

# The Superluminous Transient ASASSN-15lh as a Tidal Disruption Event from a Kerr Black Hole

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When a star passes within the tidal radius of a supermassive black hole, it will be torn apart<sup>1</sup>. For a star with the mass of the Sun and a non-spinning black hole with a mass  $< 10^8 M_\odot$ , the tidal radius lies outside the black hole event horizon<sup>2</sup> and the disruption results in a luminous flare<sup>3, 4, 5, 6</sup>. Here we report observations over a period of 10 months of a transient hitherto interpreted<sup>7</sup> as a super-luminous supernova<sup>8</sup>. Our data show that the transient re-brightened significantly in the UV and that the spectrum went through three different spectroscopic phases without ever becoming nebular. Our observations are more consistent with a tidal disruption event than a super-luminous supernova because of the temperature evolution<sup>6</sup>, the presence of highly ionised CNO gas at the line of sight<sup>9</sup> and our improved localisation of the transient at the nucleus of a passive galaxy, where the presence of massive stars is highly unlikely<sup>10, 11</sup>. While the supermassive black hole has a mass  $> 10^8 M_\odot$ <sup>12, 13</sup>, a solar-mass star could be disrupted outside the event horizon if the black hole were spinning rapidly<sup>14</sup>. The rapid spin and high black hole mass can explain the high luminosity of this event.

ASASSN-15lh was discovered by the All-Sky Automated Survey for SuperNovae (ASAS-SN) on 2015 June 14 at a redshift of  $z = 0.2326$ . Its light curve peaked at  $V \sim 17$  mag implying an absolute magnitude of  $M = -23.5$  mag, more than twice as luminous as any known supernova (SN)<sup>7</sup>.

Our long-term spectroscopic follow-up reveals that ASASSN-15lh went through three different spectroscopic phases (Figure 1). During the first phase<sup>7</sup>, the spectra were dominated by two broad absorption features. While these features appear similar to those observed in super-luminous

supernovae (SLSNe; Supplementary Figure 1), their physical origin is different. The features in SLSNe are due to O II<sup>8, 15</sup> but this would produce an additional strong feature at  $\sim 4400 \text{ \AA}$  (Supplementary Figure 2). The feature at  $\sim 4100 \text{ \AA}$  cannot be easily identified in the tidal disruption event (TDE) framework either. Two possibilities are that it could be due to Mg II or high-velocity He II absorption<sup>16</sup>. After the initial broad absorption features disappeared, the spectra of ASASSN-15lh were dominated by two emission features. A possible identification for these features is He II  $\lambda\lambda 3202$  and  $4686 \text{ \AA}$  both consistently blueshifted by  $\sim 15,000 \text{ km s}^{-1}$  (Supplementary Figure 3). He II emission is commonly seen in optically discovered TDEs<sup>4, 5</sup> at different blueshifts, albeit typically at lower velocities, but it has not been seen in H-poor SLSNe. These features disappeared after day +75 (measured in rest frame from peak) and the later spectra are mostly featureless, with the exception of two emission features at  $\sim 4000$  and  $5200 \text{ \AA}$ . The spectra remain much bluer than those of SLSNe<sup>17</sup> during many months after peak and never reveal nebular features, even up to day +256.

A UV spectrum obtained with *HST* at day +168 does not show any broad features<sup>18</sup>. At the redshift of the host, we identify weak Ly- $\alpha$  absorption and disproportionally strong high-ionisation lines (N V, O VI, C IV). Combined with the weakness (or absence) of common<sup>19</sup> low-ionisation absorption lines (Fe II, Si II, Mg II), this aspect appears similar to what was observed in ASASN-14li, the only available UV spectrum of a TDE<sup>9</sup> (Methods and Supplementary Figure 4). The highly-ionised gas appears at slightly different velocities, suggesting that it could be due to material in the vicinity of the TDE and ionised by its radiation. A difference with the case of ASASSN-14li<sup>9</sup> is that we do not observe any broad features in the UV, but the optical spectrum is also mostly

featureless at these phases.

In addition, we detect the presence of hydrogen in ASASSN-15lh. A weak  $H\alpha$  emission line is unambiguously detected in our highest signal-to-noise spectra (Figure 1) and in more spectra at lower significance (Supplementary Figure 3). Its presence cannot be excluded in any spectrum and its strength ( $EW \sim 4-8 \text{ \AA}$ ) is consistent with no evolution. The velocity of the  $H\alpha$  line ( $FWHM \sim 2,500 \text{ km s}^{-1}$ ) is different than those of other features, implying that it is formed in a different emitting region.

The light curve evolution of ASASSN-15lh is shown in Figure 2. After the initial peak and decline, around September 10 (day +60), the UV started re-brightening, an effect that was more prominent in the far-UV bands<sup>20, 21, 18</sup>. The dense photometric follow-up with *Swift* and LCOGT reveals that ASASSN-15lh reached a secondary UV maximum at around +110 days, followed by another decline. Interestingly, after day +100, the colours of ASASSN-15lh have remained almost constant for over 120 rest-frame days (Supplementary Figure 5). By fitting a black body to the multi-wavelength photometry of ASASSN-15lh, we are able to estimate the temperature evolution, black-body radius and bolometric luminosity (Figure 3). While the UV rebrightens and the spectrum changes, the blackbody radius decreases and the temperature increases again, stabilising at  $\sim 16,000 \text{ K}$ . This is neither expected from a SN photosphere, nor observed for SLSNe<sup>22, 23, 24</sup>. However, the TDE candidate ASASSN-14ae<sup>6</sup> showed a very similar temperature evolution as ASASSN-15lh. Even if this happened at faster timescales, the qualitative similarity between the evolution of the two events suggests that they might be due to the same mechanism.

On the other hand, the radius of ASASSN-15lh is larger by a factor of  $\sim 7$ , and ASASSN-14ae has a much stronger  $H\alpha$  line (Figure 1). By integrating the bolometric luminosity, we estimate that ASASSN-15lh has radiated a total of  $2.93 \pm 0.23 \times 10^{52}$  erg (depending on the assumed bolometric correction) until 2016 May 25 (day +288). Including kinetic energy, which can reach an additional  $10^{52}$  erg for SLSNe<sup>15, 25</sup>, the total energy budget approaches the theoretical limit of what SN explosions models can accommodate<sup>26, 27</sup>. It is possible that UV re-brightening could occur in a SLSN, due to either strong circumstellar interaction or the ionization breakout powered by a central magnetar. However, the observed  $H\alpha$  line is much weaker than in SLSNe that have shown signs of late interaction<sup>28</sup> (Supplementary Figure 1) and there are no features indicative of interaction in the UV spectrum. In addition, predictions for ionisation breakout suggest that the spectrum should turn nebular<sup>26</sup>, although this might apply better to an X-ray rather than a UV breakout. Nevertheless, it is true that no detailed model has yet been calculated that can naturally explain the entire spectroscopic and photometric properties observed, neither in the SN nor in the TDE scenario. A single epoch of imaging polarimetry with *HST* shows low levels of polarisation<sup>18</sup>, similar to what was obtained for a SLSN<sup>29</sup>, and suggesting an only mildly asymmetric geometry (in projection). Polarisation measurements and predictions for optical TDEs are still lacking.

Strong evidence for ASASSN-15lh being a TDE comes from its environment. H-poor SLSNe are found in blue, metal-poor, dwarf galaxies with average masses  $\log_{10} M_{\star} = 8.24 \pm 0.58 M_{\odot}$ , and none so far exceeding 9.60 at  $z < 1$ <sup>10, 11</sup>. These galaxies typically have strong emission lines, pointing to active ongoing star formation and young progenitor ages not exceeding a few Myr<sup>11</sup>. In contrast, the host of ASASSN-15lh is a massive and passive red galaxy. By fitting the available

photometry (see Methods) we estimate that the mass of the host is  $\log_{10} M_{\star} = 10.95^{+0.15}_{-0.11} M_{\odot}$ , with a dominant stellar population of  $3.9^{+3.2}_{-1.3}$  Gyr. The spectral energy distribution fit provides a star formation rate (SFR) of  $0.05^{+0.15}_{-0.05} M_{\odot} \text{ yr}^{-1}$ , consistent with the improved limit on SFR  $< 0.02 M_{\odot} \text{ yr}^{-1}$  that we obtain from our highest signal-to-noise spectrum. The derived specific star formation rate of  $\log \text{sSFR} < -12.5 \text{ yr}^{-1}$  is thus three orders of magnitude lower than in any H-poor SLSN host (Supplementary Figure 7). Furthermore, the transient is positionally coincident with the nucleus of its host. By aligning post-discovery *HST*+ACS images with a pre-discovery image taken with the CTIO 4m+DECam (Supplementary Figure 8), we are able to improve the positional accuracy<sup>7</sup> of ASASSN-15lh by a factor of  $\sim 4$ , corresponding to a projected nuclear offset of  $131 \pm 192 \text{ pc}$ .

It has been argued that the large host galaxy mass may imply the presence of a SMBH too large to disrupt stars outside its horizon<sup>7</sup>. Because the tidal radius scales as  $R_t \propto M_{\bullet}^{1/3}$  while the gravitational radius  $R_g \propto M_{\bullet}$ , stars can only be disrupted outside an SMBH horizon if the black hole is below a certain size, the Hills mass<sup>2</sup>. Larger SMBHs swallow stars whole. For a non-spinning, Schwarzschild SMBH, the Hills mass is  $M_H \approx 9 \times 10^7 M_{\odot} r_{\star}^{3/2} m_{\star}^{-1/2}$ , where  $m_{\star} \equiv M_{\star}/M_{\odot}$  and  $r_{\star} \equiv R_{\star}/R_{\odot}$  (see Methods). Using an empirical relation between SMBH mass and total stellar mass for ellipticals and S/S0 galaxies with classical bulges<sup>12</sup>, we find  $\log_{10} M_{\bullet} = 8.88 \pm 0.60 M_{\odot}$ , far above the Schwarzschild Hills mass for solar-mass stars. Using an  $M_{\bullet} - L$  relation for early-type galaxies<sup>13</sup> we obtain  $\log_{10} M_{\bullet} = 8.50 \pm 0.52 M_{\odot}$ . However,  $M_H$  increases by almost an order of magnitude for rapidly spinning Kerr SMBHs and favorable orbital orientations<sup>14</sup>. For an optimal (prograde equatorial) orbit and our range of SMBH mass



estimates, we find that a solar-mass star can be disrupted by a SMBH with dimensionless spin parameter  $a_{\bullet} = 0.68$  ( $a_{\bullet} = 1$ ) if  $\log_{10} M_{\bullet} = 8.28$  ( $\log_{10} M_{\bullet} = 8.86$ )  $M_{\odot}$ . We show the exact, relativistic  $M_{\text{H}}(a_{\bullet})$  in Figure 4. For stars less massive than the Sun, the spin is constrained to even higher values. ASASSN-15lh could be compatible with a TDE by a Schwarzschild SMBH provided  $M_{\star} \gtrsim 3M_{\odot}$ . However, the typical tidally-disrupted star comes from the lower end of the stellar mass function and this hypothesis is further disfavored by the old age of the galaxy’s stellar population<sup>30, 31</sup>. Observations of active galactic nuclei suggest that rapid SMBH spins are common<sup>32</sup>; TDEs present a method to probe the SMBH spins of quiescent galaxies. Given the inferred rapid spin of the SMBH, our radio non-detection implies that black hole spin alone is not sufficient for launching powerful jets (see Methods).

