

# A very luminous jet from the disruption of a star by a massive black hole

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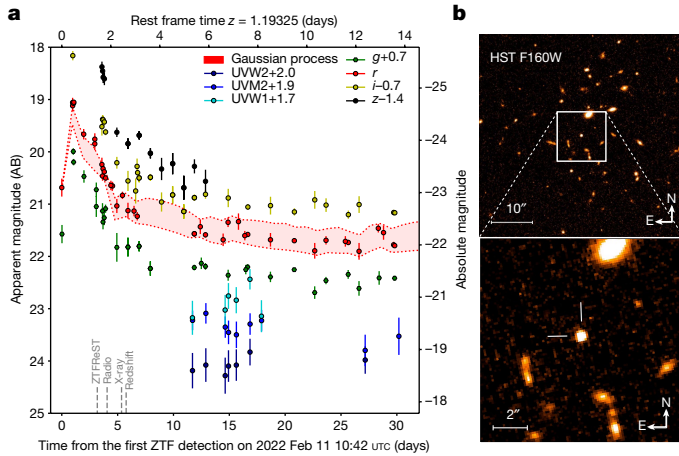
Tidal disruption events (TDEs) are bursts of electromagnetic energy that are released when supermassive black holes at the centres of galaxies violently disrupt a star that passes too close<sup>1</sup>. TDEs provide a window through which to study accretion onto supermassive black holes; in some rare cases, this accretion leads to launching of a relativistic jet<sup>2–9</sup>, but the necessary conditions are not fully understood. The best-studied jetted TDE so far is Swift J1644+57, which was discovered in  $\gamma$ -rays, but was too obscured by dust to be seen at optical wavelengths. Here we report the optical detection of AT2022cmc, a rapidly fading source at cosmological distance (redshift  $z = 1.19325$ ) the unique light curve of which transitioned into a luminous plateau within days. Observations of a bright counterpart at other wavelengths, including X-ray, submillimetre and radio, supports the interpretation of AT2022cmc as a jetted TDE containing a synchrotron ‘afterglow’, probably launched by a supermassive black hole with spin greater than approximately 0.3. Using four years of Zwicky Transient Facility<sup>10</sup> survey data, we calculate a rate of  $0.02^{+0.04}_{-0.01} \text{ Gpc}^{-3} \text{ yr}^{-1}$  for on-axis jetted TDEs on the basis of the luminous, fast-fading red component, thus providing a measurement complementary to the rates derived from X-ray and radio observations<sup>11</sup>. Correcting for the beaming angle effects, this rate confirms that approximately 1 per cent of TDEs have relativistic jets. Optical surveys can use AT2022cmc as a prototype to unveil a population of jetted TDEs.

On 2022 February 11 10:42:40 UTC Zwicky Transient Facility (ZTF) detected a transient, ZTF22aaajecp (Fig. 1), located at right ascension  $\alpha = 13 \text{ h } 34 \text{ min } 43.20232 \text{ s}$  and declination  $\delta = +33^\circ 13' 00.6565''$  (equinox J2000, obtained via radio data analysis with uncertainty 0.01<sup>12</sup>; Methods section ‘Very Large Array’) in its nightly cadenced survey. Our ‘ZTFReST’<sup>12</sup> pipeline, using data obtained on the next two nights, flagged it to be atypical, owing to its rapid rise and fade (considerably faster than typical supernovae; Methods sections ‘Identification of

AT2022cmc’ and ‘Comparison between AT2022cmc and other energetic transients’).

We reported the source to the Transient Name Server, with assigned IAU name AT2022cmc. Multiwavelength observations were triggered, enabling the observation of a bright counterpart in the X-rays<sup>13</sup>, with a 0.3–6 keV flux of  $(3.04 \pm 0.05) \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$  (Methods sections ‘Neutron Star Interior Composition Explorer’ and ‘Neil Gehrels Swift Observatory’), as well as counterparts in the decimetre<sup>14</sup> and

A list of affiliations appears at the end of the paper.



**Fig. 1 | AT2022cmc light curve and images in the near infrared, optical and ultraviolet.** **a**, Apparent and absolute magnitudes show the fast evolution (greater than 1 mag day<sup>-1</sup>) at early times, the transition into a plateau, and the large luminosity of the transient in the optical in both phases. Magnitudes in this plot are corrected for Galactic extinction  $E(B - V) = 0.01$  mag (ref. <sup>143</sup>). A Gaussian process regression estimate is shown for the  $r$ -band data to guide the eye (the coloured band represents the standard deviation from the central prediction). More observations are available in the  $o$ ,  $H$ ,  $J$ ,  $K_s$ ,  $F606W$  and  $F106W$  bands, all of which are reported, along with some upper limits in other bands, in Supplementary Table 1. Error bars shown are  $\pm 1\sigma$ . **b**, AT2022cmc was clearly detected in Hubble Space Telescope (HST) images in F606W (optical) and F160W (near infrared) filters. A host galaxy probably underlies the bright transient and might be revealed by future observations from space.

submillimetre<sup>15</sup> bands (Fig. 2; Methods sections ‘Very Large Array’–‘JCMT SCUBA-2 submillimetre observations’). The redshift of the transient,  $z = 1.19325 \pm 0.00024$  (luminosity distance  $D_L = 8.444$  Gpc, assuming a Planck cosmology)<sup>16</sup>, was first secured by absorption lines in the spectrum obtained with the X-shooter instrument on the Very Large Telescope<sup>17</sup> (Fig. 3; Methods sections ‘Redshift’ and ‘Very Large Telescope’). This redshift measurement implies an absolute optical luminosity of  $M_i \approx -25$  mag (AB) for the observed peak. However, the host galaxy must be very faint (below approximately 24.5 mag), as it was not found in deep archival images (Methods section ‘Host galaxy’).

We undertook an intensive multiwavelength monitoring programme from radio to X-ray frequencies. Submillimetre and radio observations revealed a heavily self-absorbed radio spectrum up to hundreds of GHz (Methods sections ‘Very Large Array’–‘JCMT SCUBA-2 submillimetre observations’; Extended Data Fig. 1). The X-ray, radio and submillimetre counterparts to AT2022cmc are all among the most luminous identified so far for high-redshift transients (Fig. 2). The long-term evolution has shown a decline in X-ray luminosity, and a radio peak moving to lower frequencies.

The infrared/optical/ultraviolet light curve (Fig. 1) revealed a red colour and dramatic rise and decay for about four days post-observation, before the evolution slowed and the colour became bluer. Optical/IR spectra were acquired in both phases, but never showed the broad features that are typically observed in explosive transients<sup>18</sup>.

The exceptionally high isotropic-equivalent luminosity across wavelength, and rapid spectral and temporal evolution on sub-day timescales, mark AT2022cmc as extremely unusual, even amongst the rapidly expanding ‘zoo’ of astronomical transients (Fig. 2), with approximately 100 new objects reported publicly per night. In Methods section ‘Comparison between AT2022cmc and other energetic transients’, we compare AT2022cmc with energetic transients, some well known and others exotic. These include a kilonova arising from  $r$ -process element production in a compact binary merger, a luminous fast blue optical transient (LFBOT), which is a poorly understood class probably related

**Table 1 | Comparison of observational and inferred properties of AT2022cmc and the well-studied jetted TDE Swift J1644+57**

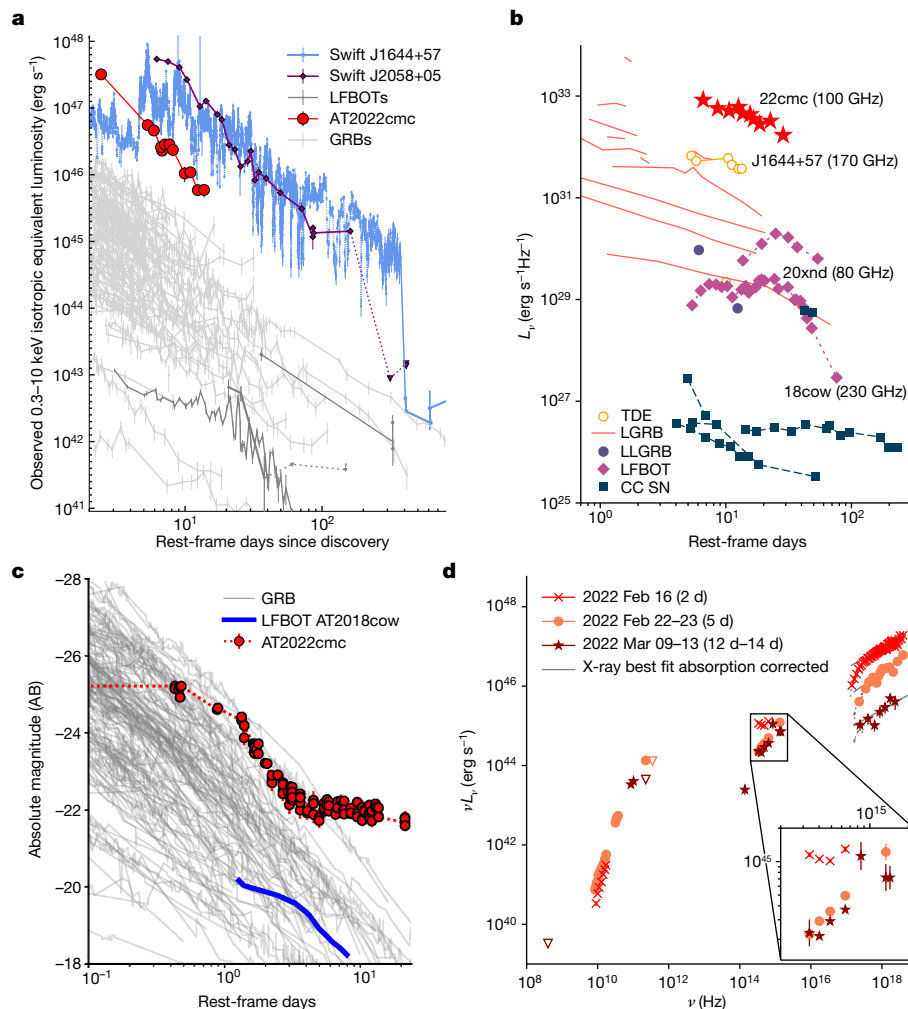
| Property                            | AT2022cmc                                               | Swift J1644+57                                          | References                                                   |
|-------------------------------------|---------------------------------------------------------|---------------------------------------------------------|--------------------------------------------------------------|
| Redshift ( $z$ )                    | 1.19325                                                 | 0.3534                                                  | <sup>17,132</sup> , this work; <sup>4</sup>                  |
| $\gamma$ -ray burst                 | No                                                      | Yes                                                     | This work; <sup>2,3</sup>                                    |
| X-ray $L_{\text{iso}}$ (0.3–6 keV)  | $2.4 \times 10^{47}$ erg s <sup>-1</sup>                | $\sim 3 \times 10^{48}$ erg s <sup>-1</sup>             | <sup>13</sup> , this work; <sup>2–4</sup>                    |
| X-ray hour timescale variability    | Yes                                                     | Yes                                                     | <sup>21</sup> ; 2–4                                          |
| Ultraviolet transient               | Yes                                                     | No                                                      | This work; <sup>3,4</sup>                                    |
| Optical transient                   | Yes                                                     | No                                                      | This work; <sup>3,4</sup>                                    |
| Optical transient spectra           | Featureless                                             | Not available                                           | This work                                                    |
| Infrared transient                  | Yes                                                     | Yes                                                     | This work; <sup>3,4</sup>                                    |
| Millimetre $L_\nu$ (100–170 GHz)    | $\sim 10^{33}$ erg s <sup>-1</sup> Hz <sup>-1</sup>     | $\sim 10^{32}$ erg s <sup>-1</sup> Hz <sup>-1</sup>     | <sup>15</sup> , this work; <sup>5,9</sup>                    |
| Radio transient                     | Yes                                                     | Yes                                                     | This work;                                                   |
| Lorentz factor                      | $\Gamma \approx 12$                                     | $2 \lesssim \Gamma \lesssim 20$                         | This work; <sup>2,3,5</sup>                                  |
| X-ray column density $N_{\text{H}}$ | $< 6.4 \times 10^{21}$ cm <sup>-2</sup>                 | $\sim 1 \times 10^{22}$ cm <sup>-2</sup>                | This work; <sup>3,4</sup>                                    |
| Host galaxy in archival images      | No                                                      | Yes                                                     | This work; <sup>2–5</sup>                                    |
| Host galaxy luminosity              | $M_i > -21.4$ mag                                       | $M_V \approx -18.19$ mag                                | This work; <sup>4,5</sup>                                    |
| Host galaxy star-formation rate     | $< 135 M_\odot \text{ yr}^{-1}$                         | $0.5 M_\odot \text{ yr}^{-1}$                           | This work; <sup>4</sup>                                      |
| Optical polarization                | $P_{\text{lin}} \sim 0\%$                               | $P_{\text{lin}} = 7.4\% \pm 3.5\%$                      | A. Cikota et al. (manuscript in preparation); <sup>142</sup> |
|                                     | $P_{\text{circ}} \sim 0\%$                              |                                                         |                                                              |
| Radio polarization                  | Not available                                           | $P_{\text{lin}} < 9.7\%$                                | <sup>142</sup>                                               |
| SMBH mass                           | $< (5 \times 10^8) M_\odot$                             | $\lesssim 10^7 M_\odot$                                 | This work; <sup>2,3</sup>                                    |
| SMBH spin                           | $\gtrsim 0.3$                                           | $\gtrsim 0.7$                                           | This work                                                    |
| Inferred on-axis jetted TDE rate    | $0.02^{+0.04}_{-0.01} \text{ Gpc}^{-3} \text{ yr}^{-1}$ | $0.03^{+0.04}_{-0.02} \text{ Gpc}^{-3} \text{ yr}^{-1}$ | This work; <sup>11</sup>                                     |

The inferred on-axis jetted TDE rate in the Swift J1644+57 column was calculated using the entire population of X-ray jetted TDEs.  $M_\odot$ , mass of the Sun;  $M_i$  and  $M_V$  are absolute magnitudes in optical  $r$  and  $V$  filters (AB system);  $P_{\text{lin}}$  ( $P_{\text{circ}}$ ), linear (circular) polarization, where the error on  $P_{\text{lin}}$  was obtained from ref. <sup>142</sup> by propagating errors on the Stokes parameters and correcting them for polarization bias; SMBH, supermassive black hole.

to stellar collapse to a black hole, and a  $\gamma$ -ray burst (GRB) arising owing to the collapse of a star. Although astronomical surveys may not have sampled the full region of parameter space available to each class, we exclude an association between AT2022cmc and these transient classes.

