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Illuminating gravitational waves: A concordant picture of photons from a neutron star merger

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Merging neutron stars offer an exquisite laboratory for simultaneously studying strong-field gravity and matter in extreme environments. We establish the physical association of an electromagnetic counterpart (EM170817) to gravitational waves (GW170817) detected from merging neutron stars. By synthesizing a panchromatic dataset, we demonstrate that merging neutron stars are a long-sought production site forging heavy elements by r-process nucleosynthesis. The weak gamma-rays seen in EM170817 are dissimilar to classical short gamma-ray bursts with ultra-relativistic jets. Instead, we suggest that breakout of a wide-angle, mildly-relativistic cocoon engulfing the jet elegantly explains the low-luminosity gamma-rays, the high-luminosity ultraviolet-optical-infrared and the delayed radio/x-ray emission. We posit that all merging neutron stars may lead to a wide-angle cocoon breakout; sometimes accompanied by a successful jet and sometimes a choked jet.

On 2017 August 17 at 12:41:04 UTC, gravitational waves from the merger of two neutron stars (NS-NS) were detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO) and dubbed GW170817 (*1*). Two seconds later, the first temporally-coincident photons were detected as γ-rays by the *Fermi* satellite (*2*–*4*). GW170817 was a sufficiently loud event that the joint on-sky localization from the LIGO and Virgo interferometers was 31 square degrees (Fig. 1) with an initial distance estimate of 40 ± 8 Megaparsec (*5*). To identify potential host galaxies (*6*, *7*), we cross-matched to our Census of the Local Universe [CLU; (*8*)] galaxy catalog and found only 49 galaxies in this volume (*9*, *10*). To prioritize follow-up, we ranked the galaxies by stellar mass [see table S1 and the supplementary materials (*10*)]. A multitude of telescopes promptly began multi-wavelength searches for an electromagnetic counterpart in and around these galaxies. Ground-based searches were systematically delayed (due to the Southern location) by half a day until sunset in Chile (*11*, *12*). A bright optical transient was identified and announced by the Swope telescope team at Las Campanas Observatory (*13*, *14*) in the 3rd ranked galaxy in our list, named NGC 4993 . This source, SSS 17a, is located at right ascension $13^h09^m48.071^s$ and declination $-23^d22^m53.37^s$ [J2000 equinox, (*10*)], with a projected offset from the nucleus of NGC 4993 of 2.2 kiloparsec and away from any sites of star formation [fig. S1 (*10*)]. We also detect this transient in the infrared and ultraviolet wavelengths [see companion paper; (*15*)]. Nine days later, an x-ray counterpart was identified (*16*, *17*). Fifteen days later, a radio counterpart was identified [see companion paper; (*18*)].

Initially, the bright luminosity and the blue, featureless optical spectrum of SSS17a appeared to be consistent with a young supernova explosion that should brighten (see figs. S2 and S3). However, on the second night, the source faded substantially in the optical and brightened in the infrared (Fig. 4). Combining ultraviolet-optical-infrared (UVOIR) data from 24 telescopes on 7 continents, we constructed a bolometric light curve [Fig. 2; see (*10*) for details]. The bolometric luminosity evolves from 10^{42} erg s^{-1} at 0.5 d to 3×10^{40} erg s^{-1} at 10 d (Fig. 2). By estimating the black-body effective temperature evolution, we find that the source rapidly cools from ≈11000 K to ≈5000 K in a day to ≈1400 K in ten days. The inferred photospheric expansion velocities span 0.3c to 0.1c, where c is the speed of light (*10*). Furthermore, infrared spectroscopy shows broad features that are unlike any other transient seen before (Fig. 3 and figs. S4 and S5). The combination of high velocities, fast optical decline, slow infrared evolution and broad peaks in the infrared spectra are unlike any other previously known transient and unlikely to be due to a chance coincidence of an unrelated source. We thus establish that the panchromatic photons, hereafter EM170817, are spatially, temporally and physically associated with GW170817. With this firm connection, we now turn our attention to understanding the astrophysical origin of EM170817 .