The luminosity and energetics of ASASSN-15lh are also explained by a very massive SMBH. The expected radiative efficiency of accretion increases from  $\eta \approx 0.05$  (for a Schwarzschild SMBH) to  $\eta \approx 0.42$  for a rapidly spinning SMBH disrupting stars on prograde, near-equatorial orbits. A massive SMBH is further biased towards disrupting the most massive stars near the main sequence turn-off mass, increasing accretion rates and total energy release. Finally, it is well known that most TDEs only release a small fraction of  $\eta M_{\star} c^2$  in accretion power (the so-called “missing energy problem”<sup>30, 33</sup>); one compelling explanation for this is that circularization of debris and formation of the accretion disk is mediated by relativistic apsidal precession, and that the majority of TDEs circularize inefficiently due to weak apsidal precession<sup>34</sup>. For a fast-spinning massive SMBH, efficient circularization is favoured because  $R_{\text{t}} \sim R_{\text{g}}$ , ensuring large per-orbit precession. The peculiar light curve may also be a natural consequence of tidal disruption by extremely mas-

sive black holes. In Methods we combine two competing models (the “circularization”<sup>33</sup> and the “accretion/reprocessing”<sup>35</sup> paradigms) for optical emission in TDEs and show that the most massive SMBHs produce an unusual hierarchy of tidal disruption timescales. Because the viscous time in the accretion disk is much longer than the debris fallback time when  $M_{\bullet} \gtrsim \text{few} \times 10^7 M_{\odot}$ , TDEs around the most massive SMBHs can display an early peak in the light curve from circularization luminosity, and a second peak from reprocessed accretion luminosity.

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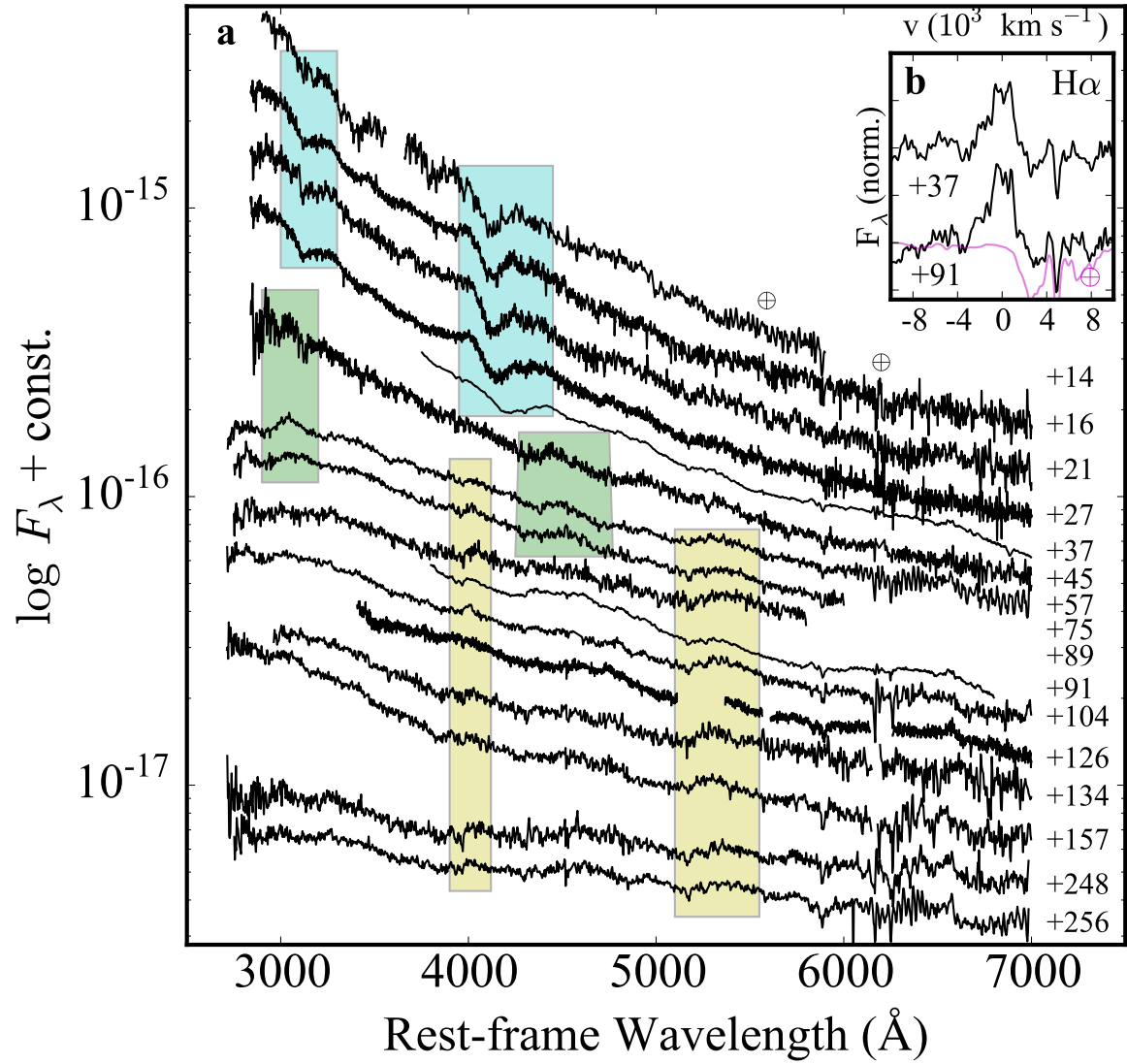
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**Author Contributions** GL coordinated the PESSTO observations, was PI of the FORS2 program, analysed the data and wrote the paper. MF provided the astrometric localisation and reduced the PESSTO spectra. NCS calculated the relation between the BH spin and the Hills mass and edited the manuscript. SvV made the *Swift* photometry. PGJ analysed XMM data and helped coordinating the project. IA is the

PESSTO PI for TDEs and provided LCOGT data. CF made the LCOGT photometry. JRM reduced the FORS2 spectra. SJS is the PI of PESSTO and helped coordinating the project. TKr provided the SED fit of the host galaxy. JCAMJ provided the radio observations. PMV helped with the analysis of the spectra. GL, MF, NCS, SvV, PGJ, IA, SJS, JCAMJ, AG-Y and PAM contributed to the discussions. AdUP and ADC worked on the UV spectrum. DAH is the PI of the LCOGT observations. CI and OY are PESSTO builders and helped with the analysis. FP, DM, JS and JCW provided FORS2 data and analysis. MC and BET provided the WIFES spectra. SS and SK provided the Magellan spectrum. GH, CMcC and SV obtained and reduced LCOGT data. EK, KM, KWS, MS, and DRY are PESSTO builders and CA, JH, SM, TWC, TKa, SP, CRC, HK, MN, JL, NER, HC, IB, JJ, MRM contributed with PESSTO observations or data reductions. Many authors provided comments on the manuscript.

**Competing Interests** The authors declare that they have no competing financial interests.



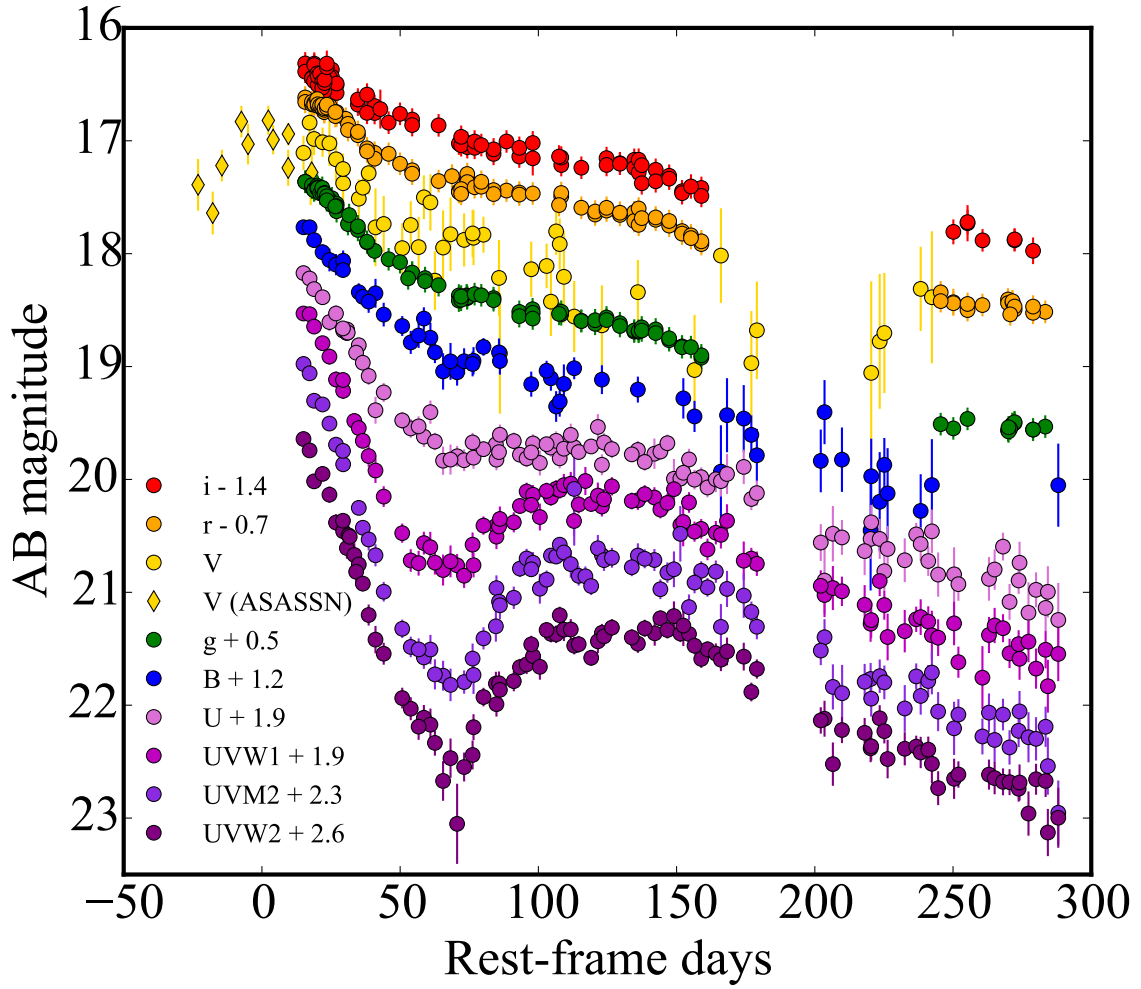


**Figure 1 | Spectral sequence of ASASSN-15lh showing three spectroscopic phases.**

The main features during the different phases have been highlighted with different colours.