The only remaining class of objects that can produce the observed optical, X-ray and submillimetre luminosities is a rare jetted TDE. Space-based observatories performing searches in  $\gamma$ -rays and X-rays have disclosed a handful of TDEs with relativistic jets<sup>7</sup>, the last one more than a decade ago. The best-studied jetted TDE so far is Swift J1644+57<sup>2–5</sup>, which showcased several exceptional characteristics: long-lived X-ray emission with variability on very short time scales (approximately 100 s), radio emission indicating a newly formed relativistic jet, and an origin in the nucleus of a galaxy. The near-infrared transient associated with Swift J1644+57 faded beyond the detection limit in approximately 10 days (ref. <sup>3</sup>). Unlike AT2022cmc, no optical or ultraviolet transient was detected<sup>3</sup>, although this was unsurprising given the large inferred host galaxy extinction<sup>3</sup>. A direct comparison between the properties of AT2022cmc and Swift J1644+57 is presented in Table 1.

We now describe a possible explanation for AT2022cmc, aided by the broad-brush picture shown in Fig. 4. The event started when an ill-fated



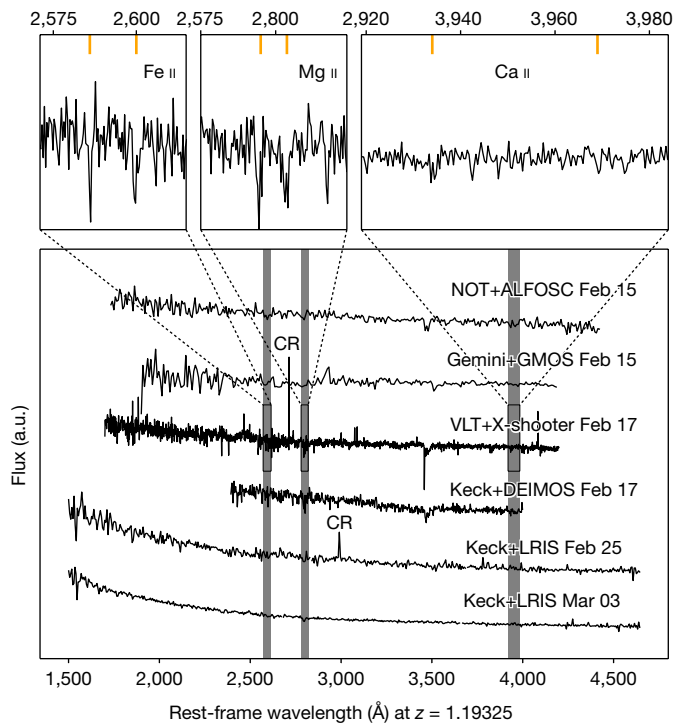
**Fig. 2 | AT2022cmc is among the most luminous extragalactic transients ever observed.** **a**, Comparison between the X-ray observations of AT2022cmc, the jetted TDE candidates Swift J1644+57 and Swift J2058+05, GRBs, and luminous fast blue optical transients (LFBOTs). The onset time is here set to the first ZTF detection, but its true value is poorly constrained. **b**, Submillimeter Array (SMA) millimetre light curve of AT2022cmc compared to light curves of millimetre-bright cosmic explosions at similar frequencies (frequencies provided in the rest frame): long-duration  $\gamma$ -ray bursts (LGRBs), low-luminosity GRBs (LLGRBs), LFBOTs, core-collapse supernovae (CC SN) and TDEs.

**c**, Comparison between the optical light curve of AT2022cmc K-corrected to  $r$ -band (see Methods section ‘Comparison between AT2022cmc and other energetic transients’), the light curves of GRB afterglows, and the light curve of the prototypical LFBOT AT2018cow. **d**, Radio to X-ray spectral energy distribution (SED). A change in the shape of the SED is especially evident in the optical/UV between 2022 February 16 and March 09–13 (2 days, 5 days, and 12–14 days in the rest frame from the first detection), suggesting a transition between two different emission components.

star approached the supermassive black hole (SMBH) on a nearly parabolic trajectory and was ripped apart into a stream of gaseous debris. About half of the mass stayed bound to the black hole, underwent general-relativistic apsidal precession as the gas fell back towards the pericentre, and then produced strong shocks at the self-crossing point<sup>19</sup>. The shocked gas then circularized to form an accretion disk around the black hole the rapid spin of which generated a pair of relativistic jets<sup>20</sup>. The high X-ray luminosity (Fig. 2a) and flux variability on a timescale of  $t_{\text{var}} \approx 1$  h (refs. <sup>21,22</sup>) suggest that the X-rays were generated by internal dissipation within the jet at a distance of less than  $2t_{\text{var}}\Gamma^2c \approx 0.01$  pc ( $t_{\text{var}}/h$ )( $\Gamma/10$ )<sup>2</sup> from the black hole and that our line of sight was within the relativistic beaming cone of the jet, as was also the case for Swift J1644+57. Here,  $\Gamma \approx 10$  is the jet Lorentz factor (as constrained by the radio spectrum, see Methods section ‘Relativistic evolution of the radio source’) and  $c$  is the speed of light. The jet power of AT2022cmc inferred from X-ray observations is consistent with being generated by the Penrose–Blandford–Znajek mechanism in a magnetically arrested

disk<sup>23</sup>. Under this mechanism, we infer from the jet power that the SMBH is rapidly rotating with a spin parameter  $a \gtrsim 0.3$  for AT2022cmc and  $a \gtrsim 0.7$  for Swift J1644+57. We conclude that a high spin is probably required to launch a relativistic jet.

The optical and ultraviolet observations revealed a fast-fading red ‘flare’ (approximately 1 d) that transitioned quickly to a slow blue ‘plateau’, enabling the study of two components generated by the tidal disruption: the relativistic jet and the thermal component from bound stellar debris accreting onto the black hole. The fast-fading red component can be explained as follows. As the jet, which carried  $10^{53}$  to  $10^{54}$  erg of isotropic-equivalent energy, propagated to large distances of  $r_{\text{dec}} \approx 0.2$  pc, it was greatly decelerated by driving a forward shock into the surrounding gas of hydrogen with number density of the order  $1 \text{ cm}^{-3}$  (see Methods). At the same time, a reverse shock was propagating into the jet material, similar to cosmological GRBs<sup>24</sup>. Electrons were accelerated to relativistic speeds by these shocks and then produced synchrotron emission at wavelengths of radio/millimetre to X-ray.

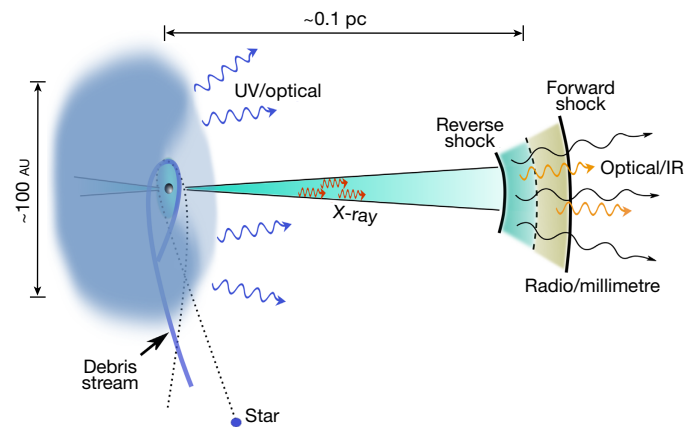


**Fig. 3 | Spectra at rest frame for redshift  $z = 1.19325$ .** Optical spectra were acquired from the night after the identification of AT2022cmc until several weeks afterwards. Observed wavelengths were corrected for the redshift by a multiplicative factor  $(1+z)^{-1}$ . Features in the VLT/X-shooter spectrum (top panels) enabled the redshift to be firmly established; orange bars mark the wavelengths of Fe II, Mg II, and Ca II lines. In the month since its first detection, the spectra of AT2022cmc appear otherwise featureless. The absorption line around 3,500 Å is telluric (non-astrophysical) and the apparent narrow emission features are cosmic rays (CR). a.u., arbitrary units.

The bright millimetre emission was dominated by the reverse-shock-heated electrons at early time before the reverse shock crossed the most energetic parts of the jet, but the forward shock emission dominated at later time.

The slowly fading blue, thermal optical/UV emission was produced by the optically thick outflows from the self-crossing shock and the accretion disk<sup>19</sup>, which can be responsible for the blue plateau observed for weeks after the initial flare. As is known from non-jetted TDEs, this gas component produces a blackbody-like spectrum with temperature  $10^4$ – $10^5$  K and peak luminosity of  $10^{44}$ – $10^{45}$  erg s<sup>-1</sup>, consistent with our optical observations. The high rest-frame UV luminosity (approximately  $10^{45}$  erg s<sup>-1</sup>) and blackbody temperature (approximately  $3 \times 10^4$  K) of AT2022cmc (see Methods section ‘Optical light curve modelling’) are probably due to a viewing angle close to the jet axis<sup>25</sup>.

Given the above properties, on balance we conclude that AT2022cmc is most probably generated by (nearly) on-axis jetted relativistic material from the tidal disruption of a star by a massive black hole at the centre of a galaxy with low dust extinction. This would, to our knowledge, make AT2022cmc the furthest jetted TDE discovered so far and the only one for which it was possible to observe a complex optical light curve that transitions from a fast red component into a blue plateau. Our interpretation of a TDE naturally leads to the prediction that, if a host galaxy is eventually detected (for example, with HST or James Webb Space Telescope), then the transient position should be astrometrically coincident with the nucleus and/or host light centroid. Under the TDE interpretation, because the jet is already ongoing when the blue UV component is observed, this suggests that the disk formation occurs on a timescale shorter than the evolutionary time of the blue UV component, which is of the order of weeks in the rest frame. This provides



**Fig. 4 | Our interpretation of AT2022cmc as a jetted TDE.** This illustration offers a visual representation (not to scale) of the physical processes explained in the text. Black dotted line: original geodesic of the star (note the general-relativistic apsidal precession). Thick blue line: the stellar debris gas undergoing self-intersection. Thick blue envelope of size approximately 100 AU (or  $10^{15}$  cm; AU, astronomical units): optically thick gas (probably an outflow) reprocessing the X-rays and extreme-UV emission from the accretion disk into the UV/optical band, as observed from other non-jetted TDEs. Light blue disk of size approximately 1 AU (of the order of the tidal disruption radius): accretion disk near the black hole. Light blue cones: relativistic jets launched from the innermost regions of the disk. Shocks at a distance of approximately 0.1 pc (or  $3 \times 10^{17}$  cm) from the black hole: reverse shock dominates the radio/millimetre emission, and both reverse shock and forward shock contribute to the non-thermal optical/IR emission.

important constraints on the highly uncertain hydrodynamics of the disk-formation process<sup>26</sup>.

Besides Swift J1644+37, which triggered the Swift Burst Alert Telescope (BAT) onboard, two more jetted TDE candidates have been detected by BAT ground-based analysis with similar X-ray and radio properties: Swift J2058+05<sup>6,8</sup> and Swift J1112–82<sup>7</sup>. We find that less than 5% of GRBs, such as that associated with Swift J1644+57, would result in a Swift/BAT onboard trigger if the source is placed at the same distance as AT2022cmc. Another jetted TDE<sup>27</sup> was identified in the radio and infrared bands in the Arp 299 galaxy, but not in the optical and X-rays. On the basis of these, a jetted TDE rate of approximately  $0.03^{+0.04}_{-0.02}$  Gpc<sup>-3</sup> yr<sup>-1</sup> was obtained<sup>11</sup> (where the error in the rate was calculated using small sample statistics), which is small compared to the rate of non-jetted TDEs<sup>28</sup> (approximately  $10^3$  Gpc<sup>-3</sup> yr<sup>-1</sup>). A major open question then is why apparently only a small fraction of TDEs launch jets<sup>29</sup>. The solution to this question will probably shed light on the decades-old puzzle of jet-launching from accreting SMBHs. However, a more complete survey of jetted TDEs is needed to pin down their event rate.

Using the optical light curve of AT2022cmc and the ZTF survey footprint so far, we calculate an intrinsic rate of  $0.02^{+0.04}_{-0.01}$  Gpc<sup>-3</sup> yr<sup>-1</sup> for jetted TDEs oriented towards Earth, obtained independently of discoveries made by high-energy and radio surveys. This rate is consistent with previous estimates of the on-axis rate of jetted TDEs, which suggests that host galaxy extinction is often small. This result confirms that a very small fraction, approximately  $10^{-2}(f_b/10^{-2})^{-1}$ , of TDEs launch relativistic jets with properties similar to AT2022cmc<sup>30</sup>, where  $f_b$  is the relativistic beaming factor (probably of the order of  $f^{-2} \approx 10^{-2}$ ). However, the connection between routinely discovered TDEs and rare jetted TDEs remains unclear. On the basis of the observations of AT2022cmc, we suggest that a connection exists between jetted TDEs and the newly identified class of luminous featureless TDEs<sup>31</sup> (Methods section ‘A possible connection between jetted TDEs and luminous featureless TDEs’), which could harbour relativistic jets, but might be observed

off-axis. This hypothesis can be tested with future, deep follow-up observations in the radio and X-rays. If this connection is confirmed, it will offer a new way to study the system geometry and rapidly grow the known samples thanks to the high luminosity of these transients.