Evidence for nucleosynthesis of heavy elements

It is well established that chemical elements up to iron in the periodic table are produced either in the Big Bang or in cores of stars or in supernova explosions. However, the origin of half the elements heavier than iron, including gold, platinum and uranium, has remained a mystery. These heavy elements are synthesized by the rapid capture of neutrons (r-process nucleosynthesis). Some models have proposed that the decompression of neutron-rich matter in a NS-NS merger may provide suitable conditions to robustly synthesize heavy r-process elements (*19*, *20*). Radioactive decay of freshly synthesized unstable isotopes should drive transient electromagnetic emission known as a kilonova or macronova [e.g., (*21*, *22*)]. We test this hypothesis with the optical and infrared data of EM170817 .

First, we compare the spectra of EM170817 to a library of astronomical transients (*10*) and theoretical models for macronova spectra (*23*). The optical spectra exhibit a featureless continuum (figs. S2 and S3). Infrared spectra (Fig. 3) have two distinct, broad peaks in *J*-band (10620 ± 1900 Angstrom) and *H*-band (15500 ± 1430 Angstrom). Due to the high velocities in the ejecta material, each peak may be produced by a complex blend of elements instead of a single element. Although the *J*-band peak is reminiscent of either helium or hydrogen, the corresponding feature in the *H*-band seen in core-collapse supernovae is not present (fig. S5). If instead we compare to Type Ia supernovae, the *J*-band peak could be similar to iron group elements. However, once again, the second *H*-band peak is dissimilar to that seen in Type Ia supernovae (fig. S4). By comparing predictions of spectra of macronovae (*23*), based on the assumption that neodymium (Nd) is representative of lanthanides synthesized via the r-process, we find a reasonable match to both the *J*-band and *H*-band features for ejecta mass (M_{ej}) of 0.05 solar masses ($M_\odot$) and velocity (v) of 0.1c (Fig. 3). Recent updates to these models, incorporating line transitions from 14 elements and tuning the relative abundance ratios, indicate that Nd plays a crucial role in explaining these features (*24*). We conclude that a blend of elements substantially heavier than elements produced in supernovae is a viable explanation for the spectra of EM170817 .

Next, we compare our infrared light curves of EM170817 (Fig. 4) to a suite of existing macronova models by various groups (*25*–*28*). The slow, red photometric evolution seen in EM170817 is a generic feature of all macronova models despite their differing treatments of matter dynamics, matter geometry, nuclear heating, opacities and radiation transfer. The observed late-time emission (>3 d) is fully consistent with radioactive decay of the dynamical ejecta containing elements from all three r-process abundance peaks (fig. S10). The observed luminosity, temperature and temporal evolution roughly matches model predictions for an ejecta mass of ~0.05 $M_\odot$, an ejecta velocity of ~0.1c and an opacity (κ) of ~10 $cm^2 g^{-1}$.

We examine this match further with simple analytics. Dividing the observed bolometric luminosity ($\approx 6 \times 10^{41}$ erg s^{-1} at 1 day) by the beta-decay heating rate of r-process elements [$\approx 1.5 \times 10^{10}$ erg s^{-1} g^{-1}; (*29*)] gives a lower limit on the r-process ejecta mass of >0.02 $M_\odot$. The decline rate of the bolometric luminosity also matches that expected from the beta-decay heating rate of r-process elements with the time-dependent thermalization efficiency of the decay products (Fig. 2). The expansion velocity of the ejecta, 0.1 – 0.3c, derived from the photospheric radius is consistent with the results of merger simulations (*30*–*32*). Ejecta mass estimates based on observed emission are necessarily lower limits as a significant amount of additional matter can be hidden at lower velocity.

Next, we focus on the early-time emission of EM170817 that is hotter, more luminous and faster-rising than predicted by the suite of macronova model predictions discussed above (Fig. 4). Decay of free neutrons would give an unphysically large ratio of neutron mass to ejecta mass (*10*). Ultraviolet flashes predicted by (*33*, *34*) are on much shorter timescale than observed for EM170817 . Instead, we propose two possible explanations: (i) If some fraction of the ejecta is boosted to mildly relativistic speeds, the relativistic expansion shortens the observed peak time and the Doppler effect results in bluer, brighter emission. The jet cocoon model (see below) can accelerate enough material at higher latitudes. All material would have $\kappa \gtrapprox 1$ $cm^2 g^{-1}$ in this scenario. (ii) A disk-driven wind enriched with lighter r-process elements with $\kappa \approx 0.5$ $cm^2 g^{-1}$ could also produce early, blue emission (*15*). This wind could be driven from a merger remnant that is a massive neutron star with an accretion torus. We could have distinguished between these two possibilities if data were available at even earlier times.