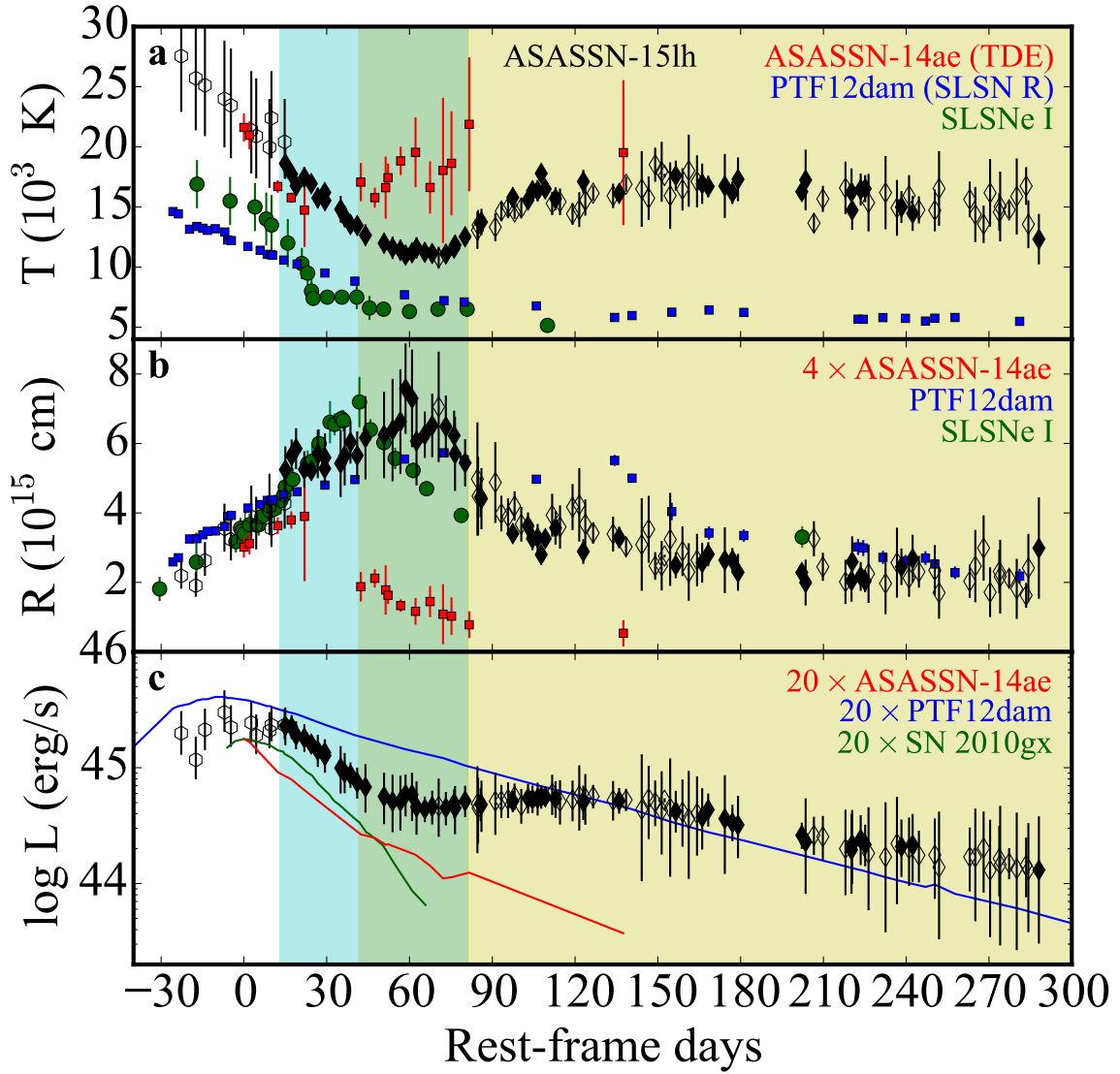
The last two spectra appear redder due to the increased host contamination. Rest-frame phases are indicated, the spectra have been offset for clarity and the earth symbol marks

the strongest telluric features. Panel b shows a detection of  $H\alpha$  ( $\text{FWHM} \sim 2,500 \text{ km s}^{-1}$ ) in a telluric-free region of our best spectra. The magenta line is a telluric spectrum.



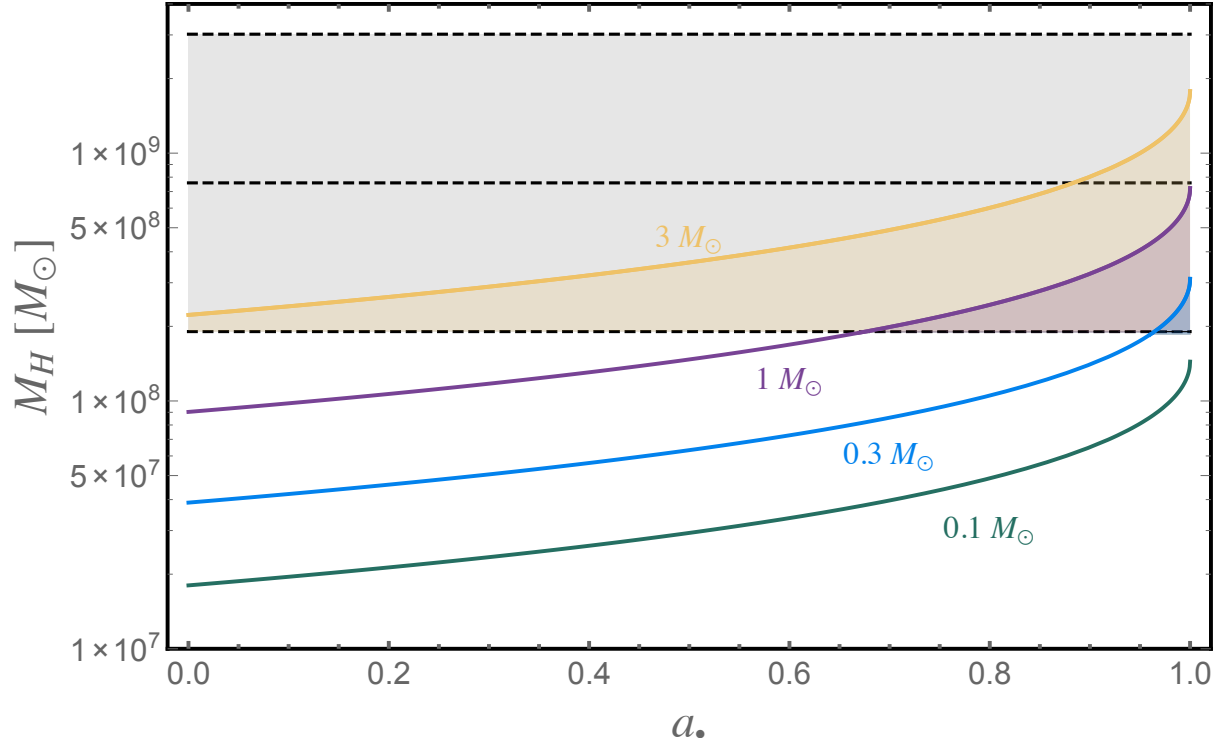
**Figure 2** | **The light curve evolution of ASASSN-15lh in the rest frame.** The data is from LCOGT (*gri*) and *Swift*, supplemented by the ASASSN *V*-band data<sup>7</sup>. We have adopted a peak time at 2015 June 5 (MJD 57178.5)<sup>7</sup>. The light curves are shifted for clarity as indicated. Errorbars are  $1\sigma$  uncertainties. The optical bands show a monotonic decline, but the UV bands show a re-brightening after 60 rest-frame days. A significant secondary dip is also observed in the bluest bands around 120 days. The photometry

has been corrected for foreground extinction and the host contribution has been removed (see Methods).



**Figure 3** | The evolution of the temperature, radius and luminosity of ASASSN-15lh, compared to TDEs<sup>6</sup> and SLSNe<sup>17, 22, 23, 24</sup>. The coloured areas correspond to the different spectroscopic phases in Figure 1. For ASASSN-15lh, open symbols show fits based on less than 5 filters. In particular, empty hexagons show early data, based only on  $V$  band and derived with a temperature prior<sup>7</sup>. Errorbars are  $1\sigma$  uncertainties. The curves

are shown with respect to peak time and some comparison objects have been scaled as indicated in the legend. The temperature (a) and radius (b) evolution of ASASSN-15lh is qualitatively similar to those of the TDE ASASSN-14ae, although this is happening in longer timescales and larger radii. All types of SLSNe cool down with time. The bolometric luminosity (c) of ASASSN-15lh shows an extended plateau between 70-160 days.



**Figure 4 | The Hills mass  $M_H$  plotted as a function of SMBH spin  $a_*$  for main sequence stars of different masses.** The SMBH mass estimate<sup>12</sup> for the host of ASASSN-15lh, and the corresponding  $1\sigma$  uncertainty region, are marked in dashed lines and grey shading. The plot shows that a  $0.1M_\odot$  star cannot be disrupted by the SMBH, as the Hills mass is always below the mass of the SMBH.  $0.3M_\odot$  and  $1M_\odot$  stars can be disrupted by rotating Kerr BH of different spins. Only  $3M_\odot$  stars lie in the allowed region for TDEs from a non-rotating Schwarzschild BH, but TDEs from such stars are unlikely<sup>30, 31</sup>.

## Methods

This section describes the data, methods and theoretical calculations used in the main paper. We provide details on the localisation of ASASSN-15lh and on the host galaxy properties. We present the different data used, we describe the reductions and comment on the implications. Finally, we demonstrate that a TDE can easily accommodate the luminosity and energetics of ASASSN-15lh, we show that combining two luminosity mechanisms for TDEs can result in light curves with two different timescales, and we present our derivation of the relativistic Hills mass as a function of the SMBH spin. We assume a *Planck* cosmology<sup>36</sup>.

**Astrometric localisation of ASASSN-15lh** *HST* observations of ASASSN-15lh were obtained under programme 14348 (PI: Yang) with ACS and a broad-band polarimetry filter (POL0V) and F606W. All analysis was performed on the reduced drizzled image obtained from the MAST archive. The image was taken on 2015 August 3, and the total exposure time for this frame was 366 s. The DECam image was a 90 s image taken on 2014 October 22 using an *r*-band filter. The DECam data were reduced using the DES Data Management Pipeline and made available online<sup>37</sup>. The measured FWHM is 0.8''.

Eight sources common to both the DECam and ACS images were used to derive a geometric transformation (allowing for rotation, translation and a single scaling factor) between the two frames. Of these sources, five were unresolved in the ACS image, while the remaining three had a FWHM of  $\lesssim 2$  times that of the point sources. The rms error in the transformation was 0.19 DECam pixels, or 52 mas. To measure the position of the host galaxy in the DECam frame, we fitted



a model galaxy profile using the GALFIT code; uncertainties in the galaxy centroid were estimated to be only a few  $\times 0.01$  pixels from Monte Carlo tests. The position of ASASSN-15lh on the ACS image yields an accuracy of 0.05 pixels (or 3 mas) using three different centering algorithms within the IRAF PHOT package.

**The host galaxy** To derive physical properties of the host galaxy of ASASSN-15lh through modeling of its spectral energy distribution (SED), we use *grizY*<sup>37</sup>, *J* and *K<sub>s</sub>*<sup>38</sup>, as well as 3.4  $\mu\text{m}$  and 4.6  $\mu\text{m}$  *WISE* photometry. We also performed aperture photometry on *GALEX* images yielding no significant detections.