Previous work<sup>4–6</sup> presents prospects for radio and X-ray discovery of a population of jetted TDEs. Here we demonstrated that the discovery of such energetic phenomena has not only become accessible to the optical community, but that optical may also be the best technique for discovery at the highest redshifts, which uniquely enables the study of distant quiescent SMBHs. Future observations of AT2022cmc-like systems will provide statistical samples required to understand the dynamics of TDE jets, why some TDEs produce relativistic jets and others do not, and the degree of multi-messenger emission in jetted TDEs.

## Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41586-022-05465-8>.

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## Methods

### Identification of AT2022cmc

In recent years, the immense growth in size and complexity of datasets produced by modern astronomical facilities—for example, refs. <sup>10,32–36</sup>—has required a revolution in the data science principles applied to facilitate discovery of very rare phenomena such as AT2022cmc. For optical astronomy in particular, the advent of time-domain surveys such as ZTF requires techniques developed for parsing, in real time, the  $\sim 1$  million alerts produced every night. This real-time aspect is essential, as the rapid evolution of the many systems requires that they are discovered and characterized as fast as possible, or the opportunity to acquire crucial data is lost. It is these multiwavelength sources for which follow-up (or even coordinated wide-field observations with rapid triggering) are immediately required, and it is these sources that we target with real-time algorithms such as the ZTFReST project<sup>12,37</sup>.

ZTFReST uses ZTF alert packets combined with forced point-spread-function photometry (ForcePhotZTF)<sup>38</sup> to search for exotic extragalactic transients, including kilonovae from binary neutron star mergers. The ZTF22aaajecp transient, which was assigned<sup>39</sup> the IAU name AT2022cmc, was identified as being unusual for both its rapid rise ( $-0.48 \text{ mag d}^{-1}$ ) and subsequent rapid decay ( $-1.29 \text{ mag d}^{-1}$ ). This can be compared to, for example, core-collapse supernovae models, which across parameter space show both shallower rises ( $-0.13 \text{ mag d}^{-1}$ ) and decay rates ( $-0.74 \text{ mag d}^{-1}$ ) maximized across the parameter space. The discovery of AT2022cmc by ZTF demonstrates that modern optical telescopes are capable of finding jetted TDEs independently of  $\gamma$ -ray monitors. The lack of an associated  $\gamma$ -ray signal shows that optical discovery of these events reduces the limitations in their study owing to the Malmquist bias in the  $\gamma$ -ray band. Both optical and  $\gamma$ -ray identification of jetted TDEs will increase the detection rates and enable greater understanding of this rare class of transient, analogous to recent advances in understanding stars collapsing to black holes producing GRBs, for example, ref. <sup>12</sup>.

### Comparison between AT2022cmc and other energetic transients

We compare AT2022cmc to four known transient classes that exhibit fast optical variability and the existence of radio and X-ray counterparts: (i) kilonovae, (ii) luminous fast blue optical transients (LFBOTs), and (iii)  $\gamma$ -ray bursts (GRBs). Blazars are another source class that could potentially generate a multiwavelength transient similar to AT2022cmc; however, the spectral energy distribution of AT2022cmc is inconsistent with those observed in blazars<sup>29</sup>. This comparison will be addressed in detail by Y.Y. et al. (manuscript in preparation).

The initially red colour and rapid evolution of AT2022cmc resemble the behaviour of the optical/infrared kilonova<sup>40</sup> AT2017gfo<sup>41</sup> associated with GW170817<sup>42</sup>, the first binary neutron star merger detected in gravitational waves. Indeed, AT2022cmc was observed by the ZTFReST pipeline, which was designed for enabling real-time discovery of elusive fast transients such as kilonovae and GRB afterglows in optical survey data. However, the luminosity of kilonovae is expected to be orders of magnitude fainter than AT2022cmc, owing to the low ejecta masses expected<sup>40</sup>,  $\sim 0.05 M_{\odot}$ . Furthermore, kilonova models evolve from blue to red as the heavier  $r$ -process synthesized elements are produced, whereas AT2022cmc evolved from red to blue.

The recently discovered LFBOTs<sup>43–49</sup> have observer-frame light curves similar to AT2022cmc, as well as X-ray and radio counterparts<sup>45–47,49–51</sup>. However, unlike the prototypical LFBOT AT2018cow<sup>43–45</sup>, the optical light curve of AT2022cmc is much redder,  $\geq 100\times$  brighter in  $r$ -band at peak, and fades  $\sim 2\times$  faster at early phases in the rest frame. A long-duration blue component has not been observed in any LFBOT so far. The X-ray ‘isotropic equivalent luminosity’ of AT2022cmc is  $\geq 10,000\times$  higher than LFBOTs (Fig. 2). Altogether, these properties strongly disfavour this scenario.

The observed redshift of AT2022cmc implies that the optical isotropic equivalent luminosity is comparable to the brightest relativistic

transients (Fig. 2c). This high luminosity ( $M_r \approx -25 \text{ mag}$ ), in addition to the red colour at peak and rapid decline, is consistent with synchrotron emission, which arises from charged particles accelerated near to the speed of light. This emission arises in the decelerating blast wave of material identified in cosmological afterglows associated with GRBs, and has been used as a diagnostic to identify these afterglows in ZTF data<sup>12</sup>. The large isotropic equivalent luminosities and the long-lived nature of the radio/millimetre and X-ray emission, along with the fast X-ray variability<sup>21</sup>, however, separate AT2022cmc from the class of GRB afterglows and is in contrast with an off-axis GRB interpretation (however, an extremely long GRB lasting for a few days that mimics jetted TDEs remains a possibility)<sup>52</sup>. Direct multiwavelength comparisons between AT2022cmc and other energetic transients are shown in Fig. 2. In particular, data for millimetre-band previously observed transients include long-duration GRBs<sup>53–57</sup>, low-luminosity GRBs<sup>58,59</sup>, LFBOTs<sup>50,51</sup>, core-collapse supernovae<sup>60–64</sup> and TDEs<sup>5,9</sup>.

Extended Data Fig. 2 shows where AT2022cmc, in the first few days since observation, is placed in the optical transient parameter space. The peak luminosity and duration of AT2022cmc well separate it from most transient classes and are consistent with GRB afterglow observations. Figure 2c, more specifically, shows a comparison between the observer-frame optical light curve of AT2022cmc and GRB afterglows. The light curves are taken from the samples presented in refs. <sup>65–67</sup> and D.A.K. et al. (manuscript in preparation). They have initially been corrected for all line-of-sight extinction, potential host-galaxy and supernova contribution, and shifted to  $z = 1$  following a previous method<sup>65</sup>. Then, we determined the individual distance modulus  $m - M$ , where  $m$  is the apparent magnitude and  $M$  is the absolute magnitude, on the basis of the intrinsic spectral slope  $\beta$  of each afterglow to transform the light curves into absolute magnitudes. A luminous slow component at late time, as seen for AT2022cmc, has, to our knowledge, never been observed for GRB afterglows. The light curve of the prototypical LFBOT AT2018cow<sup>44</sup> is also shown in Fig. 2c for comparison.

### Relativistic evolution of the radio source

Our goal for this section is to constrain the shock radius  $r$  from the self-absorbed part of the radio spectrum and then constrain the Lorentz factor of the emitting plasma and hence the beaming angle of the jet. We take the standard approach in modelling the synchrotron afterglow from relativistic jets<sup>24</sup>. See, for example, refs. <sup>26,68–72</sup> for extended discussions of the hydrodynamics of the stellar debris and the accretion disk, which are not discussed here. All quantities (time, frequency, energy, luminosity, and so on) in this section are defined in the rest frame of the SMBH or the host galaxy. It is straightforward to convert these quantities to the observer’s frame by multiplying the relevant cosmological factors for a given redshift.

Consider a jet with an isotropic equivalent energy of  $E_{\text{iso}} \approx 10^{53} - 10^{54} \text{ erg}$  (as implied by the X-ray emission) and a hydrogen number density ahead of the forward shock of  $n_0$ . From energy conservation, we write

$$E_{\text{iso}} \approx \frac{4\pi}{3} n_0 r^3 \Gamma^2 m_p c^2, \quad (1)$$

where  $\Gamma$  is the Lorentz factor of the shock-heated gas,  $m_p$  is the proton mass, and the numerical pre-factor depends on the radial density profile of the medium (here taken to be uniform, but the shock radius depends very weakly on this profile). The magnetic field strength in the comoving frame of the shocked region is given by the Rankine–Hugoniot jump conditions

$$\frac{B^2}{8\pi} = 4\Gamma^2 \epsilon_B n_0 m_p c^2, \quad (2)$$

# Article

where  $\epsilon_B$  is the fraction of the thermal energy shared by the magnetic fields. Combining equations (1) and (2), we obtain the magnetic field strength

$$B \approx 2\sqrt{6} \left( \frac{E_{\text{iso}} \epsilon_B}{r^3} \right)^{1/2}. \quad (3)$$

The isotropic-equivalent specific luminosity at the self-absorption frequency  $\nu_a$  (defined where the absorption optical depth  $\tau(\nu_a) = 1$ ) is given by

$$L_{\nu_a} \approx 4\pi^2 \Gamma^{-2} r^2 I_{\nu_a}, \quad (4)$$

where we have considered an emitting area of  $\pi r^2$  as a result of relativistic beaming and the specific intensity on the surface area  $I_{\nu_a}$  to be related to that in the plasma's comoving frame  $I'_{\nu_a}$  by a Lorentz transform  $I_{\nu_a} \approx \Gamma^3 I'_{\nu_a}$ . Because the plasma is optically thick, the intensity in the comoving frame is given by the Planck function and the plasma temperature of the electrons responsible for the absorption is  $T_e \approx \gamma_a m_e c^2 / k_B$  ( $m_e$  and  $k_B$  being the electron mass and Boltzmann constant, respectively), that is,

$$I'_{\nu_a} \approx 2\nu_a^2 \gamma_a m_e, \quad (5)$$

and the frequency in the comoving frame is given by Lorentz transform  $\nu'_a \approx \nu_a / \Gamma$ . The electron Lorentz factor  $\gamma_a$  is related to the emitting frequency  $\nu_a$  by

$$\nu_a \approx \Gamma \gamma_a^2 \frac{3eB}{4\pi m_e c}, \quad (6)$$

where  $e$  is the charge of the electron. We plug the expressions for  $B$ ,  $\gamma_a$ , and  $I_{\nu_a}$  into equation (4) and obtain

$$L_{\nu_a} \approx r^{11/4} \Gamma^{-3/2} \nu_a^{5/2} E_{\text{iso}}^{-1/4} \epsilon_B^{-1/4} \times \frac{23.2 m_e^{3/2} c^{1/2}}{e^{1/2}}. \quad (7)$$

The strong dependence of  $L_{\nu_a}$  on  $r$  means that it is possible to constrain the shock radius  $r$  using observed values of  $L_{\nu_a} \approx 10^{33} \text{ erg s}^{-1} \text{ Hz}^{-1}$  and  $\nu_a \approx 10^{11} \text{ Hz}$ . Putting this all together, the result is

$$r \approx 0.22 \text{ pc} \times L_{\nu_a,33}^{4/11} \nu_{a,11}^{-10/11} \Gamma_1^{-6/11} E_{\text{iso},53}^{1/11} \epsilon_{B,-2}^{1/11}, \quad (8)$$

where we have used, for notational brevity,  $Q = 10^Q$  in cgs units (for example,  $\Gamma = 10\Gamma_1$ ). We also know that the radio fluxes evolved on a timescale of  $t_{\text{var}} \approx r / (2\Gamma^2 c) \approx 1 \text{ d}$ , and this constrains the Lorentz factor of the emitting plasma,

$$\Gamma \approx 12 (t_{\text{var}} / \text{day})^{11/16} L_{\nu_a,33}^{1/4} \nu_{a,11}^{-5/8} E_{\text{iso},53}^{1/16} \epsilon_{B,-2}^{1/16}. \quad (9)$$

Thus, this confirms the relativistic jet picture. The shock radius can be plugged back into equation (1) to estimate the density of the gas ahead of the shock to be  $n_0 \approx 0.5 \text{ cm}^{-3}$  and the magnetic field strength in the comoving frame of the emitting region to be  $B \approx 0.3 \text{ G}$ , under our fiducial values of  $L_{\nu_a,33} = \nu_{a,11} = E_{\text{iso},53} = \epsilon_{B,-2} = 1$ ; however, the values of  $n_0 \propto (E_{\text{iso}} / \epsilon_B)^{1/2}$  and  $B \propto (E_{\text{iso}} \epsilon_B)^{5/16}$  are uncertain by about an order of magnitude, owing to their stronger dependence on  $E_{\text{iso}}$  and  $\epsilon_B$ .

Next, we address the origin of the emitting plasma. When the jet reaches the deceleration radius, a strong reverse shock (RS), which is mildly relativistic in the comoving frame of the unshocked jet, heats up most of the material inside the jet<sup>73</sup>. About half of the energy is deposited in the RS-heated gas and the other half in the gas swept up by the forward shock (FS). In the rest frame of the black hole, the FS-heated gas has a specific energy  $\Gamma^2 m_p c^2$  per proton (due to bulk plus random motions), whereas the RS-heated gas has  $\Gamma m_p c^2$  per proton (mainly

due to bulk motion). This means (i) there are many more electrons in the RS-heated region than in the FS-heated region by a factor of  $\sim \Gamma$  and (ii) electrons have lower Lorentz factors in the RS-heated region than in the FS-heated region by a factor of  $\sim \Gamma$ . These low Lorentz factor electrons in the RS-heated region, with a typical Lorentz factor of  $\gamma_{\text{RS}} \approx 0.5 \epsilon_e m_p / m_e \approx 100$  (where  $\epsilon_e \approx 0.1$  is the fraction of thermal energy in relativistic electrons), dominate the emission and absorption at radio frequencies. Indeed, their characteristic synchrotron frequency is  $\nu_{\text{RS}} \approx 10^{11} \text{ Hz}$  under our fiducial parameters (see equation (6)). The high-Lorentz-factor electrons in the FS region dominate the red component of the optical emission, although electrons in the RS region may also contribute a substantial fraction (depending on the Lorentz factor distribution of the shock-accelerated electrons).