A synthesized model explaining the panchromatic photons

We discuss three models in an effort to build a self-consistent picture that explains the γ-ray, x-ray, ultraviolet, optical, infrared and radio photons (Fig. 5).

A classical, on-axis short hard gamma ray burst: Ruled out

A classical short hard gamma ray burst (sGRB) is produced by a jet in the line-of-sight of the observer (Model A in Fig. 5) that is narrow (opening angle $\theta_{jet} \sim 10°$) and ultra-relativistic (Lorentz factor $\Gamma >\sim 100$). The progenitors of sGRBs have long been hypothesized to be NS-NS mergers (*35*). However, the observed γ-ray luminosity of EM170817 [~10^{47} erg s^{-1}, (*3*, *4*)] is lower than typical sGRBs by four orders of magnitude (*36*, *37*). If EM170817 were simply an extremely weak sGRB, then the successful breakout of a narrow, ultra-relativistic jet would require < 3×10^{-6} $M_\odot$ of material that was previously ejected in the direction of the jet (*10*). If the jet opening angle were wider, it would require even less material to successfully break out (*10*). Such a low ejecta mass is in contradiction with the observed bright UVOIR counterpart, which indicates $\approx$ 0.05 $M_\odot$ of ejecta. Furthermore, this scenario cannot account for the delayed onset of x-ray emission (*15*) and radio emission (*18*).

A classical, off-axis short hard gamma ray burst: Unlikely

Next, we consider the possibility of a classical off-axis sGRB where the observer is not in the line-of-sight of a strong, ultra-relativistic jet (Model B in Fig. 5). Given the sharp drop in observed γ-ray luminosity with observing angle, we find that the observer could only be off-axis by <8° (*10*). Such a slightly off-axis orientation is unlikely as only a small fraction (≈5%) of observing angles are consistent with the observational constraints. Moreover, in this scenario, EM170817 is expected to exhibit a bright afterglow at all wavelengths roughly one day after the NS-NS merger, when the external shock decelerates to $\Gamma \sim 10$. Initial non-detections in the radio (*18*) and x-ray (*15*) observations at this phase constrain the circummerger environment to an implausibly low density (<10^{-6} cm^{-3}). Another problem is that a hypothetical on-axis observer to such a sGRB would expect to see photons harder than we have thus far seen in sGRBs (*10*). Thus, it is unlikely that the γ-rays are produced by a slightly off-axis sGRB.

We conclude that EM170817 is not similar to the classical population of previously observed sGRBs. While the observed γ -rays are indicative of a relativistic outflow (with or without a jet), they must originate in a different physical mechanism (*10*). We explore the possibility of a structured jet in sGRBs with a distribution of Lorentz factors and identify multiple challenges with this model (*10*). Therefore, next, we propose a model with a wide-angle mildly relativistic outflow that propagates in our direction with a relatively small Lorentz factor.

Cocoon breakout: A concordant picture

Based on our UVOIR observations, we estimate that a few hundredths of a solar mass of ejecta are propelled into the circummerger medium of a NS-NS merger with velocities spanning a few tenths the speed of light. We consider a model where a relativistic jet is launched after a short delay, perhaps on account of a delayed collapse of the hyper-massive neutron star into a black hole. As the jet drills through the ejecta, the material enveloping the jet inflates to form a pressurized cocoon that expands outward at mildly relativistic speeds. There are two possibilities: If the jet is wide-angle (≈30°), it will become choked and fail to drill out (Model C in Fig. 5). If the jet is narrow (≈10°) and long-lived, it could penetrate the ejecta and look like a classical sGRB to an on-axis observer (Model D in Fig. 5).

Independent of the fate of the jet that created the cocoon, recent numerical simulations (*34*) show that the cocoon would expand at mildly relativistic velocities ($\Gamma \approx 2$–3) over a wide opening angle (≈40°) with energy comparable to the jet. The cocoon has a wide enough angle and sufficient kinetic energy to easily explain the observed γ-rays. However, it remains unclear how a cocoon would dissipate its energy internally at the radius where γ-rays are observed, given its ballistic and homologous expansion (unlike sGRB jets which are expected to be variable with irregular internal velocities and structure that can dissipate the jet energy by internal shocks or magnetic reconnection). A wide angle mildly relativistic cocoon, found by (*34*), was recently proposed as a source of wide-angle γ-ray emission (*38*). However, this was based on an ad hoc dissipation process that is somehow at work near the photosphere (*38*). We suggest that the dissipation mechanism is the interaction of the cocoon with the ejecta and that the observed γ-rays result from the breakout of the mildly relativistic shock (driven by the cocoon) from the leading edge of the ejecta. We find that such a breakout can explain all properties of the observed low-luminosity γ-rays if its Lorentz factor is ≈ 2–3 and the breakout radius is ~ 3×10^{11} cm (*10*).