We fit the Galactic extinction-corrected<sup>39</sup> photometry of the host with stellar population synthesis models<sup>40</sup> using *Le Phare*<sup>41, 42</sup>. Our galaxy templates are based on a Chabrier initial mass function<sup>43</sup>, and span different stellar metallicities, e-folding timescales  $\tau$  (0.1 to 30 Gyr), stellar population ages (0.01 to 10 Gyr) and dust attenuations<sup>44</sup>. The galaxy stellar mass and SFR are  $\log_{10} M_{\star} = 10.95^{+0.15}_{-0.11} M_{\odot}$  and  $0.05^{+0.15}_{-0.05} M_{\odot} \text{ yr}^{-1}$ , respectively. Physical parameters are given as the median of the probability distribution of all templates, with error-bars containing the  $1\sigma$  probability interval. The best fit model is shown in Supplementary Figure 6 and it has a low  $E(B - V)_{\text{host}} = 0.02 \text{ mag}$ . Throughout the paper we assume that the extinction at the host is negligible.

We also constrain the recent star formation in the host by placing limits on the flux of [O II] and (narrow) H $\alpha$ . Using the FORS2 spectra (S/N > 200) we obtain flux limits of  $< 1.8 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$  for [O II] and  $< 2.9 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$  for H $\alpha$  ( $2\sigma$ ). These limits constrain

the SFR to  $< 0.25$  and  $< 0.02 \text{ M}_{\odot} \text{ yr}^{-1}$  respectively<sup>45, 43</sup>, a factor of 10 improvement over previous estimates<sup>7</sup>.

***HST* UV spectroscopy** A UV spectrum of ASASSN-15lh was obtained at day +168 with *HST* under program 14450 (PI: Brown). We downloaded the reduced COS and STIS spectra from the MAST archive. The spectrum does not display any broad emission or absorption features (at similar phases the optical spectrum is also mostly featureless; Figure 1). We identify both geocoronal and absorption lines at  $z = 0$  and a number of narrow (FWHM  $\sim 200 - 400 \text{ km s}^{-1}$ ) absorption features at the redshift of ASASSN-15lh. Supplementary Figure 4 shows the COS spectrum (the STIS spectrum is more noisy and less interesting). Table 1 contains the EWs and kinematical offsets (measured relative to Ly- $\alpha$ ) for lines that are detected, as well as selected limits.

Low-ionisation features, such as Fe II and Si II, which are common in the star-forming sight-lines of SLSNe<sup>46</sup> or GRBs<sup>47, 19</sup> are weak or absent in ASASSN-15lh. In contrast, absorption from high ionisation lines from N V and O VI is remarkably strong, especially relatively to the (weak) Ly- $\alpha$ . In particular, the ratio of N V to Ly- $\alpha$  is  $\sim 4$ , while it is  $> 1000$  lower in GRBs. The same is true for column densities: by Voigt-profile modelling, we derive  $N(\text{HI}) = 14.73 \pm 0.12$ ,  $N(\text{OVI}) = 15.58 \pm 0.03$ ,  $N(\text{NV}) = 15.42 \pm 0.06$  and  $N(\text{CIV}) = 14.60 \pm 0.27$ , resulting in ratios that are highly unusual for GRB or Quasar DLAs<sup>48, 49</sup>, even if those values are lower limits due to saturation. The ratio of N V to Ly- $\alpha$  was also observed to be of the order unity in the spectrum of ASASSN-14li, the only UV spectrum of a TDE<sup>9</sup>. By complementing our measurements with those from optical spectra<sup>7</sup>, we find that the Mg II absorption is weak, below the value for GRBs<sup>47, 19</sup> and SLSNe<sup>46</sup>.

We therefore suggest that the absorbing gas can be separated in 2 components: i) a tenuous mildly-ionised medium (Ly- $\alpha$ , Mg II, Si III at velocities 0 to +44 km s<sup>-1</sup>), which is very unusual for the lack of Fe II and Si II; ii) a highly-ionised medium (N V, O VI and C IV) at negative velocity offsets -80 to -120 km s<sup>-1</sup>. We suggest that the latter is consistent with material from a disrupted low-mass star<sup>50, 9</sup> and that it is ionised by the TDE. Despite the absence of broad features, the phenomenological similarity with the UV spectrum of ASASSN-14li strongly favours a TDE origin for ASASSN-15lh. A highly-ionised outflow was detected for ASASSN-14li also in the X-rays<sup>51</sup>.

**Optical spectroscopy** Spectra were obtained with the instruments and set-ups listed in Table 2. The FLOYDS, WiFeS and EFOSC2 data were reduced using dedicated instrument pipelines<sup>52, 53, 54</sup>. The VLT+FOR2 and Magellan+IMACS spectra were reduced in standard fashion using IRAF. The FOR2 spectrum was obtained in spectropolarimetric mode, but the ordinary and extraordinary rays were combined to make an intensity spectrum.

**Imaging and removal of the host contribution** The LCOGT *gri* images were pre-processed using the Observatory Reduction and Acquisition Control Data Reduction pipeline<sup>55</sup>. To remove the host contribution we performed image subtraction using the pre-discovery DECam *gri* images as templates. The *Swift* UVOT observations were reduced following the standard procedures and software (UVOTSOURCE). To extract the photometry, we used a 4'' aperture and a curve of growth aperture correction. For the *Swift* filters we do not have pre-discovery observations, and hence use the model galaxy spectrum from the SED fit (Supplementary Figure 6) to generate synthetic magnitudes at these wavelengths. For the *B* and *V* filters, where host contamination is a concern,

we estimate the host uncertainty to be  $< 0.05$  mag, increasing to 0.1 mag for the  $U$  band. The host uncertainties in the UV filters are more significant, however, at these wavelengths the host is many orders of magnitude below the transient luminosity. In the AB system we obtain host magnitudes of  $V = 18.98$ ,  $B = 20.43$ ,  $U = 21.95$ ,  $UVW1 = 23.21$ ,  $UVM2 = 23.65$  and  $UVW2 = 23.62$  mag, which we subtract from the *Swift* measurements in order to obtain the transient photometry. Two UVOT filters suffer from a red leak but this does not affect blue sources as ASASSN-15lh to the same degree as e.g. SNe Ia<sup>56</sup>. Based on synthetic photometry of black-body spectra, we estimate that the photometry is affected by  $< 2\%$  for a black body with  $T = 15,000$  K. As this precision is significantly lower than our photometric accuracy, we did not attempt to correct for this effect. (Another study gives higher values - but still low - for this maximum contamination<sup>18</sup>).

**Radio and X-ray observations** We observed ASASSN-15lh from 0500–1400 UT on 2015 December 9, using the Australia Telescope Compact Array in 750C configuration, under project code CX340. We observed in two frequency bands of width 2.048 GHz, centered at 5.5 and 9.0 GHz. We used B1934-638 as both our flux and bandpass calibrator, and B2205-636 as our phase calibrator. We reduced the data following standard procedures in Miriad<sup>57</sup>, and carried out the imaging and self-calibration using the Common Astronomy Software Application<sup>58</sup>.

The field was dominated by PKS J2203-6130, a 9-mJy source (prior to primary beam correction) located 15 arcmin away from the target. We performed self-calibration, initially in phase only (down to a timescale of 2 min), and eventually in amplitude and phase, on a timescale of 10 min. Given the non-uniform  $uv$ -coverage, we tested a variety of image weighting schemes, finding the optimum to be a Briggs robust weighting of 0.5. ASASSN-15lh was not detected down to  $3\sigma$  upper

limits of 25 and 23  $\mu\text{Jy beam}^{-1}$  at 5.5 and 9.0 GHz, respectively, consistent with a reported upper limit from three weeks earlier<sup>59</sup>. Stacking our two frequency bands gave us a slightly deeper  $3\sigma$  radio upper limit of 17  $\mu\text{Jy beam}^{-1}$ .

The XMM-*Newton* satellite observed ASASSN-15lh as part of a Directors Discretionary Time proposal on November 18, 2015. The on-source time is 11.9 ks, and after filtering epochs of high background, 9 ks of MOS2, and 4 ks of PN data can be used. Given the lower background and the longer net exposure, we used the MOS2 detector for estimating the upper limit on the source flux. In an aperture of radius 32'' centred on ASASSN-15lh we derive a 95% confidence upper limit<sup>60, 61</sup> of 11 source counts in the 0.3–1 keV band. To convert this to a limit on the flux, we use the temperature of 70 eV found for ASASSN-14li as input, which taking into account that the  $M_{BH}$  in ASASSN-15lh is close to  $8 \times 10^8 M_{\odot}$ , and that of ASASSN-14li is closer to  $2 \times 10^6 M_{\odot}$ , implies a blackbody temperature of 18 eV (as  $T \propto M^{-0.25}$ ). With this and  $N_H = 3 \times 10^{20} \text{ cm}^{-2}$  W3PIMMS provides a 95% upper limit to the 0.3–1 keV X-ray flux of  $2 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}$ , yielding an upper limit to the source luminosity of  $3 \times 10^{40} \text{ erg s}^{-1}$ . This is significantly lower than the individual or stacked limits from the continuous *Swift* XRT observations<sup>18</sup>, but refers to a single epoch.

If TDEs do in fact all produce radio jets, as suggested by the recent detection of ASASSN-14li<sup>62</sup>, then applying the same model with appropriate scalings would predict a radio flux of 10  $\mu\text{Jy}$  at the time of the observations. Our non-detection therefore remains consistent with a TDE origin for ASASSN-15lh, and implies that the jet power of ASASSN-15lh is  $\nu L_{\nu} \lesssim 10^{38} \text{ erg s}^{-1}$ , at least 2-3 orders of magnitude lower than that of the relativistic TDE Swift J1644+57<sup>63</sup>. This difference

is likely caused by a combination of misalignment of the jet axis and our line of sight (consistent with our X-ray non-detection) and differences in accretion flow geometry, ISM density or magnetic field strength<sup>64</sup>. If black hole spin were the dominant factor in setting jet power, we would have expected ASASSIN-15lh to host a jet at least comparable in strength to ASASSN-14li (as we have inferred a high black hole spin for ASASSN-15lh). Given that our upper limit is close to the ASASSN-14li model prediction, this jet should have been detectable unless the spin of ASASSN-15lh is significantly less than we have inferred, the ISM density is extremely low, or the SMBH in ASASSN-14li is also rapidly spinning.

**Tidal Disruption Luminosities and Energetics** In Newtonian theory, a star with mass  $M_\star \equiv m_\star M_\odot$  and radius  $R_\star \equiv r_\star R_\odot$  will be tidally disrupted when it approaches an SMBH of mass  $M_\bullet \equiv M_8 10^8 M_\odot$  within a distance

$$R_t = R_\star \left( \frac{M_\bullet}{M_\star} \right)^{1/3}. \quad (1)$$

Stars passing within this tidal radius can create a luminous electromagnetic flare provided  $R_t \gtrsim R_{\text{IBCO}}$ , the location of the innermost bound circular orbit (IBCO) for the SMBH. This occurs for SMBHs smaller than the Hills mass<sup>2</sup>,

$$M_H \equiv 9 \times 10^7 M_\odot r_\star^{3/2} m_\star^{-1/2}. \quad (2)$$

Once the star has been disrupted, half of its gas is unbound from the SMBH; the other half remains bound with a characteristic spread in specific orbital energy<sup>65, 66</sup>

$$\Delta\epsilon = \frac{GM_\bullet R_\star}{R_t^2}. \quad (3)$$

If we assume a top-hat distribution of debris energy, then the fallback time for the most tightly bound debris is

$$t_f = 3.5 \times 10^7 M_8^{1/2} m_\star^{-1} r_\star^{3/2} \text{ sec} \quad (4)$$

which gives a peak fallback rate

$$\frac{\dot{M}_p}{\dot{M}_{\text{Edd}}} = 0.13 \eta_{-1} M_8^{-3/2} m_\star^2 r_\star^{-3/2}, \quad (5)$$

where  $\eta = 0.1\eta_{-1}$  is the radiative efficiency of accretion used to calculate the Eddington-limited mass inflow rate  $\dot{M}_{\text{Edd}}$ . The peak bolometric luminosity is

$$L_p = 1.9 \times 10^{45} \eta_{-1} M_8^{-1/2} m_\star^2 r_\star^{-3/2} \text{ erg s}^{-1}, \quad (6)$$

which is easily compatible with our observations for  $m_\star = 1$  and  $\eta = 0.42$ , appropriate for Kerr black holes. The radiated bolometric energy is

$$E_{\text{rad}} = 8.9 \times 10^{52} \eta_{-1} m_\star \text{ erg}. \quad (7)$$

ASASSN-15lh, although extreme as a SN<sup>26, 27, 67, 68, 69</sup>, does not strain the theoretical luminosity or energy budgets of TDEs.