Finally, we use the peak isotropic X-ray luminosity  $L_X \approx 3 \times 10^{47} \text{ erg s}^{-1}$  to constrain the spin of the SMBH. Under the assumption that the jet is powered by the Penrose–Blandford–Znajek mechanism<sup>20</sup>, the maximum jet power is given by  $L_{\text{max}} \approx \eta_{\text{BZ}} \dot{M} c^2$ , where  $\dot{M}$  is the accretion rate and the maximum power is achieved when the magnetic fields near the event horizon reach the limiting strength beyond which the magnetic pressure will expel the accreting gas—the result is a magnetically arrested disk (MAD). In the MAD limit, the jet efficiency is given by<sup>74</sup>

$$\eta_{\text{BZ}} \approx \frac{\kappa_B \phi_B^2}{4\pi} f(a), \quad f(a) = \Omega_H^2 (1 + 1.38 \Omega_H^2 - 9.2 \Omega_H^4), \quad (10)$$

where  $\kappa_B \approx 0.05$  depends weakly on the magnetic field geometry,  $\phi_B \approx 50$  is the dimensionless magnetic flux,  $\Omega_H = a / (2r_H)$  is the dimensionless angular frequency of the event horizon,  $r_H = 1 + \sqrt{1 - a^2}$  is the radius of the outer event horizon in units of the gravitational radius  $GM/c^2$ , and  $a$  is the dimensionless spin parameter. For a jet Lorentz factor of  $\Gamma \approx 10$ , the beaming fraction of the X-ray emission is  $f_b \approx 10^{-2}$  (a much smaller beaming factor is unlikely). For a radiative efficiency of 10%, we infer the beaming-corrected peak jet power to be  $L_{\text{jet}} \approx 3 \times 10^{46} \text{ erg s}^{-1}$ , although the actual peak power may be larger because (i) a fraction of the radiation is probably in the  $\gamma$ -ray band and (ii) our earliest X-ray observation may have missed the peak of the light curve.

Hydrodynamic simulations of TDEs show that the rate at which the stellar debris falls back towards the black hole is generally less than  $10 M_\odot \text{ yr}^{-1}$ —this value corresponds to the peak fallback rate for a  $M_* = 3 M_\odot$  main-sequence star disrupted by a  $M = 10^6 M_\odot$  SMBH<sup>75</sup>. Even though the peak fallback rate depends on the masses of the star and SMBH  $\dot{M}_{\text{fb,peak}} \propto M_*^{1/2} M^{-1/2}$ , at highly super-Eddington accretion rates, most of the fallback material is blown away by the radiation pressure instead of accreted by the SMBH<sup>76</sup>. Therefore, we generally expect the accretion rate to be  $\dot{M} < 10 M_\odot \text{ yr}^{-1}$ . On the basis of the above arguments, we constrain

$$f(a) \geq \frac{L_{\text{jet}}}{\dot{M} c^2} \frac{4\pi}{\kappa_B \phi_B^2}, \quad (11)$$

which provides a lower limit on the black hole spin parameter  $a \geq 0.3$  for  $L_{\text{jet}} = 3 \times 10^{46} \text{ erg s}^{-1}$  (for the case of AT2022cmc). We also obtain  $a \geq 0.7$  for  $L_{\text{jet}} = 3 \times 10^{47} \text{ erg s}^{-1}$ , as is the case of Swift J1644+57 whose peak X-ray luminosity is 10 times higher.

## Redshift

The redshift of AT2022cmc was first determined from the VLT/X-shooter spectrum (Methods section ‘Very Large Telescope’). The spectrum shows a single emission line that we identify as [O III]  $\lambda 5008$  at a redshift of  $z = 1.1933$ , as previously reported via GCN<sup>17</sup>. At a similar redshift, we detect absorption features of Al III, Fe II, Mn II, Mg II, Mg I and Ca II. The average redshift of these features is  $z = 1.19325 \pm 0.00024$ . However, we notice that there are two velocity components in these features, one at  $z = 1.19318 \pm 0.00019$  that dominates the absorption of the Al III, Fe II, Mn II, Mg II and Mg I lines and one at  $z = 1.19361 \pm 0.00010$ , which

dominates in the Ca II lines. The velocity difference between these lines is  $\sim 130 \text{ km s}^{-1}$ . Extended Data Table 1 displays the equivalent width measurements of the absorption lines.

### Spectral line strength analysis

We have performed a line strength analysis<sup>77</sup> on the VLT/X-shooter spectrum (Methods section ‘Very Large Telescope’), which compares the strength of the absorption features measured in our spectrum with those of a sample of GRB afterglow spectra. GRBs are typically found to be located well within star-forming host galaxies, and their spectra probe light paths from deep within their hosts. The spectral features imprinted in GRB afterglow spectra have been found to be at hundreds of pc or even kpc from the GRB, so they are probing the overall material in the host galaxy and not necessarily their very local environment. This is similar to what one would expect from the path probed by a jet emitted from the core of an active and similarly star-forming galaxy, but is in contrast to what one sees in the spectra of damped Lyman  $\alpha$  (DLA) absorbers in the line of sight of quasars, which probe the outskirts of intervening galaxies and show much weaker features. Extended Data Fig. 3 shows a line strength diagram, in which the average feature strength of the GRB sample is shown with a thick black line and the  $1\sigma$  deviation in the log-normal space with dotted lines. The features measured in the AT2022cmc spectrum (shown in red) closely resemble the average strengths seen in GRB spectra. Only the Ca II lines show a somewhat lower strength than average, which, as mentioned before, also display a slightly different velocity component which means that they are probably produced in a different region as the rest of the lines (this is commonly seen in GRB spectra). The overall line strength parameter (LSP) compares the line strengths with the sample using a single number. In this case we obtain  $\text{LSP} = -0.20 \pm 0.25$  (zero would be the average and  $\pm 1$  the  $\pm 1\sigma$  deviation), which implies that the lines are just slightly weaker than the average, equivalent to those of the 42nd percentile in the sample.

The fact that the spectral features are similar to those seen in GRBs implies that the environment density and composition is probably not unlike the one in which these stellar explosions are produced. Because GRBs are known to happen well within star-forming galaxies, at a median projected offset of 1.3 kpc from the core of the galaxy<sup>78,79</sup>, the observation of a similar environment in the case of AT2022cmc points towards this transient happening well within a galaxy of a similar type.

### Host galaxy

The field of AT2022cmc was observed in  $u$  and  $r$  bands with the MegaPrime camera at the 3.58-m Canada–France–Hawaii Telescope between 2015 and 2016. We retrieved the science-ready level-3 data from the Canadian Astronomy Data Centre. We used aperture photometry at the position of the optical transient (aperture radius:  $1.5 \times \text{FWHM}$  of the stellar point spread function, PSF) to try measure the brightness of the host galaxy. Once an instrumental magnitude was established, it was calibrated against the brightnesses of several stars from a cross-matched Sloan Digital Sky Survey (SDSS) catalogue. The host evaded detection in both bands. Using forced photometry, we measure  $>24.19$  and  $>24.54$  mag in  $u$  and  $r$  band;  $3\sigma$  confidence; not corrected for Milky Way extinction), respectively.

From the Swift X-ray Telescope (XRT)<sup>80</sup> data analysis of AT2022cmc (see Methods section ‘Neil Gehrels Swift Observatory’), we estimate the equivalent neutral hydrogen column density of the host galaxy to be  $N_{\text{H}} < 6.4 \times 10^{21} \text{ cm}^{-2}$  (90% confidence). The presence of a counterpart in the ultraviolet, first detected with Swift on 2022 February 23 (day 5.3) with magnitude  $UWM2 = 21.30 \pm 0.25$  mag, provides additional evidence that the host galaxy extinction is significantly lower than in the case of Swift J1644+57 ( $A_{\text{V}} \approx 4.5$  mag, corresponding to an equivalent neutral hydrogen column density of  $N_{\text{H}} \approx 1 \times 10^{22} \text{ cm}^{-2}$ )<sup>3</sup>. However, our spectral line strength analysis (Methods section ‘Spectral line strength analysis’) yielded results similar to most GRBs from stars collapsing

to black holes, which suggests that AT2022cmc happened well within its host galaxy.

To put a limit on the host galaxy properties, we create a possible model for the spectral energy distribution of the host with the software package Prospector (<https://github.com/bd-j/prospector>) version 0.3<sup>81</sup>. Prospector uses the Flexible Stellar Population Synthesis (FSPS) code<sup>82</sup> to generate the underlying physical model and python-fsps<sup>83</sup> to interface with FSPS in python. The FSPS code also accounts for the contribution from the diffuse gas based on the Cloudy models<sup>84</sup>. Furthermore, we assumed a Chabrier initial mass function<sup>85</sup> and approximated the star-formation history (SFH) by a linearly increasing SFH at early times followed by an exponential decline at late times (functional form  $\text{texp}(-t/\tau)$ ). The model was attenuated with the Calzetti dust model<sup>86</sup>. The priors were set identical to ref.<sup>87</sup>: uniform galaxy mass ( $(5-13) \log(M_*/M_{\odot})$ ), uniform  $V$ -band optical depth ( $0-8\tau_{\text{V}}$ ), uniform stellar metallicity ( $(-2-0.5) \log(Z/Z_{\odot})$ ), log-uniform age of the star-formation episode,  $t_{\text{age}}$  ( $(0.001-13.8)t_{\text{age}} \text{ Gyr}^{-1}$ ), log-uniform e-folding time-scale of the star-formation episode ( $(0.1-100)\tau \text{ Gyr}^{-1}$ ).

Upper limits on the host galaxy luminosity lead to upper limits (at 95% confidence) on galaxy mass of  $\log M/M_{\odot} < 11.2$ , star-formation rate of  $135 M_{\odot} \text{ yr}^{-1}$ , and an absolute magnitude of  $M_{\text{r}} > -21.4$  mag (corrected for Milky Way extinction but not corrected for host attenuation). These upper limits are not strongly constraining, hence deeper imaging is needed in the future.

We use a galaxy bulge–black hole mass relation<sup>88</sup> and the upper limit on the AT2022cmc galaxy mass to obtain an upper limit on SMBH mass of  $M_{\text{BH}} < (4.7 \times 10^8) M_{\odot}$ . The SMBH mass can also be (weakly) constrained based on the Hill’s mass argument—a main-sequence star of less than a few solar masses can be tidally disrupted outside the event horizon of a rapidly spinning SMBH of mass  $\lesssim 10^9 M_{\odot}$  (ref.<sup>89</sup>). The upper limit also implies an Eddington luminosity of  $L_{\text{Edd}} < 6 \times 10^{46} \text{ erg s}^{-1}$ . This Eddington limit is an order of magnitude lower than the NICER soft X-ray isotropic equivalent luminosity<sup>13</sup> of  $\sim 2.6 \times 10^{47} \text{ erg s}^{-1}$ , which confirms that a jet strongly beamed towards the Earth is potentially responsible for the X-ray emission.

Observations with HST and, possibly, with the James Webb Space Telescope, should be able to unveil the faint host galaxy once the transient has disappeared.

### Detectability of GRB 110328A (Swift J1644+57) at $z \approx 1.2$

The Swift J1644+57 event was first detected as a GRB<sup>90</sup>, labelled GRB 110328A, by the Neil Gehrels Swift Observatory (see Methods section ‘Neil Gehrels Swift Observatory’). Placing GRB 110328A at the distance of AT2022cmc would result in an onboard trigger by Swift/BAT in only the most optimal cases. It would require a maximal duration exposure (30 min) image trigger with the source near the centre of the BAT-coded field of view, and around the few-hour period when GRB 110328A was at its brightest. Assuming a uniform sky distribution of GRB 110328A-like sources at  $z = 1.19325$  and a normal Swift observing schedule, we find that fewer than 5% of such events would generate an onboard trigger. However, note that both Swift J2058+05 and Swift J1112-82 were found in automated ground analysis of Swift/BAT data with significantly longer exposures (days), which would allow the discovery of the Swift J1644+47 GRB at  $z \approx 1.2$ .

### Millimetre survey rate predictions

We consider the rate of AT2022cmc-like transients expected to be detected in two millimetre-band surveys: the South Pole Telescope Third Generation (SPT-3G) survey<sup>91</sup>, and the Stage-4 CMB experiment<sup>92</sup> (CMB-S4). SPT-3G is an ongoing 5.5-yr survey covering an area of  $1,500 \text{ deg}^2$  ( $\sim 3.6\%$  of the sky) at a frequency of 95 GHz. The observations have a single-epoch root-mean-square (r.m.s.) noise of 6 mJy and  $-1/2$ -d cadence<sup>93</sup>. CMB-S4 is likely to begin observations in 2029. Among the surveys it will be performing, CMB-S4 will observe over half the sky over a frequency range of 30–280 GHz and a daily cadence for seven

years. The 93 GHz, single-epoch r.m.s. sensitivity is 6 mJy. To determine the rate of AT2022cmc-like events in these surveys, we assume a typical  $\sim 100$  GHz luminosity of  $\sim 10^{32}$  erg s $^{-1}$  Hz $^{-1}$  for at least  $\sim 20$  d. If we define a detected source as one with a  $5\sigma$  single-epoch detection ( $\sim 30$  mJy for both surveys), AT2022cmc-like events will be detectable to  $D_L \approx 1.67$  Gpc in either survey. From the detection of three jetted TDEs in  $\sim 10$  yr of Swift observations<sup>2–8</sup>, the on-axis jetted TDE rate is  $\sim 0.03^{+0.04}_{-0.02}$  Gpc $^{-3}$  yr $^{-1}$  (ref.<sup>11</sup>). Hence, over the full survey duration, we expect a mean of  $\sim 0.05^{+0.05}_{-0.03}$  ( $0.9^{+0.9}_{-0.4}$ ) events in the SPT-3G (CMB-S4) survey. More events will be detected if the single epoch images are stacked. Because the observed 100-GHz light curve is approximately flat for at least 20 d, we conservatively assume 10-d bins. Then we expect a mean of  $\sim 0.5^{+0.5}_{-0.3}$  ( $5^{+5}_{-3}$ ) events in the SPT-3G (CMB-S4) survey. While these predictions are approximate, we generally expect millimetre rates a factor of  $\mathcal{O}(10)$  higher than those for the Swift J1644+57<sup>94</sup> because the 100-GHz luminosity of AT2022cmc is a factor of  $\sim 10$  higher than that of Swift J1644.

