The case for a minute-long merger-driven gamma-ray burst from fast-cooling synchrotron emission

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For decades, gamma-ray bursts (GRBs) have been broadly divided into long- and short-duration bursts, lasting more or less than 2 s, respectively. However, this dichotomy does not perfectly map to the two progenitor channels that are known to produce GRBs: mergers of compact objects (merger GRBs) or the collapse of massive stars (collapsar GRBs). In particular, the merger GRB population may also include bursts with a short, hard <2 s spike and subsequent longer, softer extended emission. The recent discovery of a kilonova—the radioactive glow of heavy elements made in neutron star mergers—in the 50-s-duration GRB 211211A further demonstrates that mergers can drive long, complex GRBs that mimic the collapsar population. Here we present a detailed temporal and spectral analysis of the high-energy emission of GRB 211211A. We demonstrate that the emission has a purely synchrotron origin, with both the peak and cooling frequencies moving through the γ-ray band down to X-rays, and that the rapidly evolving spectrum drives the extended emission signature at late times. The identification of such spectral evolution in a merger GRB opens avenues to diagnostics of the progenitor type.

GRB 211211A was detected by the Fermi Gamma-ray Burst Monitor (GBM) and Swift’s Burst Alert Telescope (BAT) at $t_0 = 13:09:59$ UT on 2021 December 11. It was initially classified as a long burst due to its measured duration of ~34.3 s (10 keV–10 MeV; Fermi) and 51.4 ± 0.8 s (15–150 keV; Swift), in excess of the 2 s divide. Swift promptly slewed to point its X-ray Telescope (XRT; ref. 4), which began settled observations of the field 79.2 s after the BAT trigger. X-ray observations showed bright emission (0.3–10 keV flux = $3 \times 10^{-8}$ erg s$^{-1}$ cm$^{-2}$) with an exponential decay lasting until ~300 s after trigger, consistent with previous examples of extended emission (EE; for example refs. 6–9). The Ultra-Violet/Optical Telescope (UVOT; ref. 10) began pointed observations of GRB 211211A 92 s after the BAT trigger, which began settled observations of the field 79.2 s after the BAT trigger. X-ray observations showed bright emission (0.3–10 keV flux = $3 \times 10^{-8}$ erg s$^{-1}$ cm$^{-2}$) with an exponential decay lasting until ~300 s after trigger, consistent with previous examples of extended emission (EE; for example refs. 6–9). The Ultra-Violet/Optical Telescope (UVOT; ref. 10) began pointed observations of GRB 211211A 92 s after the BAT trigger, which began settled observations of the field 79.2 s after the BAT trigger. X-ray observations showed bright emission (0.3–10 keV flux = $3 \times 10^{-8}$ erg s$^{-1}$ cm$^{-2}$) with an exponential decay lasting until ~300 s after trigger, consistent with previous examples of extended emission (EE; for example refs. 6–9). The Ultra-Violet/Optical Telescope (UVOT; ref. 10) began pointed observations of GRB 211211A 92 s after the BAT trigger, which began settled observations of the field 79.2 s after the BAT trigger.
similar to AT 2017gfo, the kilonova discovered alongside GRB 170817 and confirmed to be a binary neutron star merger by gravitational wave observations\(^1\). The detection of a kilonova establishes that GRB 211211A originated from a compact merger (Methods). Its association with a host galaxy at redshift \(z = 0.076\) (refs. 12,14) makes it the closest confirmed compact object merger discovered without gravitational waves, at a luminosity distance of just 350 Mpc. Owing to its proximity, GRB 211211A has the best-sampled high-energy emission of any merger-driven GRB, and its surprisingly long duration affords us a remarkable opportunity to investigate the underpinning processes that enable compact object mergers to create long-duration GRBs. The burst was also detected at gigaelectronvolt frequencies\(^15,16\).

We extracted time-resolved spectra in narrow windows of 2–20 s from the Swift and Fermi data and initially fitted these with a range of spectral models using XSPEC v12.11.1 (ref. 17) (Methods). Spectra from six representative epochs are shown in Fig. 1, covering the spectrally hard initial pulse complex (IPC) and softer extended emission (EE). Although these episodes are distinct in the established nomenclature and are often discussed as such in this work, we did not discriminate between them in our fitting procedure, where we chose our spectral time bins on the basis of the signal-to-noise ratio. The IPC and EE structure is reminiscent of GRB 060614, a 102-s-long GRB at \(z = 0.125\) that was strongly suspected to be a merger due to a lack of a supernova to deep limits\(^18\). The hard prompt emission is almost twice as long in GRB 211211A, further emphasizing the diversity of merger-driven events. We found that the data are well described by a double smoothly broken power-law model (2SBPL (ref. 19), shown in Fig. 1). A standard Band function\(^20\) with a single break is strongly disfavoured by the Akaike information criterion (AIC)\(^21,22\) (Fig. 2). A Band model with an additional thermal component is also disfavoured with respect to 2SBPL, especially in the brightest pulses, and further requires a high intrinsic hydrogen column density that is inconsistent with the burst’s afterglow\(^12\) (Methods).

**Fig. 1** Spectral fits with the 2SBPL model from six representative epochs in the GBM and BAT light curves. Each spectral fit has \(n = 362\) energy bins comprising three GBM detectors (n10, n2 and b0) and BAT. Data are presented as mean \(\pm 1\) s.d. The epochs bracketed by dotted lines in the light curves (middle) correspond to the spectra with frames of the same colour (top and bottom). In the spectral panels, the peak energy is shown by the dashed red line and the low energy break (where included in the fit) by the dashed blue line. The top row shows the highly variable nature of the IPC, while the EE phase along the bottom row exhibits a more gradual and coherent evolution. \(F_\nu\) is the flux at frequency \(\nu\). The light curves in the middle panel show the source count rate averaged over the detection elements (14 for GBM and 32,768 for BAT). 64 ms time bins are used. cts s\(^{-1}\) det\(^{-1}\), counts per second per detector.
The parameters derived from our full suite of fits are given in Table 1. We focus the rest of our discussion on the 2SBPL model (although for epochs where one of the breaks lies outside the observed frequency range, this reduced to the Band model; Methods).

The 2SBPL model parameterizes a synchrotron spectrum, where relativistic charged particles radiate due to acceleration in magnetic fields. The spectrum is described by power-law segments connecting characteristic break frequencies (see for example refs. 21-23). The three power-law segments have photon indices $\alpha_i$, $\alpha_p$, and $\beta$ (following the convention $F_i \propto E^{\alpha_i}$, for a photon index $\beta$), smoothly connected at two break energies, $E_b$ and $E_p$. These breaks map to the characteristic synchrotron frequency $\nu_m$, where most of the electrons radiate, or the cooling frequency $\nu_c$, above which electrons rapidly lose their energy. If $\nu_c < \nu_m$, all electrons cool down rapidly and the system is in the so-called fast-cooling regime, while $\nu_m < \nu_c$ represents a slow cooling state (see Methods for more details).