**Tidal Disruption Flare Timescales** Existing observations do not yet distinguish between two competing theories for producing TDE optical emission. In the accretion/reprocessing paradigm, the bolometric luminosity of a compact ( $\sim 10R_g$ ), efficiently circularized accretion disk is intercepted by an optically thick screen of gas at larger scales ( $\sim 10^3 R_g$ ). This reprocessing layer may be a slow outflow from the disk<sup>70</sup>, or a more hydrostatic configuration<sup>71, 35, 72</sup>. Regardless, it absorbs and re-emits a large fraction of the disk bolometric luminosity at longer wavelengths. Both cases predict a larger reprocessing layer for larger SMBHs: outflow velocities

$v_w \sim \sqrt{GM_\bullet/R_t} \propto M_\bullet^{1/3}$ , or, if we assume that a hydrostatic reprocessing layer exists at scales comparable to the semimajor axis of the most tightly bound material, its size  $\propto M_\bullet^{2/3}$ . Alternatively, in the circularization paradigm, observed optical emission arises from shocks between debris streams<sup>33</sup>, which thermalize and radiate stream kinetic energy at the (generally large) stream self-intersection radius.

The efficiency of circularization (and therefore  $\dot{M}_p$ ) depends sensitively on the dimensionless orbital pericenter  $R_p/R_g$ : small decreases in  $R_p$  quickly move the self-intersection point inward, increasing circularization efficiency<sup>73,74</sup>. The low luminosities seen in many optically-selected TDEs may reflect that most TDEs have sub-relativistic pericenters and circularize inefficiently, so that their peak luminosity is  $\ll \eta \dot{M}_p c^2$ <sup>34</sup>.

For an extremely massive SMBH with  $M_\bullet \approx M_H$ , all TDE pericenters are highly relativistic and circularization is maximally efficient (with a possible caveat if the SMBH spin is rapid and strongly misaligned<sup>75,76</sup>). Stream self-intersection points will be  $\sim R_p$ , near the IBCO<sup>34</sup>, so the circularization and accretion power will be comparable. It is therefore natural to expect that TDEs from the most massive SMBHs will be brighter and able to attain their theoretical  $L_p$ , while smaller SMBHs will often produce TDEs that (due to inefficient circularization) have luminosities well below  $L_p$ .

We propose that the two peaks in the ASASSN-15lh light curve correspond to two different energy sources: first, the circularization luminosity, and second, the accretion luminosity. The



former evolves on the fallback timescale  $t_f$  while the latter evolves on a viscous timescale,

$$t_v = \sqrt{\frac{8R_p^3}{GM_\bullet}} \alpha^{-1} \left[ \frac{H(2R_p)}{2R_p} \right]^{-2}, \quad (8)$$

where we have assumed that the disk outer edge is  $2R_p$ ,  $\alpha < 1$  is the usual Shakura-Sunyaev viscosity parameter, and  $H/R$  is the disk aspect ratio. For standard TDEs, these two sources of luminosity are difficult to disentangle, because  $t_v \ll t_f$ <sup>77,78</sup>: as soon as matter circularizes into a disk, it drains rapidly into the SMBH, and the two sources of luminosity rise and fall together.

However, for very massive SMBHs,  $\dot{M}_p < \dot{M}_{\text{Edd}}$  and the accretion disk will be geometrically thin, dramatically increasing  $t_v$  and producing an inverted timescale hierarchy:  $t_v \gtrsim t_f$ . The circularization luminosity can be released promptly, but accretion luminosity will be bottlenecked by the long  $t_v$ . The range of inferred SMBH masses for ASASSN-15lh yield  $\dot{M}_p \lesssim \dot{M}_{\text{Edd}}$  (unlike for most other TDE hosts), so it is natural to expect two power sources - circularization and accretion - to have two different peaks.

The characteristic decay time of the first peak will be  $\sim t_f$ , while that of the second will be  $t_v$ , which is a sensitive function of  $\alpha$  and  $H/R$ . Plausible parameter choices (e.g.  $M_\bullet = 10^8 M_\odot$ ,  $\alpha = 0.1$ ,  $H/R = 0.03$ ) give  $t_v \sim 6$  months, in agreement with the observed second component of the light curve. However, the first component of the light curve decays on a  $\sim 1 - 2$  month timescale, unlike the Newtonian estimate of Eq. 4:  $t_f \approx 1$  yr. In the following subsection, we argue that GR effects can increase  $\Delta\epsilon$  in TDEs with extremely relativistic pericenters, substantially reducing  $t_f$  for this subset of TDEs.

**Relativistic Alterations to the Fallback Time** Highly relativistic tidal disruption will alter the Newtonian  $\Delta\epsilon$ . The frozen-in energy spread  $\Delta\epsilon$  can increase by a factor up to  $\sqrt{2}$ <sup>79</sup>, decreasing  $t_f$  and increasing  $\dot{M}_p$  modestly. However,  $\Delta\epsilon$  may increase further by modest spin-orbit misalignments in a TDE for sufficiently relativistic pericenters<sup>66</sup>. Here, we argue that this effect can strongly reduce the fallback time from the Newtonian estimate of Eq. 4.

The extremity of a TDE is quantified not just by  $B \equiv R_p/R_g$ , but also by the penetration factor  $\beta \equiv R_t/R_p$ . Large  $\beta$  TDEs will strongly compress the star orthogonal to the orbital plane, causing a vertical collapse with velocity  $v_z \approx \beta\sqrt{GM_\star/R_\star}$ . The collapse is reversed near pericenter, once internal pressure in the disrupted star builds up to the point where it “bounces” along this vertical axis<sup>80</sup>, receiving an almost impulsive hydrodynamic kick  $\approx v_z$  along the direction of collapse. The bounce typically has little effect on the energy spread of the debris<sup>65,73</sup>, despite the fact that  $V_p v_z \gtrsim \Delta\epsilon$  for large  $\beta$  or small  $B$  (here  $V_p$  is the orbital velocity at pericenter). One could define a hydrodynamic component of the energy spread,  $\Delta\epsilon_h \equiv \vec{V}_p \cdot \vec{v}_z = V_p v_z \cos \theta$ , but in standard TDEs the misalignment angle  $\theta = \pi/2$ .

However, for very low  $B$ , modest spin-orbit misalignment will precess the orbital plane as the star passes through the tidal sphere, partially aligning the axis of vertical collapse with the orbital velocity vector. The per-orbit precession in the line of ascending nodes for a parabolic orbit is<sup>81</sup>

$$\delta\Omega = \sqrt{2}\pi a_\bullet \left( \frac{R_g}{R_p} \right)^{3/2}, \quad (9)$$

at leading post-Newtonian order. Since most of this shift occurs near pericenter, we approximate the rotation in the line of ascending nodes between  $R_t$  and the bounce (near  $R_p$ ) as  $\delta\Omega/2$ . The

misalignment angle  $\cos \theta \approx \frac{\delta\Omega}{2} \sin I$ , where  $I$  is the misalignment between spin and orbital angular momentum. Defining a total energy spread  $\Delta\epsilon_{\text{tot}} \equiv \Delta\epsilon + \Delta\epsilon_{\text{h}}$ , we find (Stone, Kennon, & Metzger in prep.)

$$\Delta\epsilon_{\text{tot}} = \Delta\epsilon(1 + a_{\bullet}\beta^{3/2}B^{-3/2}\sin I). \quad (10)$$

The above arguments are approximate, as the post-Newtonian approximation begins to break down for  $R_{\text{p}} \sim R_{\text{g}}$ , and we have treated the bounce hydrodynamics impulsively. A detailed examination of this spin-orbit coupling is beyond the scope of this paper, but order unity increases in  $\Delta\epsilon$  and decreases in  $t_{\text{f}} \propto \Delta\epsilon^{3/2}$  are expected for TDEs around SMBHs with  $a_{\bullet} \approx 1$  and  $B \sim 1$ .

**Relativistic Calculation of the Hills Mass** Some of the previous Newtonian estimates break down when the star’s orbital pericenter  $R_{\text{p}} \sim R_{\text{g}}$ . In this regime, general relativistic effects are crucial for proper modelling of the Hills mass<sup>82, 14</sup>. The increased  $M_{\text{H}}$  arises from two different effects: first, a large  $a_{\bullet}$  will lower the IBCO radius significantly. Second, the Kerr tidal field is somewhat stronger than the Schwarzschild equivalent.

To calculate  $M_{\text{H}}(a_{\bullet})$ , we employ Fermi Normal Coordinates to write a local, fully general relativistic tidal tensor<sup>83</sup>. We then employ the formalism of Ref. <sup>14</sup> to estimate relativistic Hills masses. Results are shown for equatorial orbits (which maximize  $M_{\text{H}}$ ) in Figure 4, where we see that the relativistic Kerr Hills mass can be almost an order of magnitude greater than the Newtonian (or Schwarzschild) equivalent.