### Optical rates estimates

To estimate the rates of AT2022cmc-like events using ZTF survey data, we use `simsurvey`<sup>95</sup> to simulate AT2022cmc-like light curves and estimate the efficiency of their recovery with a filter consistent with ZTFReST<sup>12,37</sup>. Using the survey bandpasses and limiting magnitudes calculated for each exposure, we injected light curves uniformly in comoving volume to a distance of  $z = 1.2$ , consistent with the distance of AT2022cmc. The light curves are reddened by Milky Way extinction. To flag them as ‘recovered’, we required (i) at least two detections with  $>3\sigma$  significance, at least one of which must have  $>5\sigma$  significance, (ii) a measured fade rate faster than  $0.3$  mag d $^{-1}$  in each band, and (iii)  $>3$  h of time separation.

We provide estimated rates under two assumptions. The first is that AT2022cmc is the only example in our dataset and only when the real-time capabilities of ZTFReST were in place, starting in August 2020. This yields an on-axis, jetted TDE rate of  $0.02^{+0.04}_{-0.01}$  Gpc $^{-3}$  yr $^{-1}$  (95% confidence), showing strong consistency with the established rate<sup>11</sup> from Swift:  $\sim 0.03^{+0.04}_{-0.02}$  Gpc $^{-3}$  yr $^{-1}$ .

A heretofore unidentified transient has been previously reported<sup>96</sup>, ZTF19aanhtzz/AT2019aacu, which shows some similar properties to AT2022cmc, including the rapid decay and lack of confirmed host. In this case, the rate estimated would be  $0.04^{+0.02}_{-0.02}$  Gpc $^{-3}$  yr $^{-1}$ . However, this transient was found during archival searches and no follow-up observations were triggered to look for a potential bright X-ray or radio counterpart. For this reason, we cannot consider ZTF19aanhtzz a jetted TDE candidate. This fact further confirms the need for real-time data analysis frameworks capable of identifying rapidly evolving transients to enable prompt follow-up.

### Optical light curve modelling

To analyse the event, we have proposed a two-component model. The model consists of a time-dependent power-law component and a static blackbody contribution. The spectral flux density  $F_\nu$  (in the rest-frame) is given by

$$F_\nu = F_{\text{pl}} \left( \frac{\nu}{10^{15} \text{ Hz}} \right)^\beta 10^{\alpha(t-t_0)} + F_{\text{bb}}(\nu, T, L_{\text{bb}}), \quad (12)$$

where  $t_0$  is the brightest time of the event, and  $F_{\text{pl}}$  is the reference spectral flux density for  $\nu = 10^{15}$  Hz at  $t = t_0$ . In the above,  $F_{\text{bb}}$  is the contribution of a blackbody at temperature  $T$  with a luminosity  $L_{\text{bb}}$ .

We have used Bayesian inference techniques to analyse the optical data from 2022 February 12 onward, with a Gaussian likelihood in AB magnitude space. The blackbody temperature  $T$ , luminosity  $L_{\text{bb}}$  and the reference spectral flux density  $F_{\text{pl}}$  are assigned log-uniform priors. Therefore, we can assign uniform priors of  $\log_{10}(T/1 \text{ K}) = \mathcal{U}(3, 6)$ ,  $\log_{10}(L_{\text{bb}}/(1 \text{ erg s}^{-1})) = \mathcal{U}(40, 50)$  and  $\log_{10}(F_{\text{pl}}/(1 \text{ erg s}^{-1} \text{ Hz}^{-1})) = \mathcal{U}(10, 80)$ . The parameters  $\beta$  and  $\alpha$  are assigned uniform priors, with  $\beta = \mathcal{U}(-10, 0)$

and  $\alpha = \mathcal{U}(-100 \text{ d}^{-1}, 0 \text{ d}^{-1})$ . The Bayesian evidence is estimated, and the posterior distribution is sampled with the nested sampling algorithm implemented in `PyMultinest`<sup>97,98</sup>.

The blackbody’s temperature is inferred to be  $30,000^{+900}_{-800}$  K and the luminosity  $L_{\text{bb}}$  is inferred to be  $10^{45.53 \pm 0.02}$  erg s $^{-1}$ ; both are median values and 90% credible regions (see Extended Data Fig. 4 for the parameter estimates). This implies a blackbody photospheric radius of  $r_{\text{ph}} = [L_{\text{bb}}/(4\pi\sigma_{\text{SB}}T_{\text{bb}}^4)]^{1/2} \approx 2 \times 10^{15}$  cm, where  $\sigma_{\text{SB}}$  is the Stefan–Boltzmann constant. This large radius suggests that the emission comes from an outflow instead of the surface of an accretion disk—the Keplerian orbital period at a distance of  $2 \times 10^{15}$  cm would be  $1.5 \text{ yr} (M/10^6 M_\odot)^{-1/2}$  which is too long for any plausible black hole mass  $M$ . For the power-law contribution,  $F_{\text{pl}} = 10^{30.51 \pm 0.02}$  erg s $^{-1}$  Hz $^{-1}$ ,  $\beta = -1.32 \pm 0.18$ , and  $\alpha = -0.48 \pm 0.02 \text{ d}^{-1}$  (again the median values and 90% credible regions). The estimate of  $\beta$  is consistent with the prediction  $\beta \in [-1.5, -0.5]$  on the basis of synchrotron afterglow theory.

We have further allowed the value of  $\beta$  to be time-dependent. For the linear case, we assumed  $\beta = \beta_0 + \beta_1(t - t_0)$ , with priors  $\beta_0 = \mathcal{U}(-10, 0)$  and  $\beta_1 = \mathcal{U}(-10 \text{ d}^{-1}, 10 \text{ d}^{-1})$ . Similarly, for the quadratic case, we assumed  $\beta = \beta_0 + \beta_1(t - t_0) + \beta_2(t - t_0)^2/2$  with priors  $\beta_0 = \mathcal{U}(-10, 0)$ ,  $\beta_1 = \mathcal{U}(-10 \text{ d}^{-1}, 10 \text{ d}^{-1})$  and  $\beta_2 = \mathcal{U}(-1 \text{ d}^{-2}, 1 \text{ d}^{-2})$ . However, the resulting logarithms of the Bayesian evidence (linear in time:  $-267.95 \pm 0.18$ , quadratic in time:  $-270.25 \pm 0.19$ ) are lower than the time-independent case ( $-263.55 \pm 0.17$ ), where the uncertainty is estimated with the negative relative entropy<sup>99</sup>. Therefore, there is no evidence that  $\beta$  varies significantly in time.

### A possible connection between jetted TDEs and luminous featureless TDEs

A class of TDEs has recently been identified<sup>31</sup> that are overluminous ( $M_r \approx -22$  mag at peak, Extended Data Fig. 5) and, unlike most TDEs, do not show any broad features in their optical spectra. A physical explanation for the nature of this class of luminous and featureless TDEs is yet to be proposed. Multiwavelength follow-up data of luminous featureless TDEs are still sparse, therefore the presence of jets cannot be excluded.

Our observations of AT2022cmc revealed remarkably consistent characteristics between its thermal (blue, slowly evolving) component and the class of luminous featureless TDEs from the ref.<sup>31</sup> sample. First, broad emission or absorption features are not observed in any optical or near infrared spectra of AT2022cmc (Fig. 3), neither during the rapidly evolving initial flare nor in the late-time blue plateau. This is consistent with observations of the jetted TDE candidate Swift J2058+05, whose (low signal-to-noise ratio) optical spectra were dominated by a blue, featureless continuum<sup>8</sup>.

Second, taking the time when the thermal component began to dominate in the optical ( $\sim 12$  d from the first detection) with luminosity  $M_r \approx -22.2$  mag (corresponding to the rest-frame UV band), the luminosity of AT2022cmc falls near to the observed peak luminosities of featureless TDEs that were found to be consistently brighter than TDEs with features<sup>31</sup> (Extended Data Fig. 5).

We therefore suggest that a connection probably exists between TDEs that generate relativistic jets and the class of luminous featureless TDEs. Deep radio observations of these transients will be able to probe the presence of a jet at all viewing angles. This connection between jetted TDEs and luminous featureless TDEs, if confirmed, will enable new studies of jet formation in TDEs and system geometry. Understanding these particularly luminous transients may be the only way to map the rate of TDEs as a function of redshift beyond  $z \approx 0.4$ , which represents the approximate limit for spectroscopic classification of  $M \approx -20$  mag transients with large 8-m-class optical telescopes.

### Observations and data processing

**Palomar 48-inch Samuel Oschin Telescope.** AT2022cmc was observed using data acquired by the ZTF camera on the 48-inch Samuel Oschin Telescope at Palomar Observatory. Observations

of AT2022cmc were conducted as part of the ZTF public survey, the Caltech high-cadence survey, and the Partnership extragalactic survey<sup>100,101</sup>. The images were processed in real time through the ZTF reduction and image subtraction pipelines<sup>102</sup> at the Infrared Processing and Analysis Center (IPAC). PSF forced photometry was obtained via the ZTF forced-photometry service<sup>102</sup> at IPAC.

**Liverpool Telescope.** Imaging of AT2022cmc using the IO:O camera on the 2-m robotic Liverpool Telescope<sup>103</sup> (LT) was obtained on several occasions beginning from 2022 February 15. Observations were conducted in Sloan Digital Sky Survey (SDSS)  $g, r, i$ , and  $z$  filters. We down-loaded images reduced using the standard LT pipeline, and performed our own astrometric alignment and stacking. Exposures showing major tracking errors or poor transparency due to cloud cover were discarded. Many exposures suffered from a failure of the IO:O shutter to close at the end of the observation, producing readout streaks across the detector, but the region around the transient was free of contamination and no discernible impact on the quality of relative photometry of nearby stars was observed, so these exposures were retained. Photometry of the transient was measured with a custom IDL routine using seeing-matched aperture photometry fixed at the transient location, and calibrated relative to a set of SDSS secondary standard stars in the field. Photometry is presented in Supplementary Table 1.

**Hubble Space Telescope.** The location of AT2022cmc was observed with the Hubble Space Telescope (HST) beginning at 2022 March 8 20:12:21 UT (-25.4 d after observation). The field was imaged with the Wide-Field Camera 3 (WFC3) in the F606W ultraviolet and visible (UVIS) and F160W (infrared) filters for 1,044 s and 1,059 s, respectively. AT2022cmc was well detected in both bands. We measured AB magnitudes of F606W =  $21.82 \pm 0.03$  mag and F160W =  $22.64 \pm 0.05$  mag (Fig. 1; Supplementary Table 1). The source appeared unresolved, without obvious evidence for extended emission directly underneath.

On the basis of the astrometry of the WFC3 images, the coordinates of AT2022cmc could be placed at J2000 right ascension  $\alpha = 13$  h 34 min 43.201 s and declination  $\delta = +33^\circ 13' 00.648''$  (see also Methods section ‘Very Large Array’).

**Very Large Array.** AT2022cmc was observed with the Karl G. Jansky Very Large Array (VLA)<sup>104</sup> on nine occasions between 2022 February 15 and 2022 March 31 under programme 2022A-405 (principal investigator (PI): D.A.P.). All visits included an integration using the X-band receivers (8–12 GHz); several of them additionally involved observations using other receivers: typically Ku (12–18 GHz) and Ka (30.5–38.5 GHz), although on 2022 February 18 complete frequency coverage from 5–48 GHz using the C, X, Ku, K, Ka, and Q bands was obtained. All observations used the 3-bit samplers and full polarization. The target source is within three degrees of the standard calibrator 3C286 (J1331+3030); this source was used as the phase calibrator, as well as the flux and bandpass calibrator, for all observations. Most observations were taken during the reconfiguration of the array from BnA to A.

Data were reduced using standard synthesis imaging techniques using the Astronomical Image Processing System (AIPS). Because the observations were taken with the VLA in a high-resolution configuration, standard models of 3C286 were required to derive the antenna delays, bandpasses and gains. Radio-frequency interference (RFI) was removed by flagging amplitudes higher than about  $5\sigma$ . Less than 1% of the data were removed by this editing.

Owing to the long baselines, atmospheric phase instabilities can cause substantial decorrelation in the image at high frequencies. Fortunately, the source was bright enough that phase self-calibration could be utilized to remove the atmospheric phase. This was done by coherently summing over both polarizations and 16 spectral windows (2.048-GHz bandwidth) for 24 s, providing enough signal-to-noise ratio to enable a phase solution using a point-source model at the known

location of the transient. This process was required only for the K-band, Ka-band and Q-band observations. Flux densities were determined with the AIPS task JMFIT and are reported in Supplementary Table 2 and Extended Data Fig. 1.

The A-configuration Ku observations provide a highly accurate measurement of the source location: standard equinox J2000 right ascension  $\alpha = 13$  h 34 min 43.2023 s and declination  $\delta = +33^\circ 13' 00.6565''$  (uncertainty 0.01").