The γ-ray and X-ray light curves of GRB 211211A and the evolution of the best-fit 2SBPL parameters are shown in Fig. 3. During the first 42 s of evolution, we see a rapid decrease in $E_\gamma$ from an initial $2,411.3 \pm 602.0$ keV to $76.3 \pm 15.9$ keV (1 sigma confidence intervals). $E_\gamma$ also shows a smooth but much slower decline from a maximum of $64.3 \pm 4.9$ keV to $17.6 \pm 4.2$ keV. We found mean indices of $\alpha_1 = 0.52 \pm 0.24$ and $\alpha_2 = 1.61 \pm 0.25$. These values are in excellent agreement with the expected values of 2/3 and 3/2 for synchrotron emission in the fast-cooling regime. Evidence for the presence of two breaks has been previously found in bright GRBs detected by both Fermi 2126-29 and Swift 30-32, but all were collapsar GRBs, rather than merger GRBs.

After 42 s, $E_\gamma$ was unresolved and we fitted a single photon index, $\alpha$, below $E_p$. Initially, the fitted values of $\alpha$ are in excellent agreement with the expected value of $\alpha_i$ (top panel of Fig. 3), indicating that $E_b$ and $E_p$ are unresolved because they are too close together, rather than $E_b$ having left the band pass. From -120 s, the measured value of $\alpha$ begins to rise. We interpret the change as being due to the synchrotron breaks now moving away from one another (Methods), resulting in $\alpha_i$ dominating the measurement as $E_b$ approaches the lower limit of the observed band pass and pushes $\alpha_i$ out of the spectrum.

By fixing the photon indices to their expected values, we could once again resolve $E_b$ in our fits starting from 120 s (open symbols in Fig. 4). The increasing separation between $E_b$ and $E_p$ and the coincident evolution of $\alpha$ from 2/3 towards 3/2 indicates that the more rapidly evolving spectral break is now the lower energy of the two, in contrast with the first 42 s of evolution. This apparent crossing of the two spectral breaks is consistent with the source having transitioned from a fast-cooling regime to slow cooling 23,24.

We further tested this scenario by fitting an exponential profile of the form $E = Ne^{-t/t}$ (where $t$ is the time since trigger and $r$ is the characteristic turnover timescale) to the evolution of both breaks (Fig. 4). The two profiles cross at $t_c = 68$ s, and their crossing is further supported by the affinity of the $E_b$ fit to the $E_b$ measurements post-$t_c$. The evolution of the breaks has a marked effect on the EE light curve. The characteristic timescale for the evolution of $\nu_c$ ($t_c = 63.3 \pm 20.2$ s) and the turnover of the X-rays ($t_c = 66.9 \pm 1.0$ s) are close to the fast-to-slow cooling transition time ($t = 68$ s), suggesting a connection between the cooling transition and the EE duration. Moreover, they are clearly driving the morphology of the late X-ray decline, which steepens when $\nu_m$ evolves below the band and ceases when $\nu_m$ follows (Fig. 4). The consistency of this X-ray feature across the EE class (for example ref. 9; see Fig. 5) hints that the shock physics may be remarkably uniform across the population of long-duration merger-GRBs.

At higher energies, the characteristic timescale of $\nu_m$ ($t_c = 14.4 \pm 1.14$ s) is well matched to the duration of the IPC (~12 s). This probably relates to the duration of the jet, which energizes the shock during the IPC, keeping $\nu_m$ consistently high. Although the duration of γ-ray EE is highly variable across the known sample (for example, Supplementary Table 1), the evolution of $E_b$ through the BAT band pass can explain the relative spectral softness of EE compared with the IPC (for example, ref. 9). This framework also naturally leads to the population of GRBs that display the same exponential X-ray light curve as GRB 211211A and other EE GRBs (for example, Fig. 5) but lack EE in γ-rays 23,24. This can be achieved with a common evolution in $\nu_m$ while $\nu_m$ is found at lower energies below the BAT band pass (after the IPC). Furthermore, if $\nu_m$ is in fact below the XRT band pass in the majority of cases, one might recover a ‘canonical’ short GRB lasting less than 2 s. However, this would imply up to a few hundred seconds of ‘unseen’ jet activity in these events.

Our analysis shows that the prompt emission spectrum of GRB 211211A is consistent with the so-called marginally fast-cooling regime, with $\nu_m \leq \nu_c$ (refs. 21-23). Detecting $\nu_m$ at roughly tens of kiloelectronvolts implies that accelerated particles do not cool completely via synchrotron processes within a dynamical timescale 23. By assuming that the electrons cool on a timescale of the order of the adiabatic one, we can derive self-consistent constraints on the magnetic field $B$ in the emitting region. For a typical emitting region radius $R$ and a bulk Lorentz factor of $\gamma = 100$ (consistent with the afterglow), our findings imply a magnetic field of the order of $B \approx 90 \mu G$ (consistent with afterglow), where $Q = Q_0 \times 10^{16}$ (the magnetic field falls in the range $B = 30-200$ G for a range of $R = 10^{14}-10^{16}$ cm). These values are consistent with those derived for marginally fast-cooling collapsar GRBs 25-30,32 but at odds with the expectations for a typical GRB emitting region ($B = 10^{-10} G$, for example ref. 39).
We found that the UVOT data at ~163 s lay below the extrapolation of the fitted synchrotron spectrum (see Methods and Fig. 6). An additional spectral break is required to self-consistently model the spectral energy distribution from UV to X-rays. In the context of synchrotron emission, this can be interpreted as the synchrotron self-absorption frequency $\nu_{ssa}$, below which the optical depth to synchrotron self-absorption is larger than unity. Following ref. 40 (but see also refs. 37,41–43), we found that this implies a low $B$ field ($\sim 100$ G) and/or compact emitting region ($R < 10^{13}$ cm). However, a self-consistent solution that incorporates incomplete electron cooling and synchrotron self-absorption at UV frequencies is challenging, and may require alternative sources of absorption or modified synchrotron models (for example, ref. 44)—particularly to avoid the bright synchrotron self-Compton emission predicted for such a system (for example, refs. 35,37,44).

