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Supplementary information: An extremely energetic supernova from a very massive star in a dense medium

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Ruling out a tidal disruption event One issue that arises in understanding the origin of the most luminous transients is the difficulty in distinguishing SLSNe from extremely bright tidal disruption events (TDEs), i.e. transients powered by the destruction of a star passing within the tidal radius of a supermassive black hole. ASASSN-15lh was previously thought to be the most luminous known SN[1], but subsequent studies argued that its properties were more consistent with a TDE interpretation[2,3].

In the case of SN2016aps, we can clearly rule out a TDE explanation. Most TDEs show a constant or even increasing temperature over time, whereas SN2016aps shows a decreasing temperature typical of SN cooling (Extended Data Figure 1). The spectrum is also typical of SLSNe IIn, in particular Lorentzian line profiles (Figure 2) and the evolution of the Hα equivalent width with time (Extended Data Figure 5). SN2016aps is inconsistent at the $\approx 5\sigma$ level with having occurred in the centre of its host, whereas a TDE would have occurred in the nucleus.

Comparison to SLSNe IIn Figures 2 and 3 show spectroscopic and photometric comparisons with a number of SLSNe IIn. Although SN2016aps is more than twice as energetic as any of the other events, there are a number of similar properties among the class. Considering only events that emit $\gtrsim 10^{51}$ erg (SN2006gy, SN2003ma, SN2008am, SN2008fz, SN2015da, CSS121015) or fade on a similar timescale to SN2016aps (SN2006tf, SN2010jl), all events show similar maximum light spectra, with blue continua and dominated by roughly symmetric, scattering-broadened (i.e. Lorentzian) Balmer lines. This similarity persists for most events[4–8] throughout their evolution, as the continuum cools and the equivalent widths of the lines increase. SN2006gy and CSS121015 are exceptions. From around 90 days after explosion, SN2006gy displays a rather asymmetric Hα line, with a serious of narrow P Cygni absorption lines from slow, unshocked CSM[9], whereas CSS121015 instead shows broad metal lines resembling[10] SLSNe I. These events may require a more complex CSM structure. However, the key point is that SN2016aps is not unusual spectroscopically for a SLSN IIn.

The host galaxy environments provide another point of overlap between many of these events. CSS121015, SN2008fz, SN2010jl and SN2006tf all occurred in dwarf galaxies, with absolute magnitudes $M_r \approx -17$ to -18 mag, comparable to SN2016aps. The host metallicities estimated from emission line diagnostics are $\lesssim 0.3 - 0.4 Z_{\odot}$ for SN2010jl[11] and SN2008am[5]. In contrast, SN2006gy, SN2003ma, and SN2015da occurred in more massive galaxies with $M \sim -21$ mag. SN2006gy exploded close to the center of a galaxy hosting an active galactic nucleus, whereas the others were significantly offset from the centers of their hosts[4,8]. There was no evidence of AGN variability in the host of SN2003ma in 7 years of pre-SN observations[4]. This will be important in the next section, when we compare to a population of transients that seem to occur exclusively in active galactic nuclei.

To summarise: of the eight SLSNe IIn that come closest to SN2016aps in photometric properties, all show similar maximum light spectra, with six showing similar spectra throughout the photospheric phases (nebular spectra are not available). Five events occurred in metal-poor or dwarf galaxy environments. Four events satisfied both of these similarity criteria. The spectroscopic consistency is not surprising, as interaction with an opaque, hydrogen-rich circumstellar shell can lead to similar spectra across a wide range of explosion parameters[12]. Pulsational PISN mass ejections have been suggested as a plausible means to build up a massive CSM in other events[9]. *The key difference with SN2016aps is that the total energy and long timescale demand an extremely high final explosion energy beyond what is possible with conventional core-collapse*. Thus while these events certainly form an observational class, and possibly a physical class if the CSM is produced by the same mechanism, SN2016aps requires an extra ingredient: either a significantly larger mass or an extremely energetic explosion.

Simulations of very energetic core collapse SNe leading to SLSNe exist[13,14], however the explosion energy is often a free parameter in these models. One physically-motivated way to get a large explosion energy is through rotation – either in the form of a magnetar central engine accelerating the ejecta on the spin-down timescale[15], or the launching of jets in a collapsar-like model[16]. In the latter case at least, the explosion may be highly asymmetric[17]. Unfortunately, the presence of dense CSM in events such as SN2016aps obscures the geometry of the underlying ejecta.