**Submillimeter Array.** AT2022cmc was regularly observed with the Submillimeter Array (SMA) under standard observing time (project 2021B-S013; PI: A.Y.Q.H.) with follow-up observations under Director Discretionary Time/Target of opportunity programme (project 2021B-S071; PI: A.Y.Q.H.), in the Compact and Extended configurations. Observations were taken during a period of engineering shut-down, so the number of antennas available ranged from three to six, and cover a range of baseline lengths from 16.4 m to 181.6 m. The quasars 1310+323 and 1159+292 were used as primary phase and amplitude gain calibrators, respectively, with absolute flux calibration performed by nightly comparison to Ceres or (maser-free) continuum observations of the emission-line star MWC349a. The quasars 1159+292 and/or 3C279 were used for bandpass calibration. Data were calibrated in IDL using the MIR package. Additional analysis and imaging were performed using the MIRIAD package. Given that the target was a point source, and often only three antennas were available, fluxes were derived directly from the calibrated visibilities, but the results agree well with flux estimates derived from the dirty and CLEANed images when the data quality and UV coverage were adequate.

SMA results are summarized in Supplementary Table 2.

**Northern Extended Millimeter Array (NOEMA).** We obtained seven epochs of observations of AT2022cmc with NOEMA in extended 11 and 12 antenna A configuration spanning band 1 (100 GHz), band 2 (150 GHz), and band 3 (230 GHz) under the target-of-opportunity programme W21BK (PI: A.Y.Q.H.); this programme is still in progress. The primary flux calibrators were MWC349 and LKHA101, and the time-dependent phase and amplitude calibrators were the quasars J1310+323 and 1315+346. The data reduction was done with the CLIC software (GILDAS package, <https://www.iram.fr>). Dual-polarization UV tables were written for each of the receiver sidebands. The resulting calibrated UV tables were analysed in the MAPPING software (also from the GILDAS package) and point-source UV plane fits were performed.

NOEMA results are also summarized in Supplementary Table 2.

**JCMT SCUBA-2 submillimetre observations.** Submillimetre observations of AT2022cmc were performed simultaneously at 850  $\mu$ m (350 GHz) and 450  $\mu$ m (670 GHz) on two nights using the Submillimetre Common-User Bolometer Array 2 (SCUBA-2) continuum camera<sup>105</sup> on the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii. The SCUBA-2 data were analysed in the standard manner using the 2021A version of Starlink<sup>106</sup>; this used version 1.7.0 of SMURF<sup>107</sup> and version 2.6-12 of KAPPA. Observations of the SCUBA-2 calibrator Arp 220 on both nights did not show any anomalous behaviours, so the current standard flux conversion factors were used for the flux normalization<sup>108</sup>. In the SCUBA-2 Dynamic Interactive Map-Maker, the Blank Field map was used for the AT2022cmc observations. The maps were smoothed using a matched filter. The r.m.s. background noise was determined in the central 2' of the map with the source excluded.

The SCUBA-2 observations of AT2022cmc are summarized in Supplementary Table 2. These expand on the preliminary results given in ref.<sup>109</sup>. There was a marginal detection of AT2022cmc at 850  $\mu$ m on both nights. This becomes more significant when all the data are combined, giving an 850- $\mu$ m flux density of  $4.9 \pm 1.3$  mJy per beam at a mid-point of 2022 February 21.510 UT.

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AT2022cmc was not detected at 450  $\mu\text{m}$  in the individual night observations or in the combined data; the r.m.s. measurement for the combined data is 10.5 mJy per beam at a mid-point of 2022 February 21 12:14 UTC.

JCMT results are also summarized in Supplementary Table 2.

**Upgraded Giant Metrewave Radio Telescope.** The event AT2022cmc was observed with the upgraded Giant Metrewave Radio Telescope (uGMRT) starting 2022 March 13 until 2022 March 26. The observations were taken in uGMRT band 5 (1,000–1,450 MHz) band 4 (550–900 MHz) and band 3 (250–500 MHz). The observations were two hours in duration, including overheads using a bandwidth of 400 MHz for bands 4 and 5, and of three hours in band 3 using a bandwidth of 200 MHz. 3C 286 was used as flux, bandpass and phase calibrator owing to its proximity with the event. The Common Astronomy Software Applications (CASA)<sup>110</sup> was used for analysing the data. The data were analysed in three major steps: flagging, calibration and imaging using a procedure laid out previously<sup>111</sup>.

The source was not detected in any of the bands (Supplementary Table 2), consistent with the expected optically thick evolution at sub-GHz frequencies based on the higher frequency radio data with the VLA. uGMRT results are also summarized in Supplementary Table 2.

**GROWTH-India Telescope.** The 0.7-m GROWTH-India Telescope (GIT), located at the Indian Astronomical Observatory (IAO), Hanle-Ladakh, started observing AT2022cmc at 19:30:26.78 UT on 2022 February 15. The data were acquired in SDSS  $g'$ ,  $r'$  and  $i'$  bands with multiple 300-s exposures. Data were downloaded in real time to our data processing unit at IIT Bombay. After a preliminary bias correction and flat fielding, and cosmic-ray removal with the Astro-SCRAPPY<sup>112</sup> package, all images acquired on the same night were stacked making use of SWarp<sup>113</sup>. The pipeline performs PSF photometry to obtain the instrumental magnitudes using standard techniques. These magnitudes were calibrated against the PanSTARRS DR1 catalogue<sup>114</sup> by correcting for zero points. Reported photometric uncertainties (Supplementary Table 1) are 1 $\sigma$  values.

**Blanco Telescope.** We conducted photometric observations of AT2022cmc using the Dark Energy Camera (DECam)<sup>115</sup> optical imager mounted at the prime focus of the Blanco telescope at Cerro Tololo Inter-American Observatory (programme ID 2022A-679480, PI: J.Z.; programme ID 2021B-0325, PI: A.R.). After standard calibration (bias correction, flat-fielding and astrometric alignment) was done by the NSF NOIRLab DECam Community Pipeline<sup>116</sup>, difference image photometry was obtained using the Photpipe pipeline<sup>117</sup>. Data are presented in Supplementary Table 1.

**Nordic Optical Telescope.** We obtained a series of  $gri$  photometry with the Alhambra Faint Object Spectrograph and Camera (ALFOSC; <http://www.not.iac.es/instruments/alfosc>) on the 2.56-m Nordic Optical Telescope (NOT) at the Observatorio del Roque de los Muchachos on La Palma (Spain) (programme ID: 64-501). The data were reduced with PyNOT (<https://github.com/jkrogager/PyNOT>), which uses standard routines for imaging data. We used aperture photometry to measure the brightness of the transient. Once an instrumental magnitude was established, it was calibrated against the brightness of several stars from a cross-matched SDSS catalogue. Data are presented in Supplementary Table 1.

The NOT spectrum in Fig. 3 was obtained with ALFOSC using Grism 4 which covers 3,200–9,600  $\text{\AA}$  at resolution  $R = 360$  and was reduced with Pypelt<sup>118</sup>.

**Palomar 60-inch telescope.** Photometry was also obtained on the robotic Palomar 60-inch telescope (P60)<sup>119</sup> equipped with the Spectral Energy Distribution Machine (SEDm)<sup>120,121</sup>. Photometry was produced

with an image-subtraction pipeline<sup>122</sup>, with template images from SDSS<sup>123</sup>. This pipeline produces PSF magnitudes, calibrated against SDSS stars in the field. Data are presented in Supplementary Table 1.

**Palomar 200-inch telescope.** We obtained one epoch of near-infrared observations from the Wide Infrared Camera on the Palomar 200 in telescope. On 2022 March 12 we performed a set of 18 dithered exposures of 45 s each in the J band (1.25  $\mu\text{m}$ ). We use standard optical reduction techniques in Python to reduce and co-add the images, using 2MASS point source catalogue for photometric calibration. We measure aperture photometry using photutils. Data are presented in Supplementary Table 1.

**Asteroid Terrestrial-impact Last Alert System.** We obtained broad-band ‘orange’ (5,560–8,260  $\text{\AA}$ ) and ‘cyan’ (4,120–6,570  $\text{\AA}$ ) light curves from the ATLAS<sup>124</sup> survey. These data are publicly available through the ATLAS Transient Science Server<sup>125</sup>. Detections of AT2022cmc were obtained only in the orange filter.

**Very Large Telescope.** The X-shooter spectrograph<sup>126</sup> installed on the European Southern Observatory (ESO) Very Large Telescope at Paranal Observatory (Chile) observed AT2022cmc on 2022 February 17 via programme 106.21T6 (PI: N.T.). The observations consisted of  $4 \times 1,200$  s in the UVB and visible arms and  $8 \times 600$  s in the near-infrared arm, using an ABBA nodding pattern. We used a 1'' slit in the UVB arm a 0.9'' in the visible and the 0.9'' JHslit in the near infrared, designed to block part of the  $K$ -band spectrum to reduce the noise in the  $J$  and  $H$  bands. The resulting spectral coverage goes from 3,000  $\text{\AA}$  to 21,000  $\text{\AA}$ . The data reduction was performed using the X-shooter pipeline<sup>127</sup> and additional scripts developed within the Stargate collaboration<sup>128</sup>. The spectrum is shown in Fig. 3.

**Gran Telescopio Canarias.** Near-infrared observations were performed using EMIR (Espectrógrafo Multiobjeto Infra-Rojo)<sup>129</sup> on three different epochs using programmes GTCMULTIPLE2H-21B (PI: A.d.U.P.) and GTCMULTIPLE2H-22A (PI: C.T.). The data reduction was performed using a custom-made pipeline that is based on shell scripts and IRAF procedures, which includes flat-fielding, background correction, bad-pixel masking, fine alignment and combination of images. Relative photometry was performed using multiple field stars from the UKIRT photometric catalogue. Data are presented in Supplementary Table 1.

**Calar Alto.** We obtained observations of ZTF22aaajecp/AT2022cmc under programme 22A-2.2-019 (PI: D.A.K.) on 2022 February 18 from 04:54:04 to 06:04:15 UT with CAFOS (Calar Alto Faint Object Spectrograph) mounted on the 2.2-m telescope at the Centro Astronómico Hispano-Alemán (CAHA), Almería, Spain<sup>130</sup>. Observing conditions were good but images were influenced by the bright Moon. Twelve images of 120-s integration time each were taken in the SDSS  $r'$  and  $i'$  bands. We reduced the images following standard procedures in IRAF (bias subtraction, flat-fielding, sky subtraction, shifting and co-adding). The source is well detected in both bands in each stacked image. Photometry was performed with respect to field stars from the SDSS photometric catalogue. Data are presented in Supplementary Table 1.

**W. M. Keck Observatory.** Spectroscopy was obtained with the DEIMOS (Deep Imaging Multi-Object Spectrograph) and LRIS (Low Resolution Imaging Spectrometer) instruments at the W. M. Keck Observatory.

DEIMOS spectroscopy covered the wavelength range 5,250–8,780  $\text{\AA}$ , consisting of three exposures of 900 s each starting at 2022 February 17 15:07 UTC. DEIMOS data were reduced using the Pypelt<sup>131</sup> data reduction pipeline. The spectrum had low signal-to-noise ratio, but the transient was detected over the full wavelength range<sup>132</sup>. Absorption lines, first identified with VLT/X-shooter, were found and interpreted at 6,132  $\text{\AA}$ , 6,148  $\text{\AA}$  as the Mg II 2,796  $\text{\AA}$ , 2,803  $\text{\AA}$  lines and the absorption lines at

5,671 Å, 5,702 Å as the Fe II 2,586 Å, 2,600 Å, agreeing with the redshift of 1.193 (ref. <sup>17</sup>). The Ca II 3,934 Å line was detected at 8,629 Å; however, the Ca II 3,969 Å line was not identifiable at 8,706 Å.

Two LRIS spectra were obtained starting on 2022 February 25 14:28:28 and 2022 March 03 11:24:06.19 UTC. The data were reduced using the LPipe<sup>133</sup> pipeline. The host galaxy lines identified in the X-shooter and DEIMOS spectra could be recognized, but the LRIS spectra appeared to be otherwise featureless.

All spectra are shown in Fig. 3.

**Gemini Observatory.** We acquired spectroscopic data of AT2022cmc using the long slit mode of the Gemini Multi-Object Spectrographs (GMOS) mounted at the Gemini-North 8-m telescope in Mauna Kea on the island of Hawai‘i, under the programme GN-2022A-Q-127 (PI: A.Y.Q.H.).

We used both the R400 and B600 gratings, and we obtained  $2 \times 450$  s exposures on each grating. We used the 1" slit, starting at 2022 February 15 14:35 UTC. After two independent reductions using DRAGONS (Data Reduction for Astronomy from Gemini Observatory North and South)<sup>134</sup> and Pyraf we report a featureless red continuum throughout our effective spectral coverage, from 3,800 Å to 9,100 Å although the signal-to-noise is low bluewards of 5,500 Å (ref. <sup>135</sup>). The spectrum is shown in Fig. 3.

**Neil Gehrels Swift Observatory.** AT2022cmc was observed by the X-ray Telescope (XRT)<sup>80</sup> and the Ultra-Violet/Optical Telescope (UVOT)<sup>136</sup> on board the Neil Gehrels Swift Observatory under a series of time-of-opportunity requests starting on 2022 February 23 03:25:55 UTC. The Swift follow-up campaign began later than expected owing to a few weeks of emergency downtime of the observatory.

All XRT observations were obtained in photon-counting mode. First, we ran ximage to determine the position of AT2022cmc in each observation. To calculate the background-subtracted count rates, we filtered the cleaned event files using a source region with  $r_{\text{src}} = 30''$ , and eight background regions with  $r_{\text{bkg}} = 25''$  evenly spaced at  $80''$  from AT2022cmc. A log of XRT observations is given in Extended Data Table 2.