### Table 1 | Parameters derived from our time-resolved spectral fitting

| Epoch(s) | $\alpha_1$ | $E_b$(keV) | $\alpha_2$ | $E_p$(keV) | $\beta$ | $N_H$(10$^{20}$ cm$^{-2}$) | Fitstatistic | d.f. |
|----------|-------------|-------------|-------------|-------------|---------|-----------------|-------------|------|
| 2SBPL | 1.0±0.1 | 0.69±0.32 | 210±8.8 | 1.50±0.06 | 2,411.3±602.0 | 4.74±1.87 | – | 315 | 353 |
| 3.0±0.1 | 0.54±0.07 | 46.7±8.2 | 1.40±0.04 | 951.6±47.4 | 2.74±0.08 | – | 480 | 353 |
| 5.0±0.1 | 0.39±0.10 | 30.7±3.3 | 1.49±0.03 | 721.0±47.5 | 2.89±0.11 | – | 401 | 353 |
| 7.0±0.1 | 0.48±0.03 | 64.3±4.9 | 1.44±0.02 | 1,543.0±47.5 | 3.09±0.07 | – | 496 | 353 |
| 9.0±0.1 | 0.33±0.09 | 30.0±2.7 | 1.49±0.02 | 1,053.6±72.0 | 2.90±0.12 | – | 378 | 353 |
| 11.0±0.1 | 0.31±0.12 | 28.5±2.4 | 1.78±0.04 | 567±135.7 | 2.99±0.36 | – | 387 | 353 |
| 14.0±2.0 | 0.27±0.37 | 19.9±3.6 | 1.84±0.29 | 257.3±205.7 | 2.29±0.52 | – | 378 | 353 |
| 17.0±1.0 | 0.35±0.25 | 20.6±4.2 | 1.64±0.09 | 275.0±40.9 | 2.74±0.23 | – | 391 | 353 |
| 19.0±1.0 | 0.39±0.12 | 27.2±2.8 | 1.68±0.04 | 580±86.5 | 3.02±0.28 | – | 389 | 353 |
| 21.0±1.0 | 0.30±0.16 | 23.8±2.9 | 1.69±0.06 | 319.6±45.8 | 2.89±0.25 | – | 366 | 353 |
| 23.0±1.0 | 0.35±0.14 | 24.2±2.6 | 1.73±0.05 | 335.2±51.5 | 3.04±0.30 | – | 363 | 353 |
| 25.0±1.0 | 0.34±0.14 | 24.8±2.7 | 1.75±0.05 | 305.5±47.9 | 3.01±0.29 | – | 353 | 353 |
| 28.0±2.0 | 0.49±0.09 | 24.3±0.9 | 1.98±0.02 | 83.9±30.3 | 3.26±0.67 | – | 393 | 353 |
| 32.0±2.0 | 0.18±0.46 | 17.2±3.7 | 1.85±0.24 | 69.8±16.9 | 2.61±0.39 | – | 341 | 353 |
| 36.0±2.0 | 0.19±0.18 | 20.2±1.6 | 1.89±0.04 | 225.6±50.9 | 3.99±0.73 | – | 381 | 353 |
| 40.0±2.0 | 0.23±0.47 | 17.8±4.2 | 1.85±0.25 | 76.3±15.9 | 2.64±0.42 | – | 331 | 353 |
| Banda | 44.0±2.0 | 0.67±0.39 | – | – | 37.7±3.06 | 2.23±0.05 | – | 334 | 355 |
| 48.0±2.0 | 0.67±0.47 | – | – | 42.2±5.61 | 2.14±0.05 | – | 337 | 355 |
| 55.0±5.0 | 0.85±0.19 | – | – | 35.5±2.29 | 2.24±0.05 | – | 384 | 355 |
| 65.0±5.0 | 0.92±0.35 | – | – | 36.4±4.32 | 2.18±0.08 | – | 317 | 355 |
| 85.0±5.0 | 0.88±0.13 | – | – | 77.4±0.81 | 2.58±0.11 | 4.81±3.99 | 373 | 453 |
| 95.0±5.0 | 0.92±0.17 | – | – | 5.81±0.83 | 2.62±0.15 | <131 | 468 | 530 |
| 105.0±5.0 | 0.63±0.75 | – | – | 4.59±0.54 | 2.42±0.10 | <11.7 | 442 | 445 |
| 115.0±5.0 | 0.87±0.30 | – | – | 4.88±0.89 | 2.26±0.12 | <20.0 | 468 | 616 |
| 125.0±5.0 | 0.71±0.63 | – | – | 3.30±0.37 | 2.56±0.54 | <14.1 | 310 | 408 |
| 135.0±5.0 | 1.06±0.35 | – | – | 4.04±0.67 | 2.61±0.74 | <15.2 | 375 | 567 |
| 150.0±10.0 | 1.15±0.15 | – | – | 3.31±0.49 | 2.47±0.39 | 0 | 372 | 427 |
| 170.0±10.0 | 1.37±0.14 | – | – | 2.51±0.30 | 2.73±0.40 | 0 | 348 | 478 |
| Power law | 75.0±5.0 | – | – | – | 2.18±0.04 | – | 360 | 357 |
| 190.0±10.0 | – | – | – | 2.38±0.11 | 9.52±2.20 | 297 | 573 |
| 210.0±10.0 | – | – | – | 2.42±0.08 | 8.33±1.51 | 345 | 528 |
| 230.0±10.0 | – | – | – | 2.86±0.13 | 8.46±2.03 | 311 | 630 |
| 250.0±10.0 | – | – | – | 3.33±0.18 | 11.6±2.64 | 228 | 714 |
| 270.0±10.0 | – | – | – | 3.46±0.20 | 14.0±3.05 | 181 | 251 |
| 290.0±10.0 | – | – | – | 3.55±0.28 | 13.4±4.08 | 122 | 523 |
| Afterglow | – | – | – | 1.56±0.07 | 1.19±1.61 | <13.1 | 337 | 425 |

Fits are grouped by model type and so are not necessarily in chronological order. Data are presented as mean values ±1 s.d. except for the epoch column, which shows the central time and range of each spectral slice. $N_H$ is the neutral hydrogen column number density along the line of sight in 1,020 cm$^{-2}$. The fit statistic represents the sum of the PGSTAT, C-stat and $\chi^2$ contributions (Methods), depending on which detectors were available in a given epoch. d.f., degrees of freedom. *For the Band data, a values (second column) are tabulated instead of $\alpha$. 
in understanding their genesis. Fundamentally, we do not know how a merger can produce -100 s of emission in some cases, as this is well in excess of the expected s accretion timescale of the post-merger torus (for example refs. 44,45). The two main explanations available in the literature are delayed fallback accretion and long-lived activity from the central engine.

Delayed fallback is typically invoked for a neutron star–black hole merger, where a larger tidial tail of ejecta is expected (for example ref. 44). In this case, EE might be related to the quantity and duration of the fallback mass (for example refs. 44,45). On the other hand, the characteristic -100 s duration of the EE has no obvious explanation in the fallback accretion scenario (however, see ref. 45). The kilonova associated with GRB 211211A is consistent with being a binary neutron star merger45, although a neutron star–black hole merger cannot be completely ruled out. In the binary neutron star scenario, EE may be powered by a temporarily or indefinitely stable magnetar remnant (for example refs. 46,47) via a relativistic magnetized wind, potentially shaped by interaction with the merger ejecta into a collimated jet (for example ref. 45). An abrupt change in jet properties is predicted to occur once the magnetar becomes optically thin to neutrinos, on a timescale of -10–100 s (ref. 45), which is suitable for EE. This transforms the composition of the magnetar outflow from an electron–ion plasma to an electron–positron outflow similar to that of a pulsar wind48. Regardless of which, if either, model is the correct physical picture, establishing the observed evolution of $\nu_c$ and $\nu_m$ across the EE population represents the first step towards mapping these spectral features to the progenitor binary and post-merger remnant.

The brightness of GRB 211211A enabled us to deconstruct both the initial prompt emission complex and the subsequent, softer EE. Our results suggest that the characteristics of EE in a merger GRB with a long-lived engine depend mainly on where the synchrotron spectral breaks reside relative to the observational band passes. For the first 10 s of the burst, $E_p$ and $E_b$ show little evolution. This period therefore shows no spectral evolution and no spectral lag, a critical distinguishing feature of EE GRBs49. After this time, $E_p$ softens rapidly, creating the observed softer EE component. This evolution thus naturally explains both the lack of spectral lag in the early emission and the later softening seen in EE bursts. While only GRB 211211A has observations of the requisite quality to measure the motion of the spectral breaks directly, there is substantial similarity in spectral evolution and X-ray light curves in all EE bursts (Methods). This implies that the same physical processes probably shape the entire class of events, and the GRB 211211A template enables this possibility to be tested with a larger

Fig. 3 | The evolution of the synchrotron spectrum from our time-resolved spectral fits. 2SBPL was fitted to the early data, but simpler models were used at late times where necessary. Shaded regions indicate the detectors available for fitting. All data are presented as mean ± 1 s.d. Top: Swift–BAT ($n_α = 1,892$ data points) and XRT ($n_α = 228$ data points) 10 keV flux density light curves of the prompt + EE phases. Middle: the evolution of $E_p$ ($n_α = 28$ measurement epochs) and $E_b$ ($n_α = 16$ measurement epochs). The BAT band pass is marked by two horizontal black dotted lines. The horizontal red dotted line shows the lower limit of fitted GBM energies and the XRT upper band-pass limit. Bottom: evolution of the photon indices derived from fitting ($n_α = 16$; $n_β = 16$; $n_γ = 12$; $n_δ = 35$, where $n$ is the number of measurement epochs). The expectation values of $α_1$ and $α_2$ in the fast-cooling regime and the nominal upper limit of $β$ are indicated by the dashed lines.

