	26.078 (0.026)	24.180 (0.042)
S15	$3^{h}22^{m}05^{s}.43040$	$-15^{\circ}23'14''.4706$	27.937 (0.164)	28.465 (0.122)	28.078 (0.208)	>26.512
S16	$3^{h}22^{m}05^{s}.42376$	$-15^{\circ}23'14''.3726$	>28.765	28.163 (0.092)	26.905 (0.072)	25.126 (0.094)
S17	$3^{h}22^{m}05^{s}.38194$	$-15^{\circ}23'14''.2494$	>28.926	29.007 (0.207)	26.957 (0.077)	26.230 (0.260)
S18	$3^{h}22^{m}05^{s}.35086$	$-15^{\circ}23'15''.2402$	27.831 (0.143)	27.819 (0.069)	26.969 (0.077)	25.581 (0.145)
S19	$3^{h}22^{m}05^{s}.39387$	$-15^{\circ}23'14''.2018$	28.670 (0.302)	28.417 (0.118)	26.616 (0.056)	25.072 (0.094)
S20	$3^{h}22^{m}05^{s}.37179$	$-15^{\circ}23'15''.6186$	>28.814	28.643 (0.147)	26.660 (0.059)	24.854 (0.075)
S21	$3^{h}22^{m}05^{s}.34566$	$-15^{\circ}23'15''.4618$	>28.813	>29.632	27.291 (0.102)	25.572 (0.138)
S22	$3^{h}22^{m}05^{s}.39179$	$-15^{\circ}23'14''.0298$	>28.809	29.135 (0.235)	27.219 (0.100)	25.685 (0.161)
S23	$3^{h}22^{m}05^{s}.43718$	$-15^{\circ}23'15''.6194$	28.340 (0.241)	29.474 (0.331)	>28.665	>26.633
S24	$3^{h}22^{m}05^{s}.35072$	$-15^{\circ}23'15''.6022$	>28.835	28.097 (0.089)	26.975 (0.078)	25.936 (0.202)
S25	$3^{h}22^{m}05^{s}.38396$	$-15^{\circ}23'13''.9958$	28.367 (0.230)	28.382 (0.119)	26.046 (0.035)	24.549 (0.057)
S26	$3^{h}22^{m}05^{s}.33025$	$-15^{\circ}23'15''.0438$	27.518 (0.109)	27.466 (0.055)	26.284 (0.048)	25.134 (0.094)
S27	$3^{h}22^{m}05^{s}.46232$	$-15^{\circ}23'14''.9126$	>28.841	28.581 (0.137)	27.093 (0.084)	25.445 (0.126)
S28	$3^{h}22^{m}05^{s}.39871$	$-15^{\circ}23'13''.9614$	>28.808	28.522 (0.132)	27.052 (0.084)	25.443 (0.137)
S29	$3^{h}22^{m}05^{s}.39210$	$-15^{\circ}23'13''.9558$	>28.908	28.386 (0.117)	28.395 (0.288)	26.075 (0.241)
S30	$3^{h}22^{m}05^{s}.40792$	$-15^{\circ}23'13''.8970$	>28.952	28.692 (0.154)	27.315 (0.102)	25.459 (0.135)
S31	$3^{h}22^{m}05^{s}.32555$	$-15^{\circ}23'14''.6310$	>28.961	>29.657	28.039 (0.201)	25.475 (0.127)
S32	$3^{h}22^{m}05^{s}.32419$	$-15^{\circ}23'15''.2534$	27.612 (0.122)	27.707 (0.062)	27.701 (0.150)	>26.591
S33	$3^{h}22^{m}05^{s}.37008$	$-15^{\circ}23'15''.9726$	28.700 (0.320)	28.055 (0.088)	28.035 (0.206)	>26.599
S34	$3^{h}22^{m}05^{s}.42642$	$-15^{\circ}23'15''.9482$	27.164 (0.086)	27.302 (0.045)	26.856 (0.072)	>26.520
S35	$3^{h}22^{m}05^{s}.38581$	$-15^{\circ}23'16''.0310$	28.710 (0.329)	27.696 (0.062)	28.152 (0.227)	>26.624
S36	$3^{h}22^{m}05^{s}.34751$	$-15^{\circ}23'15''.8186$	>28.843	>29.672	27.447 (0.120)	25.444 (0.127)
S37	$3^{h}22^{m}05^{s}.47012$	$-15^{\circ}23'15''.2990$	26.530 (0.051)	26.607 (0.024)	26.564 (0.053)	25.154 (0.095)
S38	$3^{h}22^{m}05^{s}.35077$	$-15^{\circ}23'13''.9774$	>28.916	>29.672	27.501 (0.123)	25.776 (0.173)
S39	$3^{h}22^{m}05^{s}.38399$	$-15^{\circ}23'13''.7882$	>28.831	27.847 (0.069)	27.555 (0.138)	25.455 (0.123)
S40	$3^{h}22^{m}05^{s}.42445$	$-15^{\circ}23'16''.0202$	>28.775	27.545 (0.057)	26.175 (0.040)	24.407 (0.050)
S41	$3^{h}22^{m}05^{s}.33343$	$-15^{\circ}23'14''.1682$	26.522 (0.049)	26.491 (0.022)	26.209 (0.041)	25.470 (0.128)
S42	$3^{h}22^{m}05^{s}.31449$	$-15^{\circ}23'15''.0958$	28.411 (0.246)	29.178 (0.236)	>28.665	>26.583

The 1σ photometric uncertainty is given in parentheses and non-detections are listed with 3σ upper-limits. No corrections for Galactic or host extinction are made here.

Extended Data Table 2 | Photometric variability of the SN 2012Z progenitor system S1

Date (UT)	MJD	Exposure (sec)	Counts (e^-)	F555W (mag)
2005-08-06	53588.7	2400	171 (71)	28.36 (0.45)
2005-08-17	53600.0	2400	656 (75)	26.94 (0.13)
2005-08-24	53606.8	2400	282 (67)	27.79 (0.26)
2005-08-27	53610.0	2400	392 (64)	27.49 (0.18)
2005-09-02	53615.6	2400	389 (69)	27.48 (0.19)
2005-09-03	53617.0	2400	308 (66)	27.77 (0.23)
2005-09-05	53618.6	2400	392 (71)	27.49 (0.20)
2005-09-07	53621.0	2400	329 (66)	27.66 (0.22)
2005-09-11	53624.0	2400	429 (68)	27.37 (0.17)
2005-09-16	53629.8	2400	242 (67)	27.98 (0.30)
2005-09-20	53633.4	2400	327 (64)	27.70 (0.21)
2005-09-27	53640.5	2400	193 (66)	28.25 (0.37)
2006-10-24	54032.6	2080	388 (76)	27.26 (0.21)
2006-10-07	54015.3	2080	264 (75)	27.62 (0.31)

The 1σ photometric uncertainties are given in parentheses. No corrections for Galactic or host extinction are made here.