**Data Availability Statement** The photometry and spectra of ASASSN-15lh supporting the findings of this study are available from WISEREP<sup>84</sup>:

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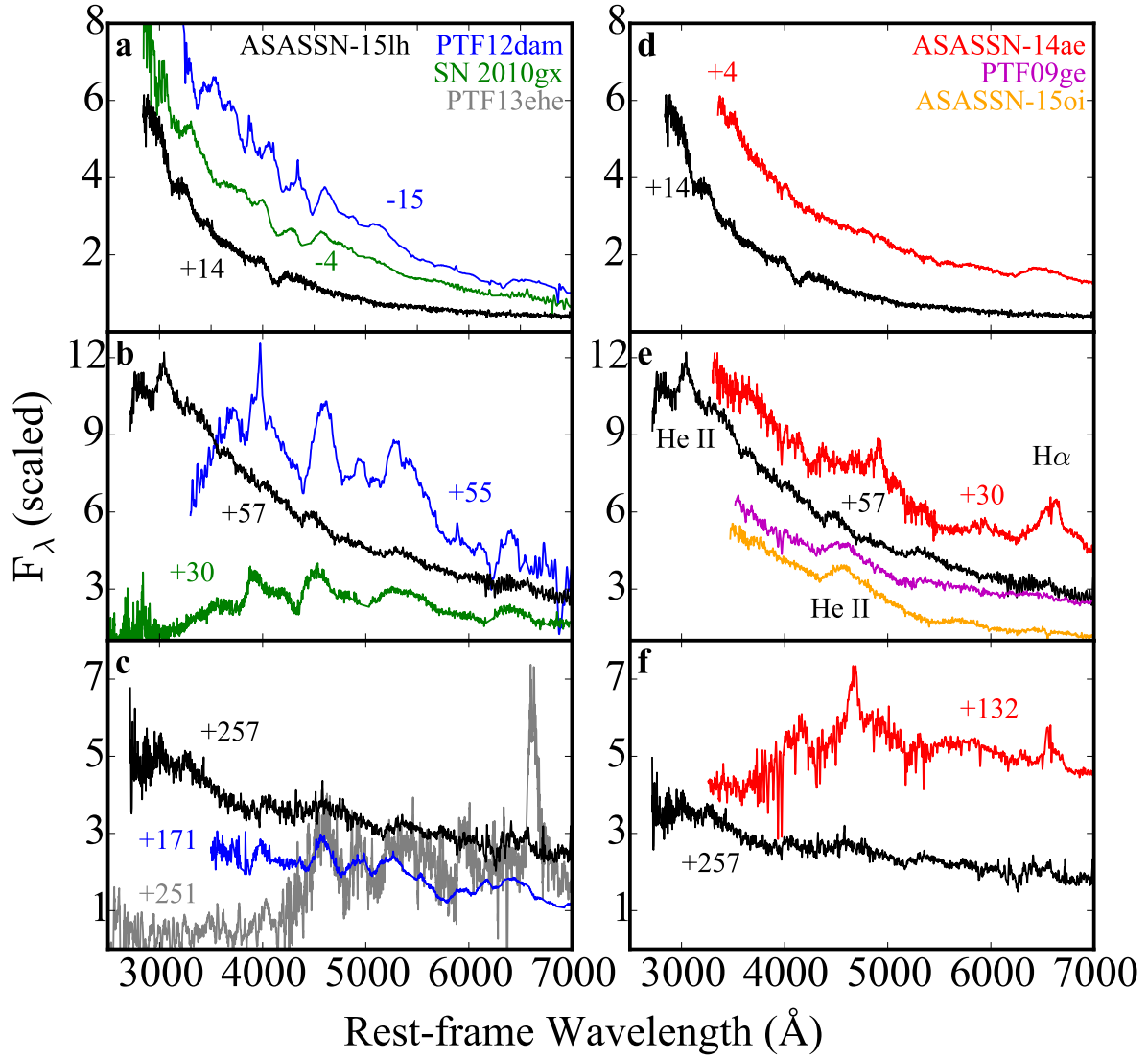
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# Supplementary Information

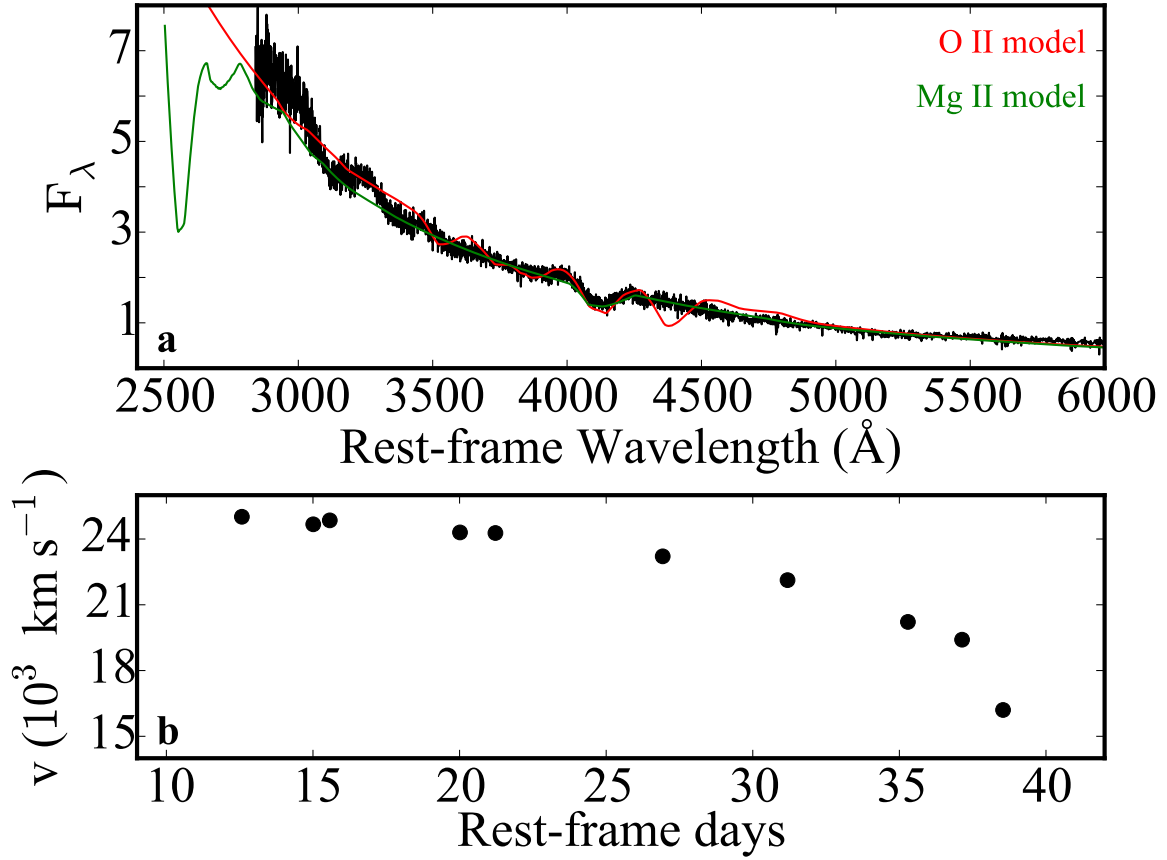


**Supplementary Figure 1 | Spectroscopic comparison of ASASSN-15lh with SLSNe and**

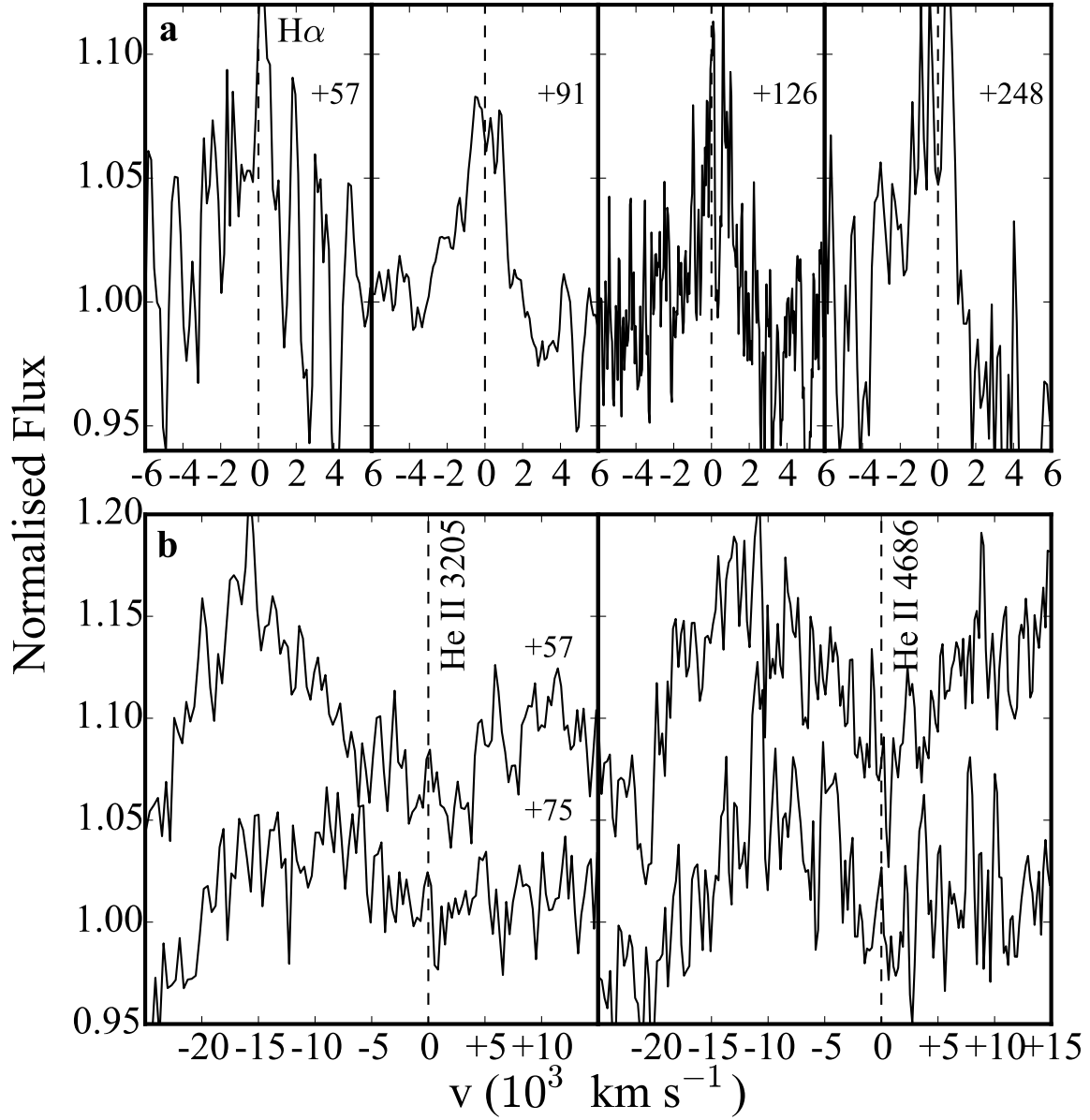
**TDEs.** The left panels compare spectra of ASASSN-15lh at different phases with those of SLSNe<sup>17, 85, 28</sup>.

The right panels compare the same spectra with TDEs<sup>5, 6, 86</sup>. At early times (a), ASASSN-15lh looks indeed similar to SLSNe<sup>7</sup> but lacks a strong O II feature. The later spectra (b,c) are very different from those of SLSNe and even at +257 days ASASSN-15lh is purely continuum-dominated

without any nebular features or signs of strong circumstellar interaction, such as in PTF13ehe<sup>28</sup>. Despite the differences with TDE spectra (d,e,f) there are also similarities, especially with TDEs showing blueshifted He II (e), or even with the early spectrum of ASASSN-14ae (d). ASASSN-15lh has H (Figure 1), but it is weaker than in ASASSN-14ae.