Fig. 4 | Evolution of the spectral breaks and their influence on the light curve. All data are presented as mean ± 1 s.d. Top: the evolution of $E_p$ ($n_α = 24$) and $E_b$ ($n_α = 16$) is well described by an exponential profile, where $n$ is the number of spectral break measurements in each fit. Exponentials were fitted to the filled symbols of their respective colours. Open symbols were obtained by fixing the spectral slopes to their theoretical expectations, and were not fitted. The affinity of the blue curve for the late red data therefore provides further support for the transition of the two breaks. Bottom: BAT ($n_α = 1,892$) and XRT ($n_α = 228$) light curves, where $n$ is the number of data points from each instrument. The rapid turnover in the light curves corresponds to the breaks exiting the band passes, implying that the duration of EE is sensitive to their evolution.
sample of merger- and collapsar-driven GRBs even at lower temporal resolution. If such behaviour can be established as unique to mergers through further studies, EE could be a smoking gun for the origin of a given GRB even in bursts at much larger distances or with much poorer localizations, for example in gravitational wave follow-up.

**Methods**

**Data products**

We retrieved GBM spectral data and their corresponding response matrix files (rsp2) from the online HEASARC archive. GBM count-rate light curves were created using time-tagged event data binned to a time resolution of 64 ms (Fig. 1). No signal was detected by the Large Area Telescope on board Fermi during the prompt emission (Fig. 1). This was combined into a 4 s bin. XRT flux density light curves were taken directly from the UKSSDC archive.

We downloaded Swift data from the UK Swift Science Data Centre (UKSSDC) and data from BAT were processed using the BATGRBPRODUCT pipeline v2.48 from NASA’s High Energy Astrophysics Centre (HEASARC) and NASA’s Wide-field Infrared Survey Explorer (WISE) archive.

We used the Burst Analyser. We used the non-evolving data products binned to a time resolution of 64 ms time resolution (Fig. 1). We also tested the addition of a blackbody component (BB), dividing the spectrum into thermal and non-thermal emission. The thermal component represents the emission from the photosphere of the illuminated BGO detector.

**Model comparison**

We fitted our data with three models. The first and simplest is the Band function, which is the standard GRB continuum model and takes the form of two power laws, with low-energy photon index $\alpha$ and a high-energy photon index $\beta$, smoothly connected at a $\nu_c$, peak energy $E_p = E_c(2 + \alpha)$:

$$N(E) = A\left(\frac{E}{100\text{keV}}\right)^\alpha \exp\left(-\frac{E}{E_c}\right)\left[\left(\alpha + \beta E_c \geq E\right) \right.$$  

$$= A\left(\frac{E - E_c}{100\text{keV}}\right)^{\alpha - \beta} \exp\left(-\frac{\beta E_c}{150\text{keV}}\right)^{\beta - \alpha} \left[\left(\alpha - \beta E_c \leq E\right)\right].$$

$N(E)$ is the number of photons of energy $E$, $E_c$ is the characteristic energy (a free parameter in the model fit) and $A$ is a normalisation factor. When there were no spectral breaks in the fitted band pass, we simplified the Band function to a power-law fit corresponding to either $\alpha$ or $\beta$.

We also tested the addition of a blackbody component (BB), dividing the spectrum into thermal and non-thermal emission. The thermal component represents the emission from the photosphere of the illuminated BGO detector (b0). We selected the energy channels in the range 10–900 keV for Na i detectors, excluding the channels in the range 30–40 keV (due to the iodine K edge at 33.17 keV) and 0.3–4 MeV for the BGO detector. We modelled the background by manually selecting time intervals before and after the burst and fitting them with a polynomial function whose order was automatically found by GTBURST.

After processing with BATGRBPRODUCT, time-resolved BAT spectra were extracted using BATBINEVT. These spectra had a systematic error vector applied via BATPHASYSERR, and BATUPDATENPHAW was run to update the ray-tracing keywords. We built a detector response matrix for each spectrum using BATDRMGEN. XRT spectra were extracted using the UKSSDC webtool.

Fitting was performed using XSPEC v12.11.1 (ref. 17). We included a free constant representing an effective area correction to account for flux offsets due to the uncertain effective areas of the GBM detectors in flight. This was found to be a few per cent for intra-GBM calibration and up to ~15% for GBM-BAT calibration.

**Details of best fits**

We fitted our data with three models. The first and simplest is the Band function, which is the standard GRB continuum model and takes the form of two power laws, with low-energy photon index $\alpha$ and a high-energy photon index $\beta$, smoothly connected at a $\nu_c$, peak energy $E_p = E_c(2 + \alpha)$:

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$N(E)$ is the number of photons of energy $E$, $E_c$ is the characteristic energy (a free parameter in the model fit) and $A$ is a normalisation factor. When there were no spectral breaks in the fitted band pass, we simplified the Band function to a power-law fit corresponding to either $\alpha$ or $\beta$.

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After processing with BATGRBPRODUCT, time-resolved BAT spectra were extracted using BATBINEVT. These spectra had a systematic error vector applied via BATPHASYSERR, and BATUPDATENPHAW was run to update the ray-tracing keywords. We built a detector response matrix for each spectrum using BATDRMGEN. XRT spectra were extracted using the UKSSDC webtool.

Fitting was performed using XSPEC v12.11.1 (ref. 17). We included a free constant representing an effective area correction to account for flux offsets due to the uncertain effective areas of the GBM detectors in flight. This was found to be a few per cent for intra-GBM calibration and up to ~15% for GBM-BAT calibration.

**Figure 5** The X-ray light curves of EE GRBs. The sample is shown in Supplementary Table 1. Data are presented as mean ± 1 s.d. The light curves have been fitted with an exponential profile, and show remarkably consistent behaviour with the exception of the poorly sampled GRB 061006. Combined with the blue print of spectral evolution found for GRB 211211A in this work, this implies very uniform emission physics. The number of data points in each fit is given by $n$ in the legend.

**Figure 6** A joint fit of XRT and UVOT data centred around 163 s. XRT ($n = 483$) and UVOT ($n = 1$) data are presented as mean ± 1 s.d. The red dashed line marks the position of $E_c$ in the fit, while $E_{\gamma}$ is marked by the blue dashed line. The expected synchrotron photon index of 2/3 overpredicts the UV detection by an order of magnitude. This requires a spectral break or an additional source of absorption that cannot be explained by host galaxy extinction along the line of sight (Methods).
GRB at typical radii of a few times $10^4$ cm from the central engine. Non-thermal emission is produced further out ($\sim 10^3$ cm), either via interactions between expanding shells of material or through magnetic processes.