For observations where the XRT net counts are greater than 100, we grouped the spectra to have at least one count per bin, and modelled the 0.3–10-keV data with an absorbed power-law model,  $\text{tbabs} \times \text{ztbabs} \times \text{powerlaw}$ . All data were fitted using C statistics via cstat<sup>137</sup>. We do not find strong evidence of spectral evolution throughout the first seven XRT observations (see Extended Data Fig. 6). Assuming  $\Gamma = 1.53$  and a host galaxy  $N_{\text{H}} = 1.1 \times 10^{21} \text{ cm}^{-2}$  (Methods section ‘Neutron Star Interior Composition Explorer’), the XRT 0.3–10-keV count rate (in count  $\text{s}^{-1}$ ) to flux (in  $\text{erg cm}^{-2} \text{ s}^{-1}$ ) conversion factor is  $4.19 \times 10^{-11}$ .

The first seven UVOT epochs (obsIDs 15023001–15023007) were conducted with UVB+all UV filters. Subsequent observations were conducted with U+all UV filters. We measured the UVOT photometry using the uvotsource tool. We used a circular source region with  $r_{\text{src}} = 5''$ , and corrected for the enclosed energy within the aperture. We measured the background using four nearby circular source-free regions with  $r_{\text{bkg}} = 10''$ . The UVOT photometry is presented in Supplementary Table 1.

**Neutron Star Interior Composition Explorer.** AT2022cmc was observed by the Neutron Star Interior Composition Explorer (NICER)<sup>138</sup> under director’s discretionary time and time-of-opportunity programmes. The NICER observations are reported in detail by D. R. Pasham et al.<sup>139</sup>. Here we analysed only the first NICER good time interval obtained on 2022 February 16.

We processed the NICER data using heasoft v6.29c. We ran nicer12 to obtain the cleaned and screened event files. We removed hot detectors. Background was computed using the nibackgen3C50 tool<sup>140</sup> with  $\text{hbcut} = 0.05$  and  $\text{s0cut} = 2.0$ . Response files were generated with nicerarf and nicerarmf. The spectrum was rebinned using ftgrouppha

with grouptype = optmin and groupscale = 50. We added systematic errors of 1% using grppha.

The final spectrum has an effective exposure time of 1,560 s, and the source is above background at 0.25–8 keV. We fitted the 0.25–8-keV data using an absorbed power-law model,  $\text{tbabs} \times \text{ztbabs} \times \text{powerlaw}$ , and  $\chi^2$  statistics. The Galactic column density  $N_{\text{H}}$  was fixed at  $8.88 \times 10^{19} \text{ cm}^{-2}$  (ref. <sup>141</sup>). We obtained a good fit with a  $\chi^2/\text{degrees of freedom}$  ( $\chi^2/\text{d.f.}$ ) of 74.91/83. The best-fit power-law index is  $\Gamma_{\text{x}} = 1.53 \pm 0.03$ , and host galaxy absorption is  $N_{\text{H}} = 1.09^{+0.14}_{-0.13} \times 10^{21} \text{ cm}^{-2}$ . The observed 0.25–8-keV flux is  $(3.29 \pm 0.07) \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$ . The inferred absorbed 0.3–10-keV flux is  $(3.75 \pm 0.09) \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$ . Errors are 90% confidence level for one parameter of interest. The data and best-fit model are shown in Fig. 2a and Fig. 2d.

## Data availability

Photometry and spectroscopy of AT2022cmc will be made available via the WISEREP public database at <https://www.wiserep.org/object/21988>. Facilities that make all their data available in public archives, either promptly or after a proprietary period, include: Very Large Telescope, Very Large Array, Liverpool Telescope, Blanco Telescope, W. M. Keck Observatory, Gemini Observatory, Palomar 48-inch/ZTF, the Neutron Star Interior Composition Explorer, and the Neil Gehrels Swift Observatory. Data from the Asteroid Terrestrial-impact Last Alert System were obtained from a public source.

## Code availability

The ZTFReST<sup>12,37</sup> code is publicly available. Upon request, the corresponding author will provide the code (primarily in Python) used to produce the figures.

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**Competing interests** The authors declare no competing interests.

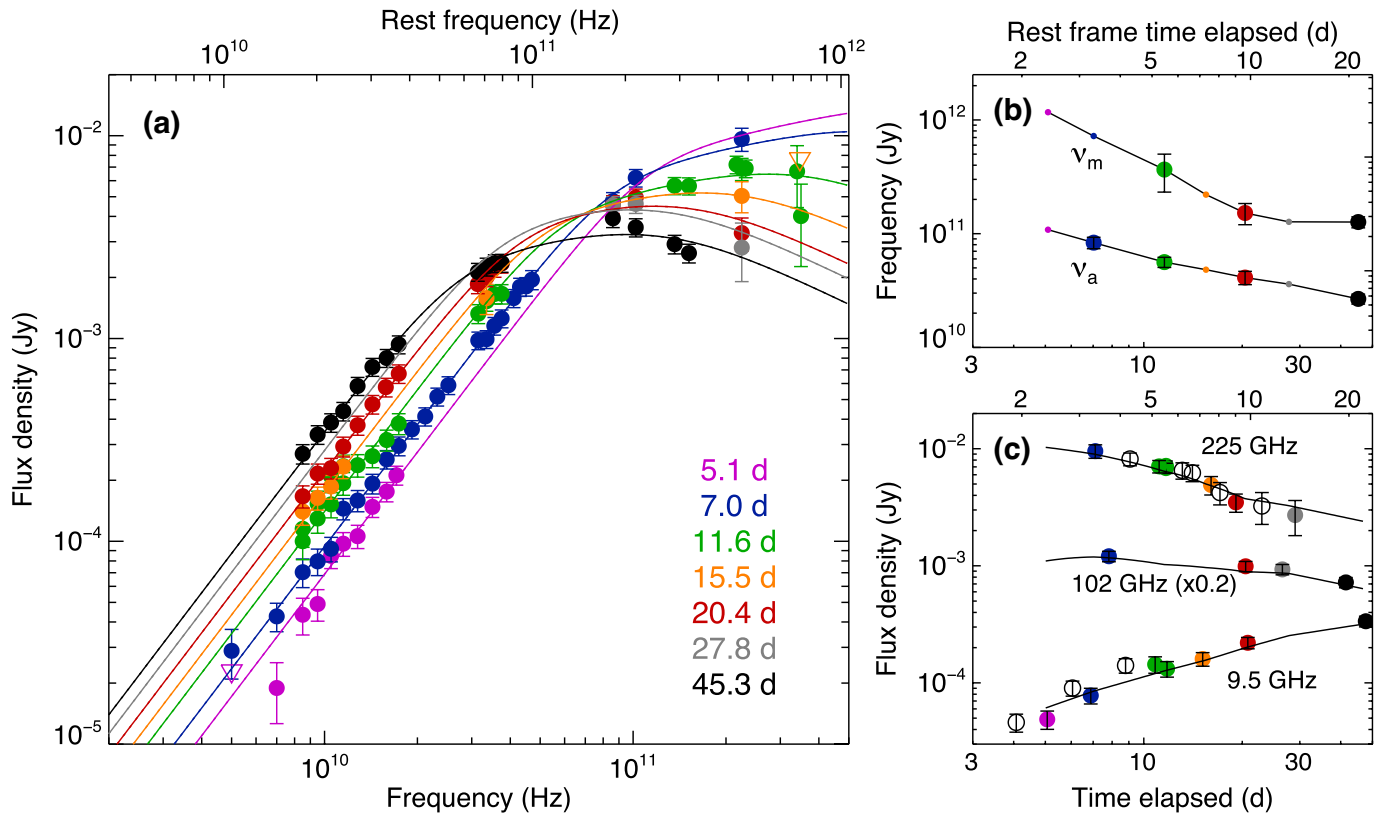
#### Additional information

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**Correspondence and requests for materials** should be addressed to Igor Andreoni or Michael W. Coughlin.

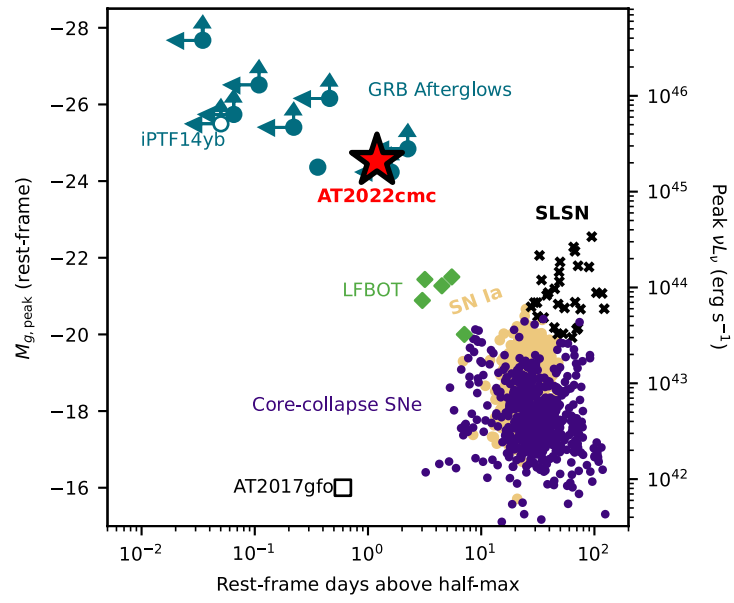
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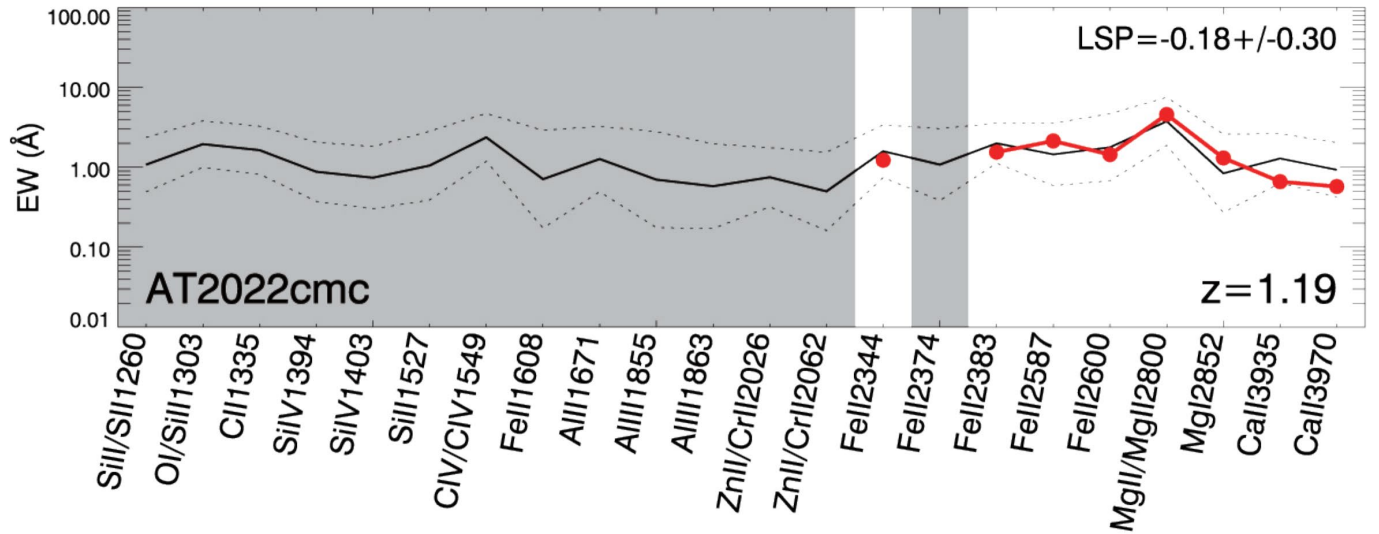
**Extended Data Fig. 1 | Time-dependent long-wavelength spectral evolution of AT2022cmc from observations with the VLA, NOEMA, SMA, JCMT, and ATCA.** **a**, Co-eval energy distributions for AT2022cmc. Measurements are shown as circles with error bars (a 10% systematic component has been included) colour-coded by observation epoch. A synchrotron broken power-law model has been fit to the data assuming a spectral index ( $F_\nu \propto \nu^\alpha$ ) of  $\alpha = +2$  at low frequencies ( $\nu < \nu_a$ ),  $\alpha = 1/3$  at mid-frequencies ( $\nu_a < \nu < \nu_m$ ), and  $\alpha = -1$  at high frequencies ( $\nu_m < \nu$ ). For the SEDs at 7.0, 11.6, 20.4 and 45.3 days (observer-frame) the model is fit with all parameters free to vary; for the

remaining epoch the break frequencies are fixed based on a plausible extrapolation/interpolation of the other epochs and only the flux scale is fit. **b**, Evolution of the spectral break frequencies. Larger circles with error bars show measured break frequencies; the remaining points are interpolated. **c**, Light curves at 9.5, 102 and 235 GHz with predictions of the interpolated SED model overplotted. (Unfilled circles show additional measurements not used in the co-eval SEDs.) The general evolution of the SED and light curve are very similar to what was seen in Swift J1644<sup>144</sup>, with a low-frequency SED that remains self-absorbed out to late times.