Comparison to hydrogen-rich transients in active galactic nuclei (AGN) Recently a population of extremely energetic hydrogen-rich transients have been discovered in the centres of active galaxies[6,18,19]. In particular, PS1-10adi radiated[19] $\sim 2 \times 10^{52}$ erg. They have been interpreted by some authors[6,19] as most likely resulting from SNe interacting with dense material in the centres of these galaxies, though they do not rule out TDEs as an alternative explanation. In this section we argue that the latter interpretation is more likely, and that despite superficial spectral similarity, the off-nuclear SN2016aps is distinct from these events.

Extended Data Figure 6 shows the spectrum[19] of PS1-10adi at around 200 days after maximum, compared to our Gemini spectrum of SN2016aps at a similar phase. Although the strongest features in both spectra are the Balmer lines, these lines show a red shoulder in PS1-10adi but are symmetric (and slightly blueshifted) in SN2016aps, more typical[20] of SLSNe IIn with electron scattering in an expanding atmosphere. The line profiles, and the presence of narrow Fe II emission, are much more similar to PS16dtm[18]. This is another transient in an AGN, but in this case there is strong evidence that the source is associated with the supermassive black hole, rather than being a SN.

In particular, historical observations from *XMM-Newton* showed that the AGN is an X-ray source, but observations with *Swift* during the optical flare showed that X-rays had faded by at least an order of magnitude. A SN is unable to obscure the AGN accretion disk, but formation of an atmosphere or disruption of the existing disk by a TDE naturally explains the X-ray fading. Interestingly, PS1-10adi showed X-rays that appeared 5 years after the optical flare, which could be due to the formation of a disk following the TDE, or an existing disk that is revealed after the debris settles down (the inverse of the process that explains PS16dtm).

Another discriminant between SN2016aps and this population of nuclear transients is the lack of a mid-IR echo. All of these event studied to date[19], including PS16dtm[18], have shown very bright mir-IR emission, detected by the *Wide-field Infrared Survery Explorer (WISE)*, following the optical flare[21]. This has been interpreted[21] as a TDE signature, as the mid-IR luminosity in these events is challenging to produce with a SN, but consistent with a dusty AGN torus. At the distance of SN2016aps, a mid-IR echo of a similar brightness to that seen[21] in PS1-10adi would have been easily detectable, but no variability is seen in WISE data spanning ≈ 1000 days around the optical peak.

The AGN torus model can also explain[21] two further features of PS1-10adi. The Fe II emission can occur from sublimation of the same dust responsible for the mid-IR echo (note that narrow Fe II can also arise from dense gas close to an accretion disk[22]). Furthermore, the observed optical re-brightening ~ 2000 days after the light curve peak (not typically seen in SNe) can arise when an outflow driven by the TDE eventually collides with the torus.

As well as the locations within their host galaxies differing, the properties of the galaxies themselves differ between SN2016aps and the nuclear events. The absolute magnitude of the SN2016aps host is $M_g \approx -16.9$ mag, whereas the hosts of the other events are brighter by $> 2.5 - 5$ mag, i.e. a factor $10 - 100$ (note that these are also significantly brigher than most of the SLSN IIn hosts discussed in the previous section). The peak luminosity of PS1-10adi is consistent with the estimated Eddington luminosity of the associated AGN[19], and the other nuclear events are either less luminous or in brighter galaxies, i.e. all are likely radiating below the Eddington luminosity for the AGN in these galaxies. In comparison, the luminosity of SN2016aps would be approximately $10\times$ Eddington if it was associated with a supermassive black hole in such a faint galaxy, assuming typical scaling of the black hole mass with the galaxy mass[23]. Thus while all the nuclear events can be naturally accommodated within the context of black hole accretion, from TDEs or otherwise, SN2016aps is much more likely a SN.

The interacting SN model proposed for the nuclear transients can account for the dense CSM, either as a result of runaway mergers, an existing narrow-line region, and/or ionisation confinement in the AGN radiation field[19]. However, dense CSM is not the only requirement; a large explosion energy $E_k > E_{\rm rad}$ is also needed to power the light curve. We are not aware of any reason why such explosions would occur preferentially near AGN. Most observed (SLSNe, long gamma-ray bursts) and theoretical (PISNe) SNe with large explosion energies favour low metallicity environments[24–26], quite unlike the centres of massive galaxies. Moreover, the integrated radiation from PS1-10adi is somewhat uncomfortable for SN models, exceeding by a factor $\gtrsim 2$ the maximum predicted emission for hydrogen rich SNe[27]. We therefore conclude that extremely energetic nuclear transients are quite unlikely to be SNe, leaving SN2016aps as the most secure case of a SN radiating $> 5 \times 10^{51}$ erg.