Finally, we fitted the 2SBPL model. This model allowed us to fit the spectra with three power-law segments (with photon indices $\alpha_1$, $\alpha_2$, and $\beta$) smoothly connected at two breaks $E_b$ and $E_c$:

$$N(E) = AE_0^\beta \left( \left( \frac{E}{E_b} \right)^{\alpha_1} + \left( \frac{E}{E_c} \right)^{\alpha_2} \right)^{\gamma} \frac{\beta}{\gamma} + \left( \frac{E}{E_b} \right)^{\alpha_1} + \left( \frac{E}{E_c} \right)^{\alpha_2} \right)^{\gamma} \frac{\beta}{\gamma}.$$  \tag{2}

where:

$$E_i = E_\beta \left( \frac{\alpha_1 + 2}{\beta + 2} \right)^{\gamma \frac{1}{\beta - \alpha_1}}.$$  \tag{3}

This function represents the synchrotron spectral shape derived from a population of electrons assumed to be accelerated into a power-law distribution of energies with an index $p$—that is, $N(E) \propto E^{-p}$. The lower-energy $E_b$ and higher-energy $E_c$ represent either the cooling frequency ($\nu_c$, mostly emitted by electrons with Lorentz factor $\gamma_c$), or the characteristic synchrotron frequency ($\nu_m$ emitted by electrons at $\gamma_m$). The order of these breaks dictates the cooling regime: slow cooling ($\gamma_m < \gamma_c$), wherein only electrons with $\gamma_c > \gamma_m$ cool efficiently within a dynamical timescale, or fast cooling ($\nu_c < \gamma_c$), in which all the electrons cool down rapidly to $\gamma_c < \gamma_m$. The two regimes have specific expectation values for the photon indices between the power-law segments. For fast cooling, we expect $\alpha_1 = 2/3$ (for $\nu_c < \nu_m$), $\alpha_2 = 2$ (for $\nu_m < \nu_c < \nu_\gamma$) and $\beta = p/2 + 1$ (for $\nu_\gamma < \nu_c$), whereas for slow cooling we expect $\alpha_1 = 2/3$ (for $\nu_c < \nu_m$), $\alpha_2 = (p + 1)/2$ (for $\nu_m < \nu_c < \nu_\gamma$), and $\beta = p/2 + 1$ (for $\nu_\gamma < \nu_c$). For the typical parameters of the emitting region ($\beta = 10^{-10}$ cm s$^{-1}$, $\Gamma = 100$), the particles are expected to efficiently radiate most of their energy on a timescale much smaller than the dynamical one, and therefore the spectra are expected to be in fast-cooling regime.

The 2SBPL function has been found to fit the spectra of the brightest Fermi long GRBs significantly better than the standard Band-like single-break function. The inclusion of the low-energy break (for example, refs. 30.31) helps to solve the tension between the typically measured values of $\alpha_1 = 1$ in GRB spectra fitted with the Band function (for example ref. 32) and the expected values of $\alpha_1 = 2/3$ and $\alpha_2 = 3/2$ from synchrotron theory (for example ref. 33). This tension may also be lessened by considering inverse Compton effects in the Klein–Nishina regime (for example ref. 32). Recent simulations suggest that $\alpha_1 = 1$ may actually represent the mean value of these two unresolved spectral slopes. Motivated by these results, we employed the 2SBPL function to test the consistency of GRB 211211A with a synchrotron-dominated spectrum.

Due to their different treatment of incident photons, the data from the three instruments used in our study must be fitted with different fit statistics. For GBM, the background was modelled before extracting a spectrum, hence the resultant spectra were fitted with PGSTAT, representing a Poissonian source over a Gaussian background. The mask weighting used in BAT meant that its data must be fitted with $\chi^2$ statistics. Finally, XRT employs straightforward photon counting, and hence was fitted with Cash statistics. As a result, different model fits cannot be reliably compared with $\chi^2$ statistic tools such as the F-test. We therefore employed the AIC to compare models. We found that both the 2SBPL and Band + BB models provided a statistical improvement over the simpler Band function during approximately the first 30 s of data (Fig. 2), with $\Delta_{\text{AIC}} > 10$ indicating no support for the Band function.

In the same epoch, early values of $\alpha_1$ showed excellent agreement with the expectation value of 2/3 before drifting downwards. The mean value of the low-energy photon index $\tilde{\alpha}_1 = 0.52 \pm 0.24$. The later discrepancy was still consistent with synchrotron expectations within 3 $\sigma$, and can be explained by $E_\gamma$ falling close to the lower GBM band pass, resulting in a poorly sampled low-energy power-law segment. A similar issue has been found previously by ref. 10 (see their Fig. B1): all spectra with notably hard values of $\alpha_1$ also had a break energy of $E_b < 20$ keV, suggesting an instrumental effect (the GBM threshold energy is -10 keV). The smoothness parameter of the fitting function could also influence the value of $\alpha_1$, especially at the edge of the detector band pass, where few energy channels are available to constrain it. We found that a sharper break resulted in $\alpha_1$ approaching the synchrotron-predicted value of 2/3. However, we retained a consistent smoothness across all of our fits to avoid biasing our results.
The slope $\alpha_p$ of the power law between $E_p$ and $E_b$ was initially in excellent agreement with the expected value of $\alpha_p = 3/2$ for fast cooling, but later evolved upwards towards a photon index of 2. This trend may be explained by uncertainties in distinguishing $\alpha_p$ and $\beta_p$ as the latter moved downwards though the band. In particular, as the source faded and the signal-to-noise ratio in the high-energy GBM BGO detectors decreased, $\beta_p$ became poorly constrained. Our mean values were $\alpha_p = 1.61 \pm 0.25$ and $\beta_p = 2.80 \pm 0.54$.

After 42 s, the 2SBPL model was no longer statistically preferred over the Band function. For consistent fitting, we approximated the Band function by freezing $E_b$ below the band pass, removing $\alpha_p$ and $\Gamma$ from the model. The fitted values of $\alpha_p$ were in excellent agreement with the expected value of $\alpha_p$ (Fig. 3, bottom, green points), indicating that $E_b$ and $E_p$ were unresolved because they are too close together, rather than $E_b$ having evolved out of the band pass. We widened our time bins to 10 s after 50 s to improve the signal-to-noise ratio of our spectra. Fitting the simpler Band model between 42 and 80 s resulted in a much tighter constraint on the post-peak photon index, which now dominated the majority of the band pass: $\beta_p = 2.19 \pm 0.04$. This included a single power-law fit in the 70–80 s bin, indicating that both $E_b$ and $E_p$ were either below or very close to the 10 keV lower band-pass limit of GBM.

We note that, assuming an isotropic-equivalent kinetic energy of the jet $E_{iso,\gamma} = 4 \times 10^{53}$ erg derived from the afterglow modelling reported in ref. 1 and the $\gamma$-ray isotropic-equivalent energy $E_{iso,\gamma} = 7.4 \times 10^{49}$ erg we observed in the energy range 10–1,000 keV during the first 50 s of emission, the implied prompt $\gamma$-ray efficiency was $\eta = E_{iso,\gamma}(E_{iso,\gamma} + E_{iso,\gamma}) = 16\%$. This value is consistent with estimates for other GRBs in the literature (for example, ref. 27), but required a large contrast in the jet bulk Lorentz factor (for example ref. 28). We note, however, that recent works in the literature found a much smaller efficiency ($\eta = 10^{-5}$) when the fraction of electrons accelerated at the shock is included as a free parameter in the afterglow model (instead of the typical assumption that all electrons participate; see for example refs. 29,30). These efficiencies are compatible with the expectations of an internal shock model with a mild contrast of bulk Lorentz factors$^{29,30}$.