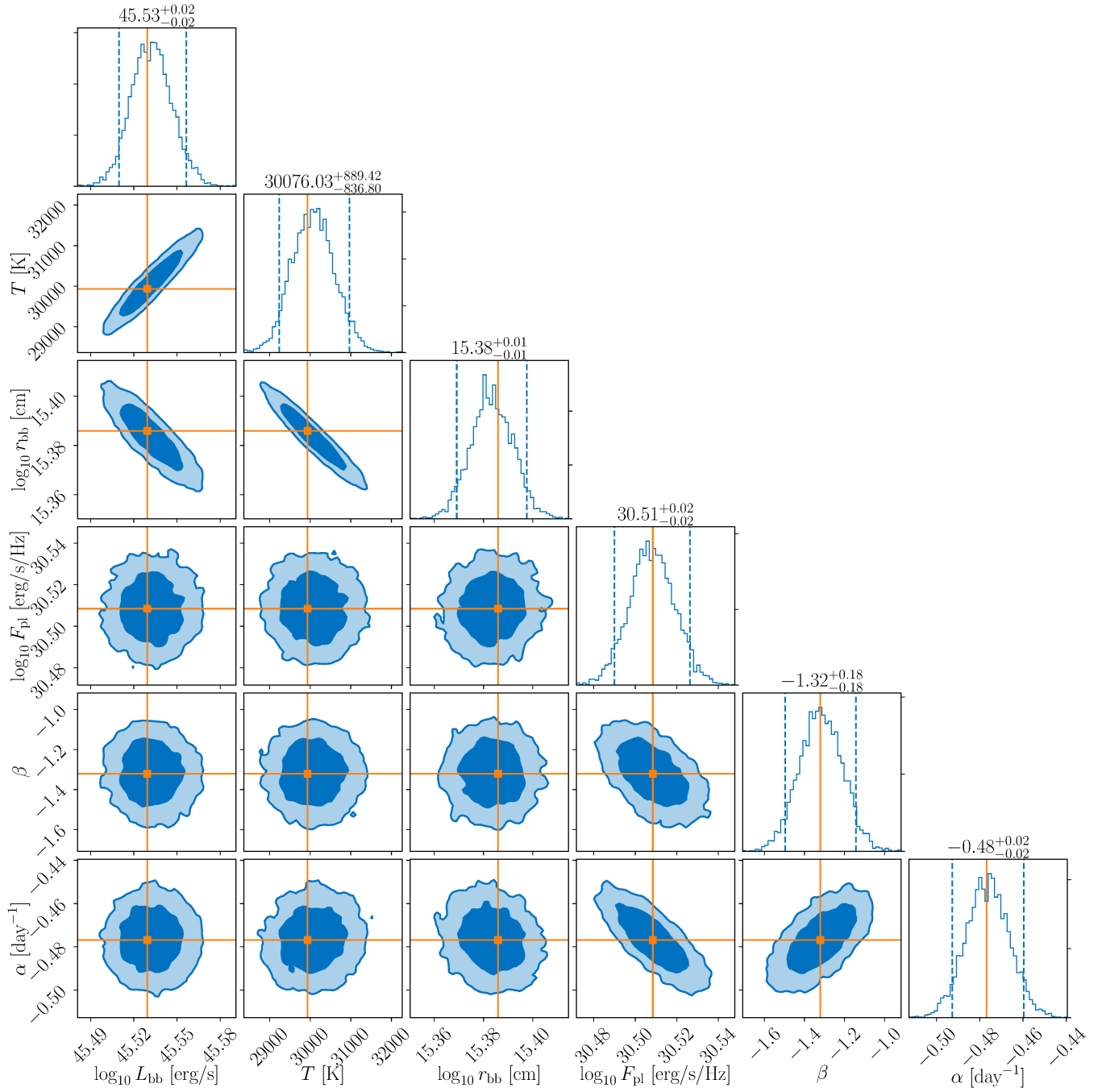
**Extended Data Fig. 2 | Duration and luminosity of optical transients compared to AT2022cmc.** Optical transients include superluminous supernovae (SNe) (SLSN), Type Ia SNe (SN Ia), core-collapse SNe<sup>145–147</sup>, luminous

fast blue optical transients (LFBOTs)<sup>43,44,47–49,147,148</sup>, GRB afterglows<sup>148,149</sup> and the kilonova AT2017gfo<sup>41,150–153</sup>.



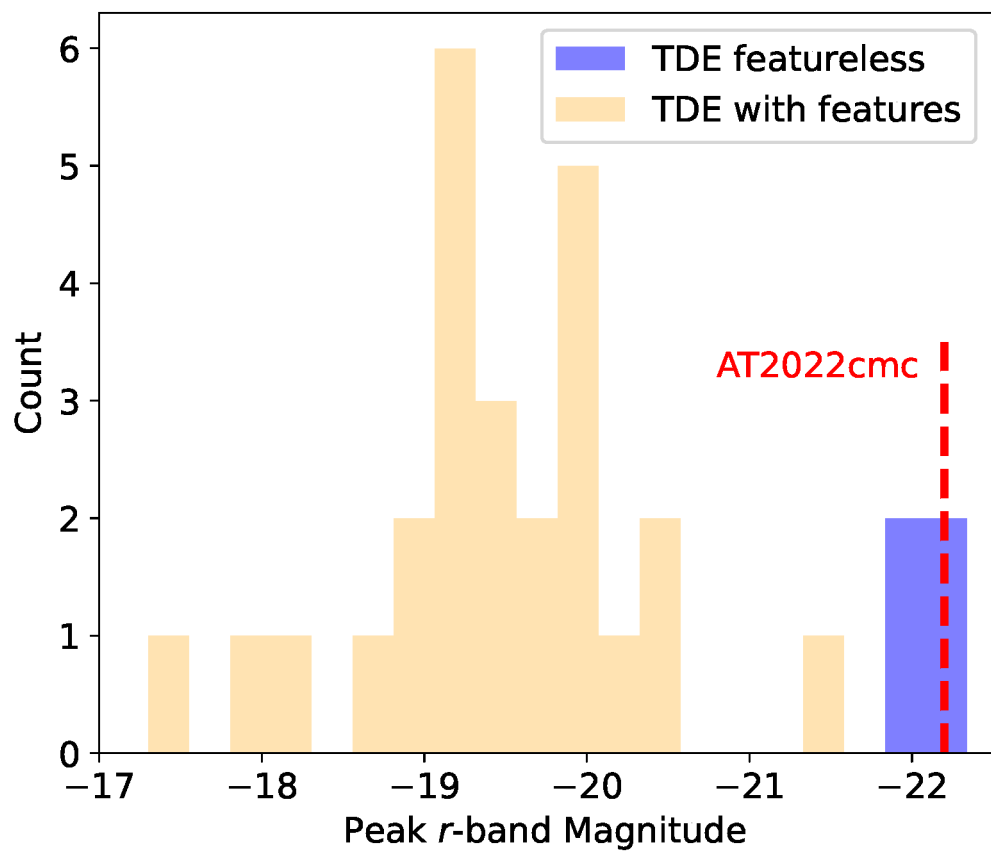
**Extended Data Fig. 3 | Line strength diagram.** The diagram compares the equivalent widths (EWs) of the absorption features measured in the X-shooter spectrum of AT2022cmc (in red) with a sample of GRB afterglow spectra. The thick black line marks the average strength of the sample and the dotted lines the standard deviation in log-normal space. The shaded features are those for

which we cannot provide reliable measurements because they fall outside the spectral range of our data, or because they are in a region of the spectrum affected by a very low signal to noise ratio or by telluric features. The features seen in the line of sight of AT2022cmc have very similar strength as those of a typical GRB. LSP, line strength parameter.



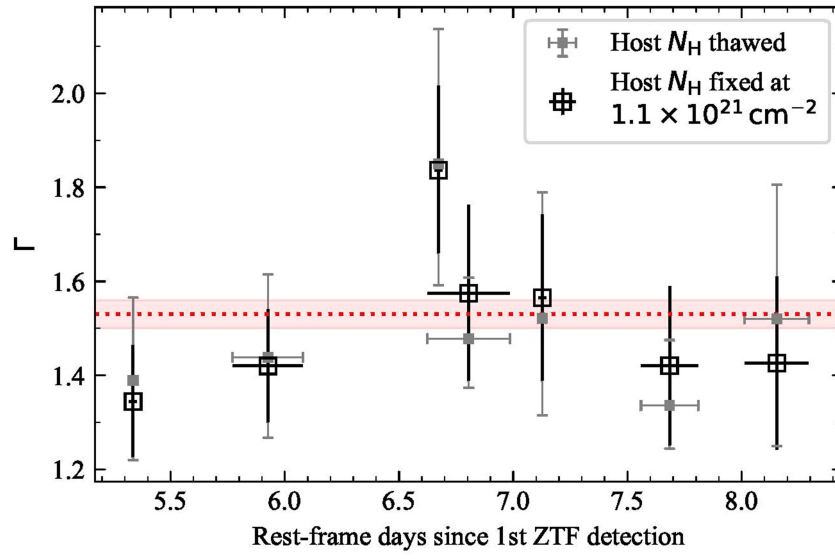
**Extended Data Fig. 4 | Marginalized histograms for the optical light curve modelling.** The modelling is discussed in Methods section ‘Optical light curve modelling’. The parameter estimates given correspond to median and 90% Bayesian credible intervals, as marked by the blue dashed vertical and

horizontal lines. The best-fit (maximum likelihood) parameters are marked with the orange lines. The 68% (95%) credible regions are coloured in dark (light) blue.



**Extended Data Fig. 5 | Distribution of the peak absolute magnitudes (r-band) for a population of TDEs<sup>31</sup>.** Featureless TDEs are consistently brighter than TDEs that show broad features in their optical spectra. The absolute magnitude of AT2022cmc when the slow/blue component dominates

falls in the ballpark of featureless TDE peak luminosities, which supports a possible connection between TDEs with relativistic jets and the class of featureless TDEs.



**Extended Data Fig. 6 | Evolution of the power-law photon index  $\Gamma_\chi$  in the first seven XRT observations.** All measurements are consistent with the best-fit  $\Gamma_\chi$  in the first NICER observation (Methods section ‘Neutron Star Interior Composition Explorer’), as marked by the horizontal dotted line.

Extended Data Table 1 | Equivalent line widths

| Observed $\lambda$ [Å] | Feature       | $z$     | EW Å            |
|------------------------|---------------|---------|-----------------|
| 4067.87                | AlIII 1854.72 | 1.19325 | $1.37 \pm 0.23$ |
| 4084.84                | AlIII 1862.78 | 1.19287 | $1.01 \pm 0.25$ |
| 5140.88                | FeII 2344.21  | 1.19301 | $3.68 \pm 0.35$ |
| 5225.70                | FeII 2382.77  | 1.19312 | $3.17 \pm 0.32$ |
| 5673.57                | FeII 2586.65  | 1.19340 | $2.54 \pm 0.27$ |
| 5703.60                | FeII 2600.17  | 1.19355 | $4.03 \pm 0.37$ |
| 5716.34                | MnII 2606.46  | 1.19314 | $1.49 \pm 0.28$ |
| 6132.95                | MgII 2796.35  | 1.19320 | $3.98 \pm 0.30$ |
| 6148.52                | MgII 2803.53  | 1.19314 | $4.68 \pm 0.34$ |
| 6256.81                | MgI 2852.96   | 1.19309 | $2.60 \pm 0.18$ |
| 8631.28                | CaII 3934.78  | 1.19359 | $1.83 \pm 0.17$ |
| 8707.82                | CaII 3969.59  | 1.19363 | $1.14 \pm 0.14$ |

Equivalent widths measured in the X-shooter spectrum, in observer frame.

Extended Data Table 2 | XRT observations of AT2022cmc

| obsID    | Start Date<br>(UT) | $\Delta t$<br>(days) | Exp.<br>(s) | Net Count Rate<br>(count s <sup>-1</sup> ) | Obs. Flux<br>(10 <sup>-13</sup> erg s <sup>-1</sup> cm <sup>-2</sup> ) | Obs. Luminosity<br>(10 <sup>45</sup> erg s <sup>-1</sup> ) |
|----------|--------------------|----------------------|-------------|--------------------------------------------|------------------------------------------------------------------------|------------------------------------------------------------|
| 15023001 | 2022-02-23.15      | 5.34                 | 2629        | 0.155 ± 0.008                              | 65.03 ± 3.32                                                           | 55.48 ± 2.83                                               |
| 15023002 | 2022-02-24.44      | 5.93                 | 3096        | 0.129 ± 0.007                              | 53.98 ± 2.78                                                           | 46.05 ± 2.37                                               |
| 15023003 | 2022-02-26.37      | 6.80                 | 2737        | 0.064 ± 0.005                              | 26.95 ± 2.12                                                           | 22.99 ± 1.81                                               |
| 15023004 | 2022-02-26.08      | 6.67                 | 2829        | 0.064 ± 0.005                              | 26.95 ± 2.12                                                           | 22.99 ± 1.81                                               |
| 15023005 | 2022-02-27.08      | 7.13                 | 2599        | 0.079 ± 0.006                              | 33.31 ± 2.41                                                           | 28.42 ± 2.06                                               |
| 15023006 | 2022-02-28.30      | 7.68                 | 2694        | 0.080 ± 0.006                              | 33.46 ± 2.37                                                           | 28.55 ± 2.02                                               |
| 15023007 | 2022-03-01.33      | 8.15                 | 2654        | 0.066 ± 0.005                              | 27.58 ± 2.19                                                           | 23.53 ± 1.87                                               |
| 15023008 | 2022-03-05.26      | 9.95                 | 664         | 0.029 ± 0.008                              | 12.27 ± 3.16                                                           | 10.47 ± 2.69                                               |
| 15023009 | 2022-03-07.46      | 10.95                | 2634        | 0.030 ± 0.004                              | 12.74 ± 1.51                                                           | 10.87 ± 1.29                                               |
| 15023010 | 2022-03-10.61      | 12.39                | 2829        | 0.016 ± 0.003                              | 6.89 ± 1.11                                                            | 5.88 ± 0.94                                                |
| 15023011 | 2022-03-13.63      | 13.76                | 1485        | 0.017 ± 0.004                              | 6.95 ± 1.56                                                            | 5.93 ± 1.33                                                |

$\Delta t$  is rest-frame days since the first ZTF detection epoch. The count rate, flux, and luminosity are given in the observer frame 0.3–10 keV. The uncertainties are represented by the 68% confidence intervals, assuming Poisson symmetrical errors.