Light curve models *Models from the literature.* We estimate the mass and energetics of SN2016aps using analytic relations[28] for the interaction of SN ejecta with a dense wind. The total radiative energy released is given by

$$E_{\rm rad} = 0.44 \times 10^{50} \kappa_{0.34}^{0.4} E_{51}^{1.2} M_{10}^{-0.6} D_{*}^{0.8}\,{\rm erg} \qquad (1)$$

where $\kappa_{0.34}$ is the opacity in units of $0.34\,\mathrm{cm}^2\,\mathrm{g}^{-1}$, E_{51} the kinetic energy in units of 10^{51} erg, M_{10} is the ejected mass in units of $10\,\mathrm{M}_\odot$, and $D_* \equiv 1000\dot{M}/v_w$ is the density parameter for pre-explosion mass-loss with rate $\dot{M}$ in $\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ and velocity v_w in $\mathrm{km\,s}^{-1}$. $E_{\rm rad}$ is obtained by integrating the bolometric light curve. The luminosity is given by

$$L = 7.6 \times 10^{43} \kappa_{0.34}^{-0.6} E_{51}^{1.2} M_{10}^{-0.6} D_*^{-0.2}\,\mathrm{erg\,s}^{-1}. \tag{2}$$

We divide these two equations to eliminate E_{51} and M_{10}, and assume $\kappa = 0.34\,\mathrm{cm}^2\,\mathrm{g}^{-1}$ as appropriate for electron scattering in hydrogen-rich material. This gives the useful relation $D_* \propto E_{\rm rad}/L$. i.e., a flatter light curve (longer time-scale) indicates a higher density. We find $D_* = 20.5$. This gives $\dot{M} \gtrsim 0.1 - 10\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ for $v_w = 10 - 1000\,\mathrm{km\,s}^{-1}$, fully consistent with our result in the main text and Figure 4 that used a different relation for the wind density[29]. Putting these values back into either equation allows one to find $E_K^2/M_{\rm ej}$.

We then find the interaction radius by putting these values into the relation

$$R_{\rm d} = 4.0 \times 10^{14} \kappa_{0.34}^{0.8} E_{51}^{0.4} M_{10}^{-0.2} D_*^{-0.2}\,\mathrm{cm}, \tag{3}$$

valid as long as the outer CSM radius is much greater than R_d. This gives $R_d = 5.3 \times 10^{15}$ cm, which is reassuringly consistent with the blackbody radius of the continuum emission (Extended Data Figure 1). This implies that most of the continuum emission comes from close to the contact discontinuity.

Finally, the shock velocity is found using

$$R_{\rm d} = 5.7 \times 10^{14} \kappa_{0.34} D_* v_{\rm sh}\,\mathrm{cm}, \tag{4}$$

where $v_{\rm sh}$ is in units of $10^4\,{\rm km\,s^{-1}}$. Putting in our earlier results gives $v_{\rm sh} \sim 4600\,{\rm km\,s^{-1}}$. Interestingly, this means that the transition to a steeper light curve at ~ 200 days (Figure 4) corresponds to the doubling timescale of the shocked region.

We also compare to published SLSN IIn models from more realistic simulations[12] in Figure 4. The data are reasonably consistent with models calculated for a CSM mass of $17.3\,{\rm M_\odot}$ and explosion energy between $3 - 10 \times 10^{51}$ erg ($3 - 10$ times larger than a canonical SN). The ejecta mass in the model is $9.8\,{\rm M_\odot}$; the sensitivity to this parameter was not explored in that study. However, we note that the steeper and earlier drop in the model luminosity compared to SN2016aps may be an indication that a larger mass is needed to match this event.

Bayesian light curve fit. We fit a circumstellar interaction model to the observed UV and optical photometry using MOSFIT: the Modular Open Source Fitter for Transients[30]. This is a semi-analytic code employing a range of modules that can be linked together to produce model light curves of astronomical transients, and determine the best fitting model parameters through Bayesian analysis. The interaction model and its implementation in MOSFIT are described in a number of previous works[31–33].