The magnetic field value implied by our findings ($B = 30–200$ G for a range of $R = 10^{13}$–$10^{18}$ cm) is consistent with the values derived in the cases of collapsar GRBs showing marginally fast-cooling synchrotron spectra$^{29,30,31,32}$, but low compared with expectations for a typical GRB emitting region ($B = 10^4–10^5$ G, for example ref. 29). For such a low magnetic field in a small emitting region, synchrotron self-Compton is expected to dominate the cooling rate (see for example refs. 30,33). A larger emitting region ($R = 10^{15}$–$10^{16}$ cm) would reduce the synchrotron self-Compton luminosity, but is more commonly associated with afterglow radiation and would be inconsistent with the rapid variability of the prompt light curve, unless the Lorentz factor is very high ($7 \geq 10^3$). One interesting solution to this problem has been recently proposed by ref. 34, ascribing the emission to proton synchrotron in dominant adiabatic cooling. Although this model offers an interesting alternative, it operates in a relatively small parameter space and its ability to explain all the observations is still under investigation (see for example ref. 35).

**80–120 s.** After 80 s there were too few GBM counts in 10 s bins to obtain sufficient signal-to-noise ratios. However, Swift-XRT began pointed observations of GRB 211211A at 79.2 s after trigger, and we were able to fit combined BAT + XRT spectra between 0.3 and 150 keV (except for a 5 keV interdetector gap between 10 and 15 keV). The extension of our spectral coverage down to 0.3 keV meant that the Band function (approximated by 2SBPL with $E_b$ held below the XRT bandpass) was preferred over the single power-law model once more. The low energy index continued to be consistent with the expectations for $\alpha_p$, indicating that $E_b$ and $E_p$ remain unresolved from one another. $E_p$ continues to evolve smoothly downwards, from $E_p = 8$ keV to ~5 keV (Fig. 3 and Table 1). The BAT data formally end at $t_0 + 122$ s.

**120–300 s.** From ~120 s, the measured value of $\alpha_p$ began to rise. We continued to measure a declining $E_b$ that evolved to just a few kiloelectronvolts and a consistent (but poorly constrained) $\beta_p$. We therefore interpret the change in $\alpha_p$ as being due to the synchrotron breaks now moving away from one another, resulting in an elongation of the 2SBPL $\alpha_p$ segment between them. Our measured $\alpha_p$ therefore evolved from being dominated by $\alpha_p$ to being a blend of $\alpha_p$ and $\alpha_p$ around the unresolved $E_b$. The power law with index $\alpha_p$ then began to dominate the measurement as it elongated, while $E_p$ approached the lower band-pass limit and pushed $\alpha_p$ out of the spectrum.

We investigated this possibility by refitting the 2SBPL model with $\alpha_p$ and $\alpha_p$ fixed to their expected values (2/3 and 3/2, respectively), leaving the break energies and $\beta_p$ free. We found that between 30 and 120 s after trigger, the two breaks could not be resolved from one another even with fixed photon indices. However, after 120 s we measured a clear division again (open symbols in Fig. 4). The fixed indices meant that the spectral shape observed at this time was still consistent with the fast-cooling regime ($\alpha_p < 2$), but it is worth noting that the increasing separation between $E_b$ and $E_p$ and the coincident evolution of $\alpha_p$ from 2/3 towards 3/2 indicates that the more rapidly evolving spectral break was now the lower energy of the two, in contrast with the first 42 s of evolution. This apparent crossing of the two spectral breaks was consistent with the source having transitioned from a fast-cooling regime to slow cooling$^{30,36}$ (see Fig. 3) for a possible slow-to-fast cooling transition.

If the spectrum was now slow cooling, $\alpha_p$ was no longer expected to have a value of 3/2, and instead should be $\alpha_p = (p + 1)/2$. We caution that slow cooling requires $p < 3$. Given that $\beta_p = p/2 + 1$, this is in contrast with the steep values of $\beta_p \geq 2$ measured in the early spikes of emission, but is consistent with the values of $\beta_p$ measured at the implied time of transition ($\beta_p < 2.5$; Fig. 3). The transition from fast to slow cooling would therefore also require a change in the electron energy distribution power-law index $p$ over time.

For the epochs in which $E_b$ and $E_p$ are unresolved (which are covered by the Band fits in Table 1) we found $\beta_p = 2.42 \pm 0.19$ which pointed to $p = 2.84 \pm 0.38$ and thus an expectation value of $\alpha_p = 1.92 \pm 0.19$ in the slow-cooling regime. Unfortunately, beyond 180 s our best-fitting model reduced to a power law while $\alpha_p$ was still evolving, meaning that we were unable to determine whether it supported fast or slow cooling. Our best-fitting 2SBPL model (which was not supported over the power-law fit by AIC) indicated $\alpha_p = 1.68 \pm 0.12$, broadly consistent with either scenario. We note that at very late times $\beta_p$ evolved to extremely soft values ($\beta_p < 3$). This is probably driven by an increase in $N_h$ (Table 1) and the decreasing signal-to-noise ratio at higher energies in the band pass.

**UVOT suggests additional absorption.** Regardless of the cooling regime, the spectral index below $E_b$ should be $\alpha_p = 2/3$. A recent analysis of optical detections obtained during the prompt emission of 21 long GRBs revealed that the spectrum between optical and $\gamma$-rays is well modelled with synchrotron emission; that is, optical data are consistent with the extrapolation of the expected 2/3 power-law index$^{12}$. The UVOT detection at 162.9 ± 74.9 s allowed us to investigate this possibility in GRB 211211A. We extracted a 10-s-wide XRT spectrum centred at 162.9 s and performed a combined fit of the UVOT and XRT data. The UVOT data required the further addition of two ZDUST components to the model to account for extinction in the GRB host galaxy and the Milky Way. The Milky Way extinction was fixed to $E(B-V) = 0.015$ (ref. 37). Host extinction was fixed to $E(B-V) = 0.18$, representing the $3\sigma$ upper limit that we derived from modelling the afterglow spectral energy distribution (SED) (see ‘Afterglow SED’).

To perform a joint fit of XRT and UVOT data, we used the 2SBPL model and fixed $\alpha_p = 2/3$, $\alpha_p = 3/2$ and $E_b = 0.3$ keV based on the results from our coincident spectral fit in Table 1. $E_b$ was allowed to vary to obtain the best match to the X-ray data, as the fitted epoch was

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offset in time with respect to the template at 170 ± 10 s. We found $E_p = 6.63 ± 1.60 \text{ keV}$.

The extrapolation of $\alpha = 2/3$ between the XRT and UVOT data overpredicted the UVOT flux by an order of magnitude (Fig. 6). Larger values of extinction would be inconsistent with the afterglow SED observations; a free fit found $E(B-V) = 0.60 ± 0.06$, which is -7.5 $\sigma$ inconsistent with our model fit with the highest $E(B-V)$ (Supplementary Table 4). An additional spectral break may therefore be required between the UVOT white filter and the XRT bandpass. One possibility for this break is the synchrotron self-absorption frequency ($\nu_{\text{ssa}}$), below which photons are absorbed by the emitting electrons. This region of the spectrum has an expected photon index of $\alpha = -1$ (or $\nu^{1/2}$ for an inhomogeneous distribution of electrons; ref. 43), and hence could resolve the tension if it lies close to (but above) the UV.