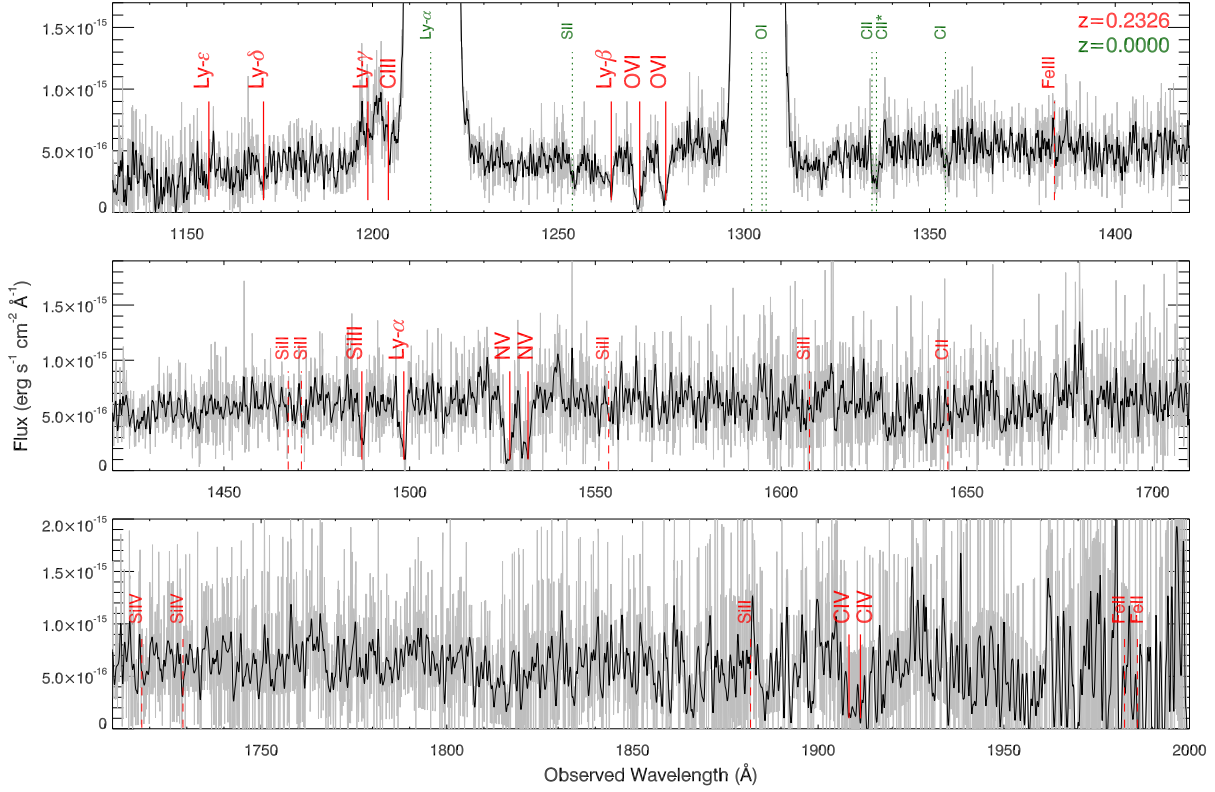


**Supplementary Figure 2 | The early phases of ASASSN-15lh.** (a) Modelling the spectra with SYNOW<sup>87</sup> and O II as in SLSNe<sup>8, 15</sup> is not possible as a strong feature at  $\sim 4400 \text{\AA}$  is inevitable. A tentative identification of the strongest feature at  $\sim 4100 \text{\AA}$  is Mg II, which however produces additional strong features in the UV. Such features (transient in nature) have been observed in a TDE candidate<sup>88</sup> and cannot be ruled out for the early phases of ASASSN-15lh, based on the available spectra. The use of SYNOW in this case is purely illustrative, as this code has not been made to model TDEs. (b) Velocity evolution of the absorption at  $\sim 4100 \text{\AA}$  assuming it is Mg II. Another possibility for this feature is that it might be due to high-velocity He II<sup>16</sup>. In this case, the velocities are larger by  $\sim 12,000 \text{ km s}^{-1}$ .



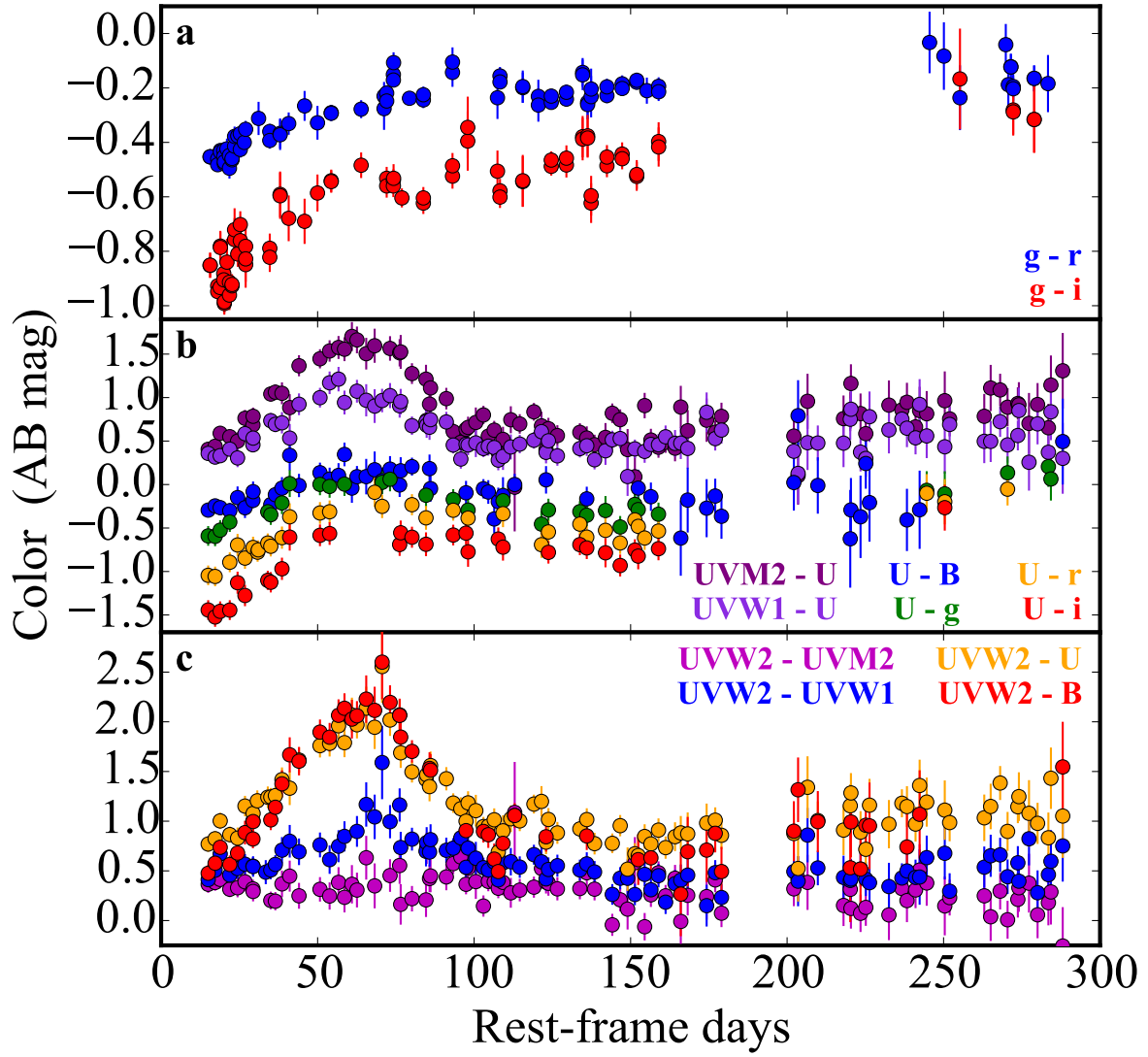
**Supplementary Figure 3 | Detection of H and possible detection of transient He in the spectra of ASASSN-15lh.** (a)  $\text{H}\alpha$  at representative epochs. The line is weak and the detection significance varies with S/N (see also Figure 1). However, there is no measurable evolution in its

strength ( $EW \sim 4 - 8 \text{ \AA}$ ), and its presence cannot be excluded in any spectrum. (b) The profiles of the lines identified as blueshifted He II at +57 and +75 days.



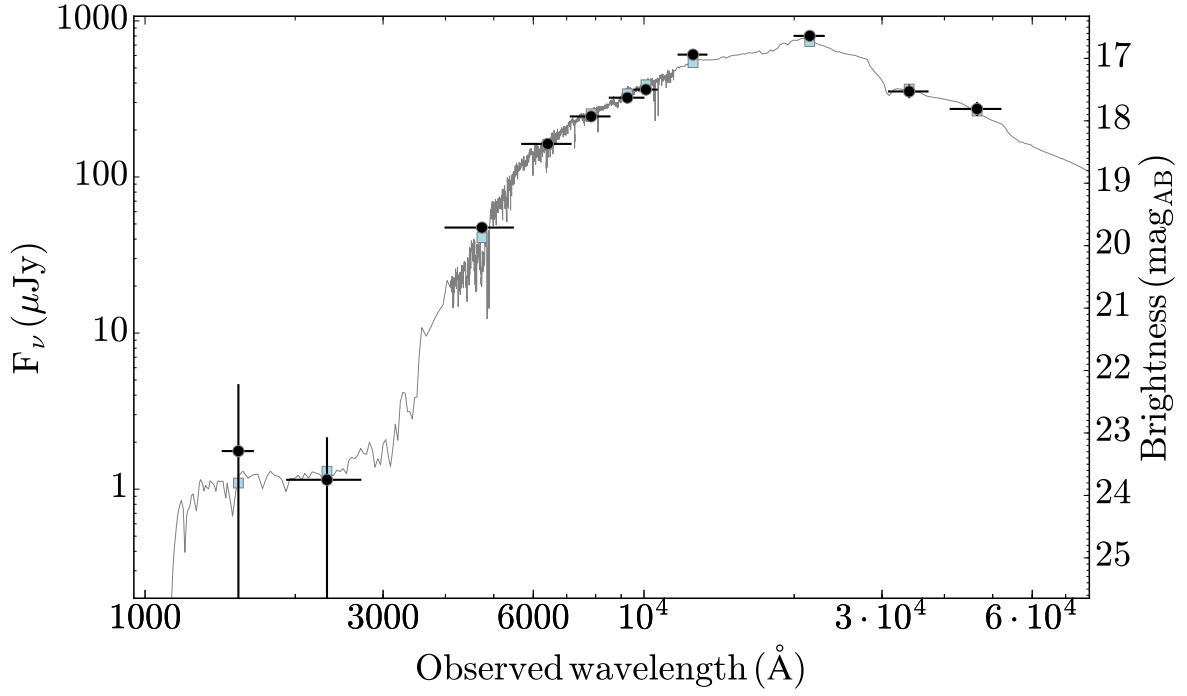
**Supplementary Figure 4 | An ultraviolet spectrum of ASASSN-15lh obtained with *HST*+COS at 168 rest-frame days past maximum.** We identify both local geocoronal lines (marked with green) and narrow absorption features associated with ASASSN-15lh at  $z = 0.2326$  (red). Detections (marked with red solid lines), include Ly- $\alpha$ , Ly- $\beta$ , Si III, C IV, and, notably, N V and O VI. The most prominent lines that are not detected are marked with a red dashed line.