We first demonstrate that the model gives a reasonable match to the light curve using the parameters derived in the previous section. We take the lower limit on ejected mass and assume $M_{\rm ej} = 52\,{\rm M_\odot}$, and the integrated shocked CSM mass[29], $M_{\rm CSM} = 40\,{\rm M_\odot}$. We further assume that the observed photospheric radius corresponds to the contact discontinuity (i.e. the inner CSM radius), and the mass above this radius is set by our derived $D_* = 20.5$ (with a corresponding wind profile for the CSM). We use $n = 10$ and $\delta = 1$ for the ejecta outer and inner density profiles, though are results are largely insensitive to these parameters. We set $v_{\rm ej} = 10^4\,{\rm km\,s^{-1}}$, larger than our derived shock velocity, but required to give a total energy $E_K = 3.1 \times 10^{52}\,{\rm erg}$ and match the peak luminosity. The result, shown in Extended Data Figure 2, gives a good match to the observations.

Next we free these parameters to find the best fit and Bayesian posteriors for our parameters. To sample the parameter space we used the affine-invariant ensemble method[34,35]. We ran the Markov Chain with 100 walkers for 25,000 iterations, checking for convergence by ensuring that the Potential Scale Reduction Factor was < 1.2 at the end of the run[36]. Our model has 7 free parameters: the masses of the star and CSM; the ejecta velocity; the inner radius of the CSM; the density at this inner radius; the time of explosion; and a white-noise term parameterising any unaccounted-for variance. We use the same priors as for SN2016iet[37], with a few modifications. We fix the opacity at $\kappa = 0.34\,{\rm cm^2\,g^{-1}}$, appropriate for electron scattering in hydrogen-rich matter, and the final continuum temperature at 6000 K based on our photometry (Extended Data Figure 1). If left free, the temperature posteriors always converged to this value anyway, so we fixed it to speed up our model runs. We run one model for a shell-like (constant density) CSM, and one for a wind-like ($\rho \propto r^{-2}$) CSM, but otherwise use the same priors for both models.

To further reduce the number of free parameters, we assume 100% efficiency in radiating the deposited energy. This efficiency follows that used in similar model fits[32]; a lower efficiency would require a correspondingly larger explosion energy. The large efficiency is warranted as this model assumes an extremely optically thick interaction and therefore applies only in the limit of large masses. We note that for the analytic wind model[29], which does not require a large CSM mass, we used a lower efficiency of 50%, also guided by previous work[38]. Assuming 100% efficiency in that model would reduce the mass-loss curves in Figure 4 by a factor of 2, resulting in a total mass $M_{\rm CSM} \gtrsim 20\,\rm M_\odot$.

We obtain a similarly good fit for either a wind or shell CSM. The Watanabe-Akaike Information Criterion (WAIC)[39,40] is essentially indistinguishable between them, with WAIC$=147.0$ for the shell and 147.6 for the wind model. We show the shell model in Figure 4 and the wind model in Extended Data Figure 2. The posterior probability densities of the free parameters is shown for both models in Extended Data Figure 3. In the wind model, some of the posteriors lie close to the upper bounds of the priors.

Uncertainties in PISN rate estimates Both our PISN and PPISN rate estimates contain significant uncertainty, particularly in the f_2 parameter (Methods). Furthermore, the MESA models underpinning these calculations were computed at SMC metallicity. Retaining sufficient mass to reach the pair-unstable threshold depends on mass-loss rates that are highly sensitive to metallicty. Single star MESA models over a wider range in metallicity[26] suggest that PISNe should not occur at all at solar metallicity. The host galaxy of SN2016aps likely has a metallicity intermediate between the LMC and SMC. At the higher metallicity of the LMC, PPISNe can occur for stars with initial masses $\gtrsim 120\,\rm M_\odot$, while full PISNe require $>\gtrsim 300\,\rm M_\odot$. On the other hand, rapid rotation can lead to chemically homogeneous evolution and a larger core mass for a given initial mass, thus lowering these thresholds[41]. This also facilitates engine formation. Given these rather large uncertainties, all rate estimates should be considered indicative only.

However it is instructive to compare them to the observed rates of strongly interacting SNe. While literature estimates to date have been based on small numbers, the best current measurement[42] of the SLSN II rate is $150^{+151}_{-82}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$, corresponding to $\approx 3\times10^{-4} - 1\times10^{-3}$ per CCSN. This is in broad agreement with the post-merger PPISN rate. The discovery of SN2016aps suggests that up to $\sim 10\%$ of SLSNe IIn may exceed the energy budget of a typical SN; the estimated rates are consistent with such events being those that form magnetars.

We also note that an alternative engine could be fallback onto a central black hole remnant[43]. Detailed rate estimates are not available for this model, but it seems to require relatively fine-tuned parameters in order to impact the observed light curve[43].

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