The co-moving frame synchrotron self-absorption frequency can be computed by equating the co-moving synchrotron flux at $\nu_{\text{ssa}}$ to the flux from a black body in the Rayleigh–Jeans part of the spectrum. Following ref. 46, we derived the distance $R$ of the emitting region from the central engine that is required to match the observations (that is, that produced $6 \times 10^{51} \text{ keV} < \nu_{\text{ssa}} < 0.3 \text{ keV}$). The value of $\nu_{\text{ssa}}$ depends on the magnetic field of the emitting region $B$ and on the bulk Lorentz factor $\Gamma$ of the jet. In our computations, we required $B$ to be consistent with the field derived from the observed $\nu_c = 20 – 60 \text{ keV}$ during the early prompt emission (Table 1 and Fig. 3) and assumed the same bulk Lorentz factor as before: $\Gamma = 100$.

We found that a compact emitting region at $R = 10^{10-12} \text{ cm}$ was required to place $\nu_{\text{ssa}}$ between UV and X-rays. We note that the variability timescale implied by such a compact source is in contrast with the smooth emission ~160 s after trigger. Moreover, such a small region would imply a high radiation density $U_{\text{rad}}$ increasing the expected synchrotron self-Compton luminosity and making it difficult to be optically thin to Thomson scattering and pair production. A larger radius (of a few $10^{12-13} \text{ cm}$) could be accommodated while still having $\nu_{\text{ssa}} \ll \nu_{\text{XRT}}$ by assuming $B = 10^{-3} – 10^6 \text{ G}$, but this is inconsistent with the observation of incomplete cooling of the electrons. We therefore conclude that it is unlikely that the UVOT flux is suppressed due to synchrotron self-absorption. Other causes of absorption (such as synchrotron photons absorbed by a cloud of not completely cooled electrons in the same line of sight, or pair production with higher-energy photons) must play a role in shaping the spectrum at low frequencies, but further, more quantitative investigations are needed to assess the feasibility of this process.

Afterglow SED

We constructed an optical–X-ray SED centred at 5.5 ks. The SED was constructed using the methodology of ref. 14, using data within a time range of 3–10 ks. To construct the pha files for the different optical filters at 5.5 ks, we first constructed a single-filter light curve by normalizing the individual filter light curves together. Then, using this single-filter light curve, we determined the temporal slope within the 3–10 ks interval. We fitted a power law to the individual filter light curves within this same time interval, fixing the slope to the value determined from the single-filter light curve. We used the derived normalizations to compute the count rate and count-rate error at 5.5 ks, which were then applied to the relevant spectral file. For the XRT data, we took photon counting mode time-slice spectral files built using the UKSSDC webtool within the 3–10 ks interval. The spectral files were normalized to correspond to the 3–10 ks flux of the afterglow at 5.5 ks. The flux, used to normalize a given spectrum, was determined by fitting a power law to the temporal data within the SED selected time range. The best-fit decay index was used to compute the flux at 5.5 ks, in the same way as was done for the optical data.

The SED was fitted using XSPEC v12.11.1, following the procedure outlined in refs. 82,84. We tested two different models for the continuum: a power law and a broken power law, with the lower energy photon index fixed at $\alpha = 2/3$, which corresponded to the expected spectral slope below the synchrotron peak frequency. In each of these models, we also included two dust and gas components to account for the Galaxy and host galaxy dust extinction and photoelectric absorption (PHABS, ZPHABS, ZDUST; we used ZDUST for both the Galaxy and host galaxy dust components, but with the redshift set to zero for the Galaxy dust component and $z = 0.076$ for the host components). The Galactic components were frozen to the reddening and column density values from ref. 84 and ref. 85, respectively. For the host galaxy dust extinction, we tested the dependence of dust extinction on wavelength for three different scenarios: the Small and Large Magellanic clouds (SMC and LMC, respectively) and on the Milky Way, and found no strong preference for any of these scenarios. We also accounted for the absorption due to the Lyman series as a function of wavelength and redshift, and we set this component to also include attenuation due to photoelectric absorption. The results are provided in Supplementary Table 4.

Comparison with other GRBs

The identification of a kilonova by ref. 12 means that, despite its duration, GRB 211211A is a high-confidence merger event. Although this discovery appears to answer the almost 20-yr-old question posed by the lack of supernovae in the nearby merger candidates GRBs 050724 and 060614 (refs. 86,87), GRB 211211A is also not a typical EE GRB. In particular, the IPC is at least a factor of two longer than any previously identified example, which are generally consistent with the $\tau_{\text{f}} < 2 \text{ s}$ hard spikes of the broader short GRB class (for example, refs. 86,87), where $\tau_{\text{f}}$ is the time in which the middle 90% of the fluence is detected. We note that in this case both BAT and GBM triggered on an extremely faint spike almost 2 s before the ‘main’ episode of prompt emission (for example, Fig. 1). Such a weak pulse would probably not be detectable from much further away than GRB 211211A, and may represent a precursor event that artificially extended the IPC duration compared with other EE GRBs. Precursors like this have been suggested to arise from flares due to the resonant shattering of the crusts of pre-merger neutron stars90–92. Quasiperiodic oscillations have also been identified in this feature.

We compared the broad properties of GRB 211211A with the sample of EE GRBs with redshifts from ref. 44, which we updated to include EE GRB 211227A. We note that ref. 44 found GRB 211211A to be spectrally harder than previous EE GRBs during both the IPC and EE phases, although their Band function and cutoff power-law model fits did not capture all of the complex evolution presented here. GRB 211211A has both the shortest $\tau_{\text{f}}$ and highest $E_{\text{iso}}$ of the known EE sample (Supplementary Table 1). 070714B has a shorter $\tau_{\text{f}}$ in the rest-frame and a comparable $E_{\text{iso}}$, although it has been shown that it is not straightforward to account for redshift in the durations of GRBs95. Despite the diversity in $\gamma$-rays, the X-ray profile of EE is highly similar across all known events (Fig. 5).

The sample of merger-driven GRBs investigated by ref. 45 present a single power-law below the $\nu_f$, peak, characterized by a hard photon index that is consistent with the expected 2/3 power law below $\nu_c$ (if in fast cooling) or $\nu_{\text{ms}}$ (if in slow cooling). In GRB 211211A, both synchrotron breaks have been distinctively identified and tracked in detail, demonstrating that the cooling of electrons via synchrotron processes occurs in merger-driven GRBs. Conversely, the discovery of a power-law segment with photon index 3/2 between $\nu_c$ and $\nu_{\text{ms}}$ in GRB 211211A is consistent with previous findings for collapsar GRBs, in addition to its long duration.

The $E_p$ measured in GRB 211211A is towards the higher end of the distribution found for the merger-driven GRBs in ref. 45, where the value of $E_p = 2.411±0.602 \text{ keV}$ was measured between 0 s and 2 s would rank 2/11 (between $E_p = 2.892±0.205 \text{ keV}$ for GRB 120624A and $E_p = 1.576±0.461 \text{ keV}$ for GRB 090227B). This is also higher than the collapsar-driven sample.
However, collapsar GRBs display a higher $E_\text{f}$ on average by a factor of several. In the extremely bright collapsar GRB 160625B, $E_\text{f}$ reached as high as $E_\text{f} = 6.596 \times 10^{42}$ keV and $E_\text{f} = 196.7 \pm 31.3$ keV at the peak of the main emission episode. There is therefore no particular trend between our 2SBPL fit results for GRB 211211A and those given in the literature for collapsar- and merger-driven GRBs.