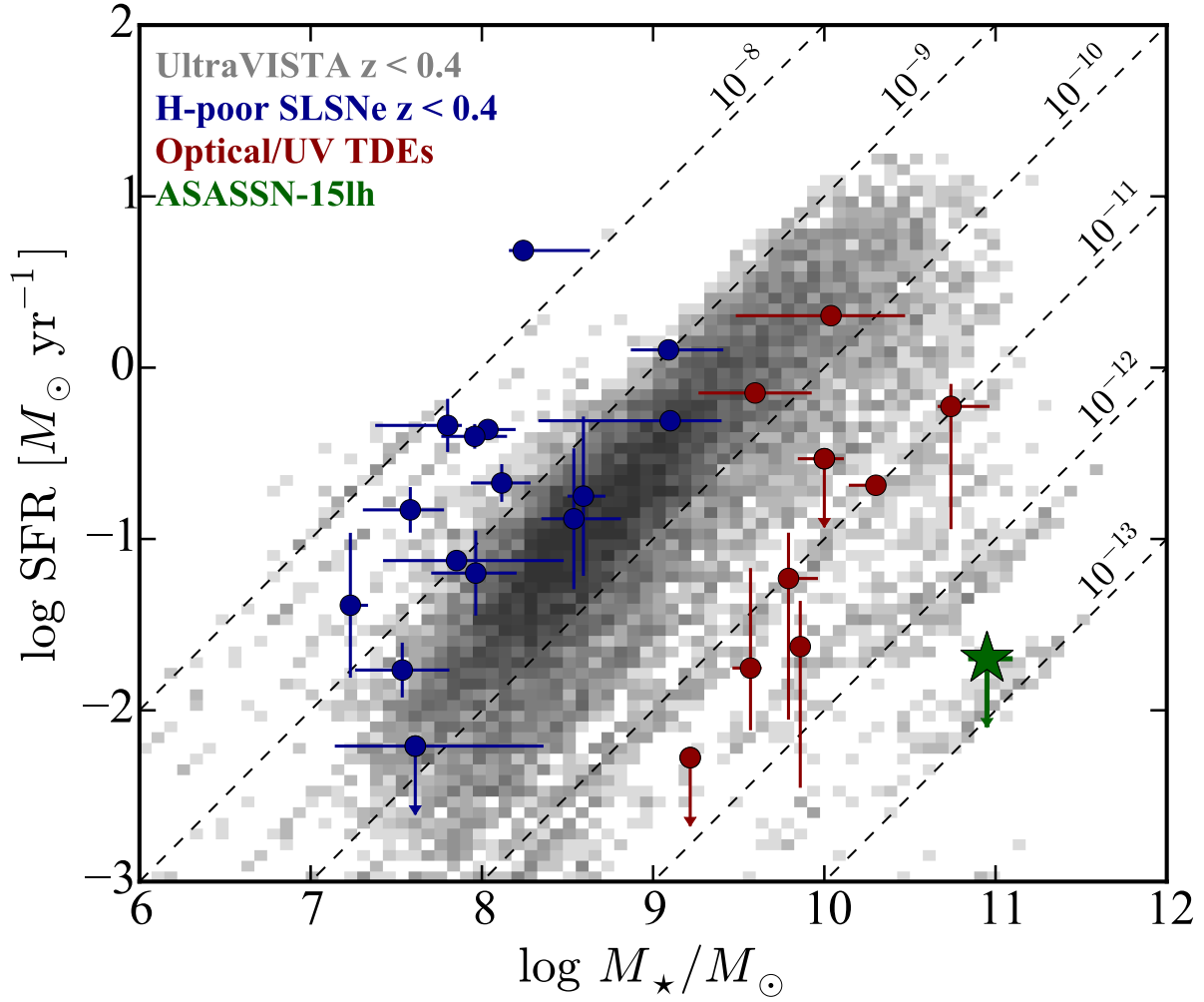


**Supplementary Figure 5 | The colour evolution of ASASSN-15lh.** We use as reference the  $UVW2$  filter for the UV colours (c), the  $g$  filter for the optical colours (a) and the  $U$  filter for additional UV and UV–optical colours (b). Errorbars are  $1\sigma$  uncertainties. Most colours show a significant evolution to the red, peaking at 60 days past-maximum and corresponding to the UV

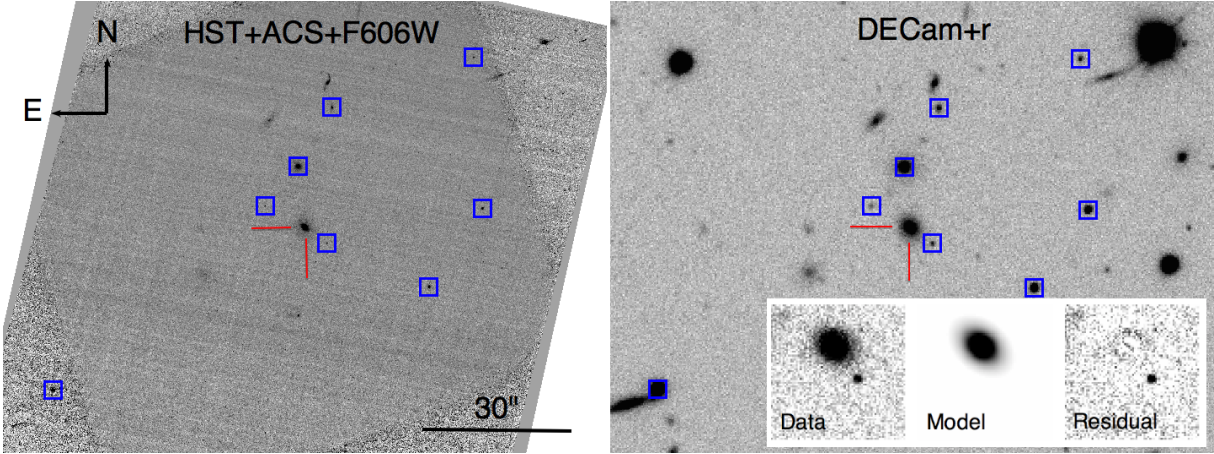
minimum in Figure 2. Subsequently, the UV colours get bluer again. All colours remain fairly constant after day +100 and for a period of over 120 days.



**Supplementary Figure 6 | SED fit for the host galaxy of ASASSN-15lh.** To perform the fit we are using the code *Le Phare* and photometric data all the way from the far-UV (GALEX) to the mid-IR (WISE). Shown is the best-fitting template (reduced  $\chi^2 = 0.998$ ). The GALEX non-detections are shown here with the nominal SExtractor photometry errors.



**Supplementary Figure 7 | The properties of the host galaxy of ASASSN-15lh compared to those of SLSNe<sup>10, 11</sup> and TDEs<sup>5, 6, 89, 86</sup>.** For comparison, we show the general galaxy population at  $z < 0.4$  from UltraVISTA and we have drawn lines of equal specific SFR. The location of ASASSN-15lh clearly stands out from those of SLSNe that are found in dwarf star-forming galaxies on or above the main sequence of star formation. The separation of ASASSN-15lh is 3 orders of magnitude in terms of specific SFR. At the same time, the host is significantly more massive from those of most optical TDEs, suggesting a large SMBH mass.



**Supplementary Figure 8** | **The localisation of ASASSN-15lh in the nucleus of its host galaxy.** On the left is an *HST* image of ASASSN-15lh obtained at day +47. On the right is a DECam image from October 2014, several months before the transient appeared. The sources used to derive the geometric transformation between the frames are marked with blue squares. The inset shows a zoom in to the host together with a *GALFIT* model and the residual from the model fit. ASASSN-15lh has an offset of  $36 \pm 53$  mas from the nucleus and it is thus consistent with the location of the central SMBH.

Line	$\lambda_{obs}$ (Å)	offset (km/s) <sup>a</sup>	EW (Å)	EW <sub>GRB</sub> <sup>b</sup> (Å)	EW <sub>SLSN</sub> (Å)
O VI 1031	1271.57	$-80 \pm 12$	$1.97 \pm 0.26$	–	–
O VI 1037	1278.55	$-80 \pm 12$	$1.57 \pm 0.24$	–	–
S III 1206	1487.26	$+44 \pm 22$	$0.79 \pm 0.26$	–	–
Ly- $\alpha$	1498.26	$0 \pm 12$	$1.15 \pm 0.32$	73.0	–
N V 1238	1526.50	$-117 \pm 12$	$1.97 \pm 0.41$	0.14	–
N V 1242	1531.26	$-117 \pm 12$	$2.07 \pm 0.43$	0.07	–
Si II 1259	–	–	$< 1.73$	1.26	–
Si II 1304	–	–	$< 2.21$	2.29	–
C II 1334	–	–	$< 2.56$	1.73	–
Si IV 1393	–	–	$< 2.75$	0.95	–
Si II 1527	–	–	$< 6.7$	0.93	–
C IV/C IV 1548	–	$-204 \pm 92$	$3.08 \pm 2.35$	2.18	–
Fe II 1608	–	–	$< 24.0$	0.85	–
Fe II 2382	–	–	$< 1.31$	1.65	$0.35 \pm 0.03$ <sup>c</sup>
Fe II 2600	–	–	$< 3.65$	1.85	$0.29 \pm 0.03$ <sup>c</sup>
Mg II 2796	3445.67	$+8 \pm 8$	$0.50 \pm 0.05$	1.71	$2.6 \pm 1.2$ <sup>d</sup>
Mg II 2803	3454.46	$+14 \pm 10$	$0.38 \pm 0.05$	1.47	– <sup>d</sup>

Table 1: Absorption lines in the spectrum of ASASSN-15lh. Upper limits are  $3\sigma$ . EWs are in rest-frame.

Notes: <sup>a</sup> The reference velocity was set to Ly-alpha ( $z = 0.23253$ ). <sup>b</sup> Based on a high S/N composite GRB afterglow spectrum<sup>47</sup>. Typical error for weak lines is 0.02 Å. <sup>c</sup> Based only on PTF13ajg<sup>46</sup>. <sup>d</sup> Total value for the doublet, based on a sample of 13 events<sup>46</sup>.

Date (UT)	Phase	Telescope+Instrument	Grism	Range (nm)
2015-06-22.7	+14.0	FTS+FLOYDS		325 - 930
2015-06-24.7	+15.6	ANU 2.3m+WiFeS	B3000+R3000	350 - 956
2015-07-01.6	+21.2	ANU 2.3m+WiFeS	B3000+R3000	350 - 956
2015-07-08.7	+26.9	ANU 2.3m+WiFeS	B3000+R3000	350 - 956
2015-07-21.3	+37.1	VLT+FORS2	300V	445 - 865
2015-07-31.5	+45.4	ANU 2.3m+WiFeS	B3000+R3000	350 - 956
2015-08-14.3	+56.6	NTT+EFOSC2	GR#11+16	334 - 999
2015-09-06.0	+75.0	NTT+EFOSC2	GR#11+16	334 - 999
2015-09-16.1	+83.2	NTT+EFOSC2 <sup>a</sup>	GR#11+16	334 - 999
2015-09-23.2	+89.0	NTT+EFOSC2	GR#11+16	334 - 999
2015-09-25.1	+90.6	VLT+FORS2	300V	445 - 865
2015-10-11.1	+103.6	NTT+EFOSC2 <sup>b</sup>	GR#11	334 - 745
2015-10-13.2	+105.2	NTT+EFOSC2 <sup>b</sup>	GR#16	599 - 999
2015-11-08.0	+126.2	Magellan+IMACS	Gri-300-17.5	400-999
2015-11-18.1	+134.3	NTT+EFOSC2	GR#13	365 - 924
2015-12-16.0	+157.0	NTT+EFOSC2	GR#11+16	334 - 999
2016-04-06.3	+248.1	NTT+EFOSC2	GR#11+16	334 - 999
2016-04-15.3	+256.2	NTT+EFOSC2	GR#11+16	334 - 999

Table 2: Log of Spectra. Notes: <sup>a</sup> Low S/N; not used. <sup>b</sup> Combined to a single spectrum.