We performed a relativistic hydrodynamical simulation in which a jet is injected into expanding ejecta to verify this picture for EM170817 (*10*). We find that even if a minute amount of ejecta ($\approx 3 \times 10^{-9}\ M_\odot$) moves at $0.8c$, the breakout radius and velocity match those needed to produce the observed γ-rays for a wide range of ejecta and jet properties (*10*). For example, in the simulation shown in Fig. 6, a shock with $\Gamma \approx 2.5$ breaks out 10 s after the merger at a radius of 2.4×10^{11} cm, generating γ-ray emission that would be observed with a delay of 2 s with respect to merger time [consistent with the *Fermi* observations; (*3*, *4*)]. After the cocoon breaks out, the photons that were deposited by the shock diffuse outwards and produce cooling emission that fades on timescales of hours (*34*). After a few hours, radioactive decay of r-process elements becomes the dominant source of the observed emission. The emission during the first day is dominated by fast cocoon material ($v \approx 0.4c$), which is composed of high-latitude, low-opacity ($\kappa \sim 1$ cm^2 g^{-1}) ejecta that was accelerated by the jet to high velocities. After a few days, the slower, higher-opacity ($\kappa \sim 10$ cm^2 g^{-1}) dynamical ejecta begins to dominate the emission. We find that the bolometric light curve evolution and the temperature evolution predicted by this simulation is consistent with our UVOIR observations (Fig. 2).

The available radio and x-ray data are broadly consistent with both cocoon scenarios albeit with slightly different circummerger densities (*15*, *18*). If the jet is choked, the radio and x-ray data could be explained by the forward shock that the expanding cocoon drives into the circummerger medium. If the jet is successful, the radio and x-ray data could be explained as a widely off-axis afterglow of the jet. If this emission is from the forward shock of a cocoon, we predict that the x-rays and radio will continue to rise. On the other hand, if this emission is from a widely off-axis afterglow of the jet, we predict that it will evolve slowly and eventually fade. In both scenarios, a cocoon would be needed to explain the γ-rays. We conclude that the cocoon model can self-consistently explain the multi-wavelength properties of EM170817 spanning γ-rays to radio.

Implications

Now we consider the question of whether EM170817 was an exceptional event or whether multi-messenger detections will soon become routine. The large ejecta masses and high velocities seen in EM170817 suggests that intrinsically luminous UVOIR macronova emission should accompany every NS-NS merger. If our proposed mildly relativistic cocoon model is correct, the wide opening angle of the cocoon implies that γ-rays would be emitted toward the observer in about 30% of NS-NS mergers. If the jet is choked, we expect to see late onset of radio and x-ray emission from the cocoon forward shock. If the jet producing the cocoon successfully breaks out, the source would appear either as a classical wide off-axis afterglow or a classical on-axis afterglow depending on the observer's line-of-sight. The launch of a successful on-axis cocoon jet may already have been seen in previous reports of possible late-time excess optical/infrared emission in sGRBs attributed to macronovae. In Fig. 4, we find that the excess seen in GRB 130603B (*39*), GRB 160821B (*40*) and GRB 050709 (*41*) are roughly consistent with our observed light curve for EM170817 . Separately, a plateau in the distribution of durations of sGRB may indicate that a large fraction of sGRBs may have choked jets (*42*). Joint gravitational wave and electromagnetic observations of NS-NS mergers will shed light on the relative fraction of cocoons with choked jets and cocoons with successful jets.

Now we consider whether NS-NS mergers could be the primary sites of r-process nucleosynthesis. This depends on both the rate of NS-NS mergers and the average amount of r-process material synthesized per merger. Based on the macronova light curve, we estimated a lower limit on the mass of the produced r-process elements in EM170817 to be $M_{\rm ej} \approx 0.05 M_\odot$. The solar abundance pattern shows that the first of three r-process peaks accounts for ≈80% of the total r-process abundance [fig. S10 and (*10*)]. To account for the observed solar abundance in all three r-process peaks with NS-NS mergers, we would need a rate of ~500 Gpc^{-3} year^{-1} ($M_{ej}/0.05M_\odot$)$^{-1}$. To account for the observed abundance in the two heavier r-process peaks with NS-NS mergers, the rate would only need to be ~100 Gpc^{-3} year^{-1}. Based on the detection of GW170817, a NS-NS merger rate of 320–4740 Gpc^{-3} year^{-1} was estimated at 90% confidence (*1*). This is larger than the classical sGRB beaming-corrected rate (*43*, *44*) and larger than the predicted fraction of NS-NS mergers based on the Galactic population (*45*). Based on an archival search for transients like EM170817 in the Palomar Transient Factory database, we find a 3-σ upper limit on the rate of 800 Gpc^{-3} year^{-1} (*10*). Therefore the large ejecta mass of EM170817 and the high rate estimates of GW170817/EM170817 are consistent with the scenario that NS-NS mergers are the main production sites of r-process elements of the Milky Way [as predicted by (*19*)].

The large rate, the wide angle for contemporaneous γ-rays, the bright UVOIR emission, the forward shock giving a late onset of x-rays and radio, the increase in sensitivity of GW interferometers, the increase in sensitivity of EM facilities [e.g., (*46*–*49*)]—all imply many more events like EM/GW170817.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/cgi/content/full/science.aap9455/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S10
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Movie S1
Data S1 and S2
Interactive Light Curves for SSS17a

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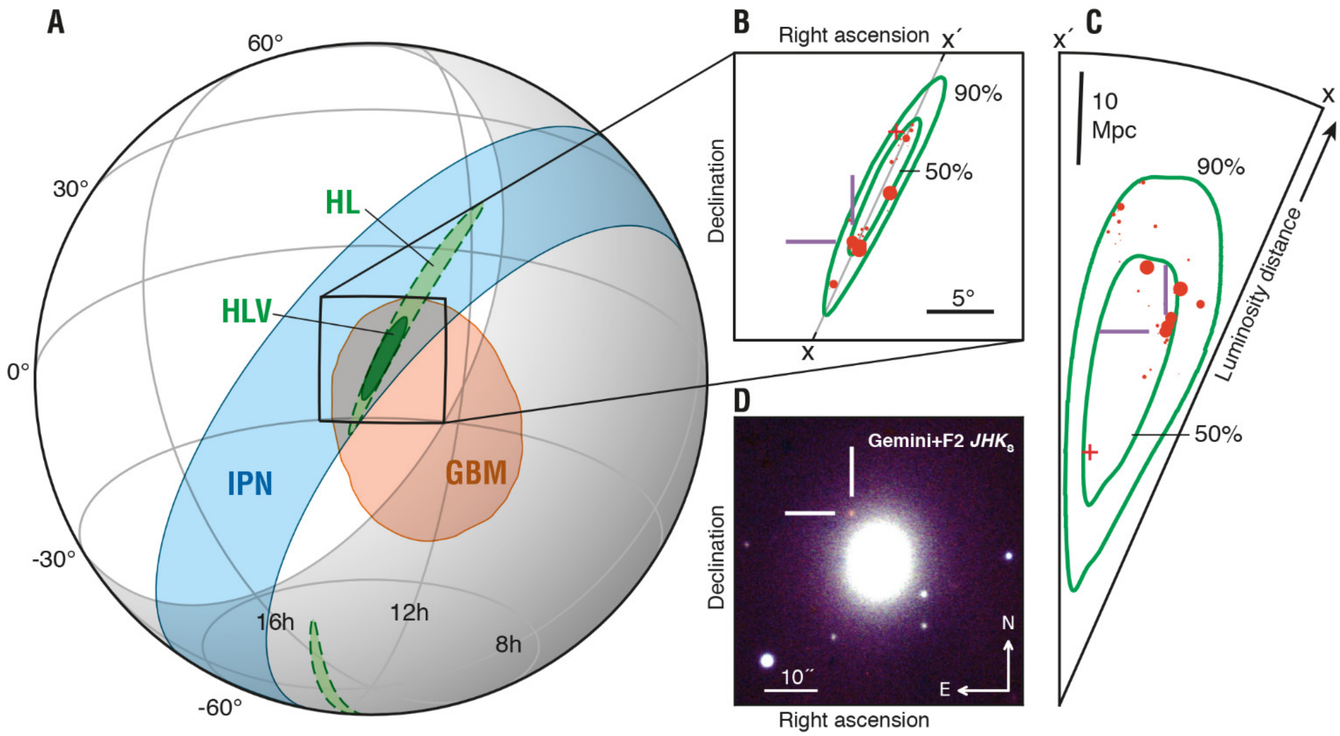

Fig. 1. Localization of GW170817 and associated transient EM170817. (**A**) Constraints at the 90% confidence level on the sky position from gravitational-wave and γ-ray observations. The rapid LIGO localization is indicated by the green dashed contour, and the LIGO/Virgo localization by solid green. *Fermi* GBM (*4*) is shown in orange, and the Interplanetary Network triangulation from *Fermi* and *INTEGRAL* in blue (*50*). The shaded region is the Earth limb as seen by *AstroSat* which is excluded by the non-detection by the Cadmium Zinc Telluride Imager instrument. (**B**) 49 galaxies from the Census of the Local Universe catalog (table S3; red, with marker size proportional to the stellar mass of the galaxy) within the LIGO/Virgo three-dimensional 50% and 90% credible volumes (green). One radio-selected optically-dark galaxy whose stellar mass is unknown is marked with a +. (**C**) Cross-section along the X-X′ plane from panel B, showing the luminosity distances of the galaxies in comparison to the LIGO/Virgo localization. (**D**) False-color near-infrared image of EM170817 and its host galaxy NGC 4993, assembled from near-infrared observations with the FLAMINGOS-2 instrument on Gemini-South (*10*), with *J*, *H*, and K_s shown as blue, green, and red, respectively. Our K_s-band detections span 2017 Aug 18.06 to 2017 Sep 5.99 and we show 2017-08-27.97 above.

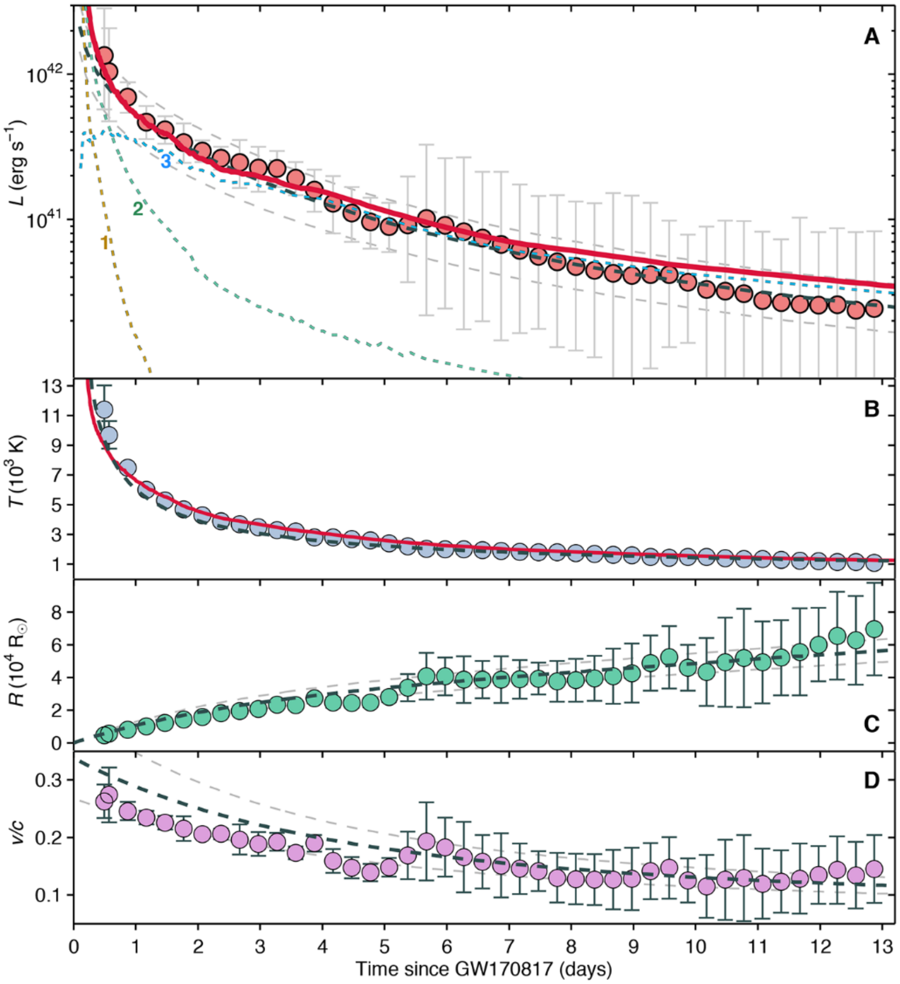

Fig. 2. The evolution of EM170817 derived from the observed spectral energy distribution. (**A**) Bolometric luminosity. (**B**) Blackbody temperature. (**C**) Photospheric radius. (**D**) Inferred expansion velocity. Individual points represent blackbody fits performed at discrete epochs to which the observed photometry has been interpolated using low-order polynomial fits. Dashed lines represent an independent Markov-Chain Monte Carlo fit without directly interpolating between data points (see (*10*) for methodology and best-fit parameter values). The solid red lines [in (A) and (B)] represent the results of a hydrodynamical simulation of the cocoon model where the UVOIR emission is composed of [in (A)] cocoon cooling (yellow dashed line labeled 1), fast macronova (>0.4*c*; green dashed line labeled 2), and slow macronova (<0.4*c*; blue dashed line labeled 3).

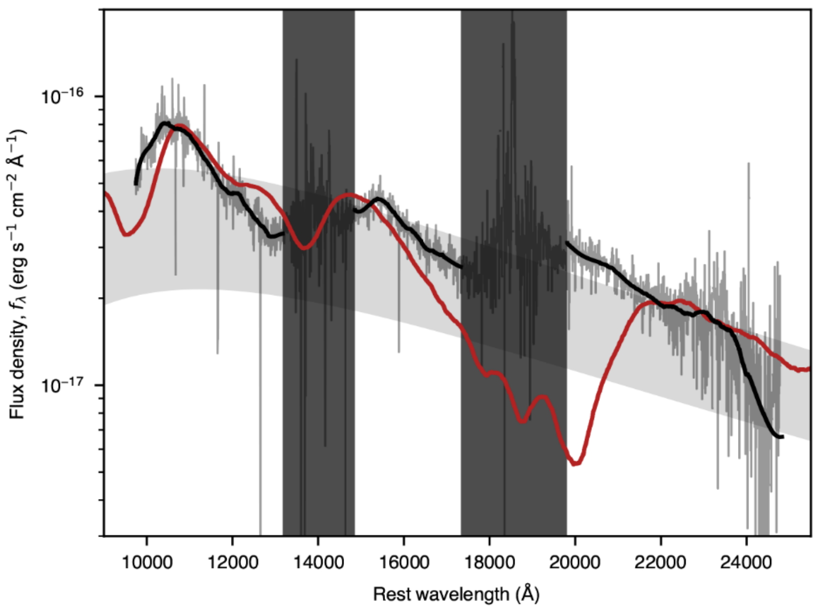

Fig. 3. Near-infrared spectrum of EM170817 at 4.5 days after merger. For display purposes, the data have been smoothed using a Savitzky-Golay filter (solid black line), and the unfiltered data are shown in grey. A predicted model macronova spectrum (*23*) assuming an ejecta mass of $M_{ej} = 0.05M_\odot$ and a velocity of $v = 0.1c$ at a phase of 4.5 days post merger is shown in red. The spectra have been corrected for Milky Way extinction assuming reddening $E(B - V) = 0.1$ (*10*). Regions of low signal-to-noise ratio from strong telluric absorption by the Earth's atmosphere between the near-infrared *J*, *H*, and *K* spectral windows are indicated by the vertical dark grey bars. The light grey shaded band is the blackbody which best fits the photometric measurements at 4.5 days (*10*).

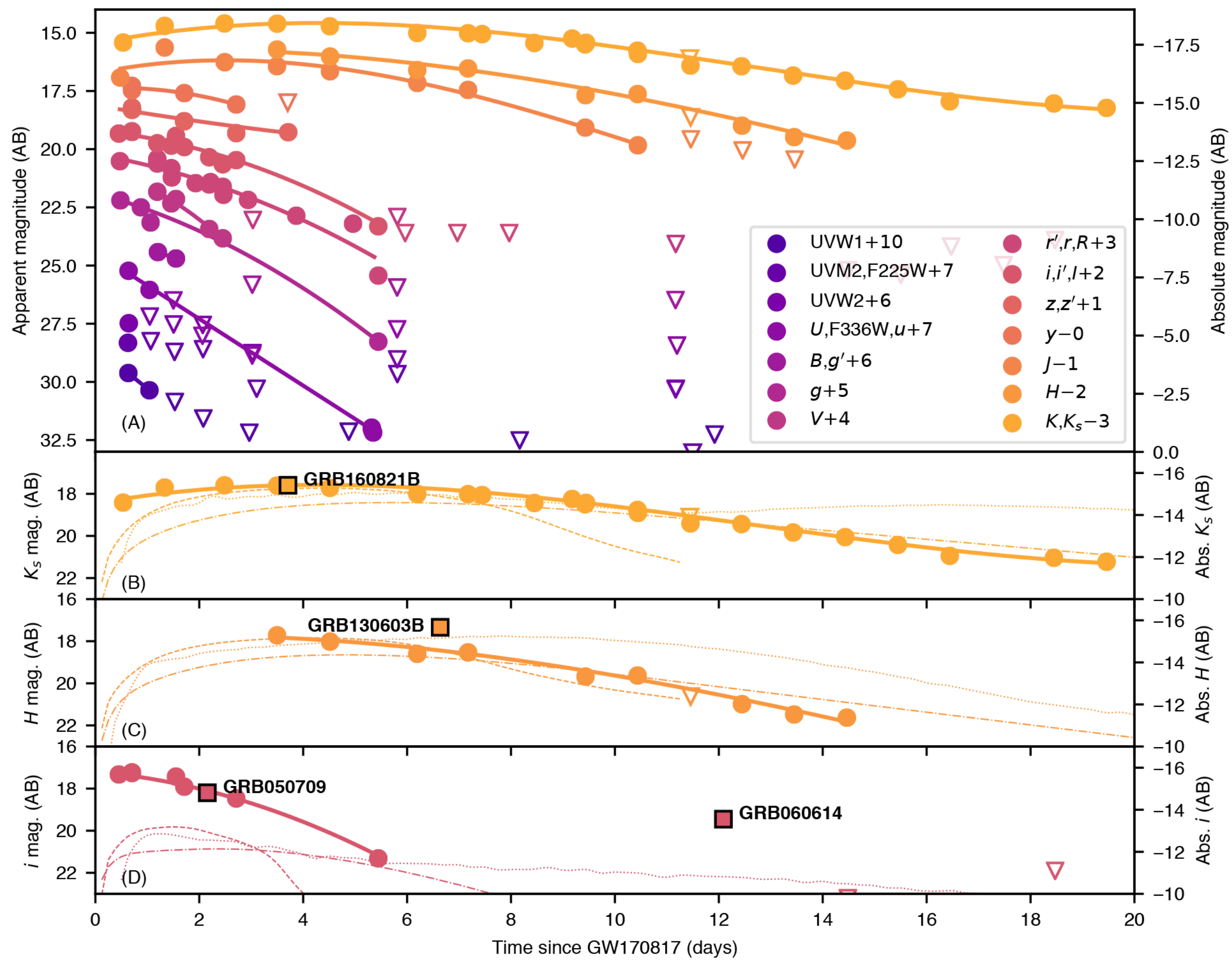

Fig. 4. Light curves of EM170817. (**A**) Multi-wavelength light curve based on the ultraviolet/optical/near-infrared photometry of EM170817 [table S1 and (*10*)] plotted as AB magnitude vs. time since merger, with open triangles indicating 5σ upper limits, colored by wavelength. (**B** to **D**) K_s, *H*, and *i*-band light curves of EM170817 with literature macronova model light curves, which show a good match in the infrared but fail to produce the observed blue emission. For all light curves we plot both apparent magnitude and absolute magnitude assuming a distance of 40 Mpc. Detections are shown as circles, upper limits as triangles. The models have been scaled to a distance of 40 Mpc and reddened with $E(B-V) = 0.1$ (*10*). The model light curves are the following: $M_{ej} = 0.05M_\odot$, $v_{ej} = 0.1c$ from (*51*), model N4 with the DZ31 mass formula from (*27*) and γA2 at a viewing angle of 30° from (*28*). Optical and near-infrared observations of previously observed short GRBs which appeared abnormally bright are shown as squares (scaled to 40 Mpc and corrected for time dilation). GRB080503 (*52*) would have had to be at a redshift of 0.22 to be consistent. GRB 060614 (*53*) is too luminous at late times. The excess emission noted in GRB 160821B (*40*), GRB 130603B (*39*) and GRB 050709 (*41*) appear to be similar to EM170817.