**Evolution of the breaks**

The evolution of the spectral breaks is well described by an exponential profile of the form $E = Ne^{-t/t_\text{break}}$ in both cases (Fig. 4). $E_\text{f}$ is best fitted with $N_\text{f} = 1.344 \pm 0.141\text{ keV}$ and $t_\text{break} = 14.4 \pm 1.6\text{ s}$, whereas for $E_\text{f}$ we find $N_\text{f} = 36.2 \pm 4.9\text{ keV}$ and $t_\text{break} = 63.3 \pm 20.3\text{ s}$. The two profiles cross at $t_\text{break} = 68\text{ s}$, suggesting a transition from fast to slow cooling. Indeed, from $-50\text{ s}$ onwards (after the IPC and the peak of the EE luminosity), the spectral shape is consistent with a slow-cooling regime with $p = 2.2$ (Fig. 3). Measurements of $\beta > 2.5$ at early times ($\Delta t < 30\text{ s}$) are not consistent with this interpretation, and require that the index of the particles' energy distribution injected by the acceleration mechanism changes before the transition to slow cooling. Notably, $\beta$ is only seen to exceed 2.5 during spikes in emission, suggesting that this may indeed be the case.

A change in cooling regimes has been claimed recently in ref. 28, where the authors found that single-pulse GRB spectra detected by Fermi-GBM are well modelled with idealized synchrotron emission. The majority of the spectra are found to be in the slow-cooling regime, while a transition from slow to fast cooling has been found in some of them during the decay of the luminosity. The associated increase in radiative efficiency of such a transition even as luminosity is seen to decrease further challenges the energetics in the jet. Conversely, the implied fast-to-slow cooling transition in GRB 211211A happens at late times, during the decaying phase of the luminosity. It is therefore more easily reconciled with the expected evolution of the jet.

Once the jet has ceased, the fading luminosity and downwards evolution of $E_\text{f}$ may be explained by a combination of adiabatic cooling (see ref. 29) and high-latitude effects. Within a structured jet, the energy dissipation that gives rise to the prompt emission may, in the wider regions where the bulk Lorentz factor is $<30$, occur below the photospheric radius, $R_\text{p}$. If this dissipation radius, $R_\text{p}$, is below the photosphere, photons will be coupled to the plasma until the optical depth reaches unity. Unless the condition for efficient thermalization is met the resultant emission will have a lower luminosity and a spectral peak energy $\propto (R_\text{p}/R_\text{p})^{1/4}$ (ref. 26).

It is not clear how the exponential profile relates to EE in the BAT band pass, although we note that Fig. 4 suggests that $t_\text{break}$ may be underestimated and perhaps includes the EE phase before the turnover. Indeed, the turnover of the BAT light curve coincides with the faster-evolving break (identified here as $\nu_{\text{obs}}$ exiting the BAT band pass). $t_\text{break}$, which measures the $\gamma$-ray duration exclusively, is highly variable across the EE sample (for example Supplementary Table 1), and this may point towards less uniform behaviour from $\nu_{\text{obs}}$ corresponding to a greater diversity in IPC durations, which is indeed observed. However, $t_\text{break}$ is also subject to other effects, such as redshift or viewing angle, which would serve to obfuscate the implied correlation between the durations of the IPC and EE at $\times\text{r}$ frequencies.

**Evidence for a merger origin**

As shown by ref. 12, the radio-to-X-ray observations following GRB 211211A can be readily explained by a kilonova with striking similarity to AT 2017gfo21,22 superimposed over a GRB afterglow. The measured offset in projection from the putative host at $z = 0.076$ is $7.91 \pm 0.03\text{ pc}$, consistent with the median offset of 7.92 kpc for merger GRBs.22 The i-band upper limit at 17.6 d after trigger excludes all known collapsar GRB supernovae out to $z = 0.5$ (ref. 23). Measurements of the lag in arrival times between high- and low-energy photons are consistent with zero, and hence merger GRBs.100. The measured spectral lag is inconsistent with the established collapsar GRB lag–luminosity relation unless the redshift is $z > 1.5$ (corresponding to $L \gtrsim 10^{51}\text{ erg s}^{-1}$), but this is ruled out by the detection in the Swift-UVOT UVM2 filter. A purely $^{56}$Ni-powered transient (a supernova or the merger of a neutron star with a white dwarf) is unable to evolve fast enough to match the GRB 211211A light curve.

Recently, ref. 103 proposed an alternative explanation for the infra-red excess in GRB 211211A by invoking a dust destruction model in which a collapsar (originating from a massive star) was embedded in a dense molecular cloud that was subsequently heated by the UV radiation from the GRB. Their primary argument against the kilonova interpretation is the seemingly large k- to i-band flux ratio at 5.1 d post-merger (43 ± 29), but this is only in L.2.3 extent23 with the ratio seen in AT 2017gfo (even before accounting for systematic uncertainty) and comfortably within the range of radioactivity-powered models20,24. In addition to the arguments above that strongly favour a merger-driven GRB, the dust destruction model requires that GRB 211211A is not associated with ‘Galaxy A’ (whose light extends to the burst position) at $z = 0.076$ and instead originated from an unseen halo galaxy associated with Galaxy B at $z = 0.459$. This would be the faintest GRB host ever identified at $z < 3$ (ref. 104) with a dust content that is atypical of very-low-mass galaxies.22,25,26 Furthermore, we detected no residual absorption in either $N_\text{H}$ or $A_v$ over the Milky Way contribution in our study; the host contribution in both metrics is consistent with zero. We therefore conclude that the observed evolution and location of GRB 211211A strongly favours the merger interpretation.

**Data availability**

The majority of data generated or analysed during this study are included in this Article and its Supplementary Information. Swift and Fermi data can be downloaded from the UK Swift Science Data Centre (https://www.swift.ac.uk/) and the online HEARSAC archive (https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html). Additional data are available from the corresponding author upon reasonable request.

**Code availability**

The codes used in this publication are all publicly available. Fitting was performed in XSPEC25, which is available from https://heasarc.gsfc.nasa.gov/xanadu/xspec/. Swift tools are available from https://heasarc.gsfc.nasa.gov/leasoft/, and Fermi tools from https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/fermi.html. The 2SBPL model is published in ref. 12. Plots were created using matplotlib in Python v3.9.7.

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**Author contributions**

B.P.G. extracted the Swift data, performed the spectral analysis, provided the interpretation of the spectral evolution and the EE context and wrote the text. M.E.R. extracted the Fermi data, performed the spectral analysis, provided the interpretation on the emission physics and co-wrote the text. M.N. and A.J.L. contributed vital insights into the direction of the study and co-wrote the text. B.D.M. provided theoretical interpretation, insights into the progenitor and contributed to the text. S.R.O. performed the afterglow SED fits, reduced the UVOT data and contributed to the text. G.P.L. provided theoretical interpretation, self-consistency checks of the physics and made contributions to the text. D.B.M. helped with the interpretation of the emission physics and writing of the text. W.F., J.C.R., N.R.T., P.G.J. and A.P. helped in the discussion and writing of the text. P.A.E. and K.L.P. provided insights into Swift data reduction and handling, and commented on the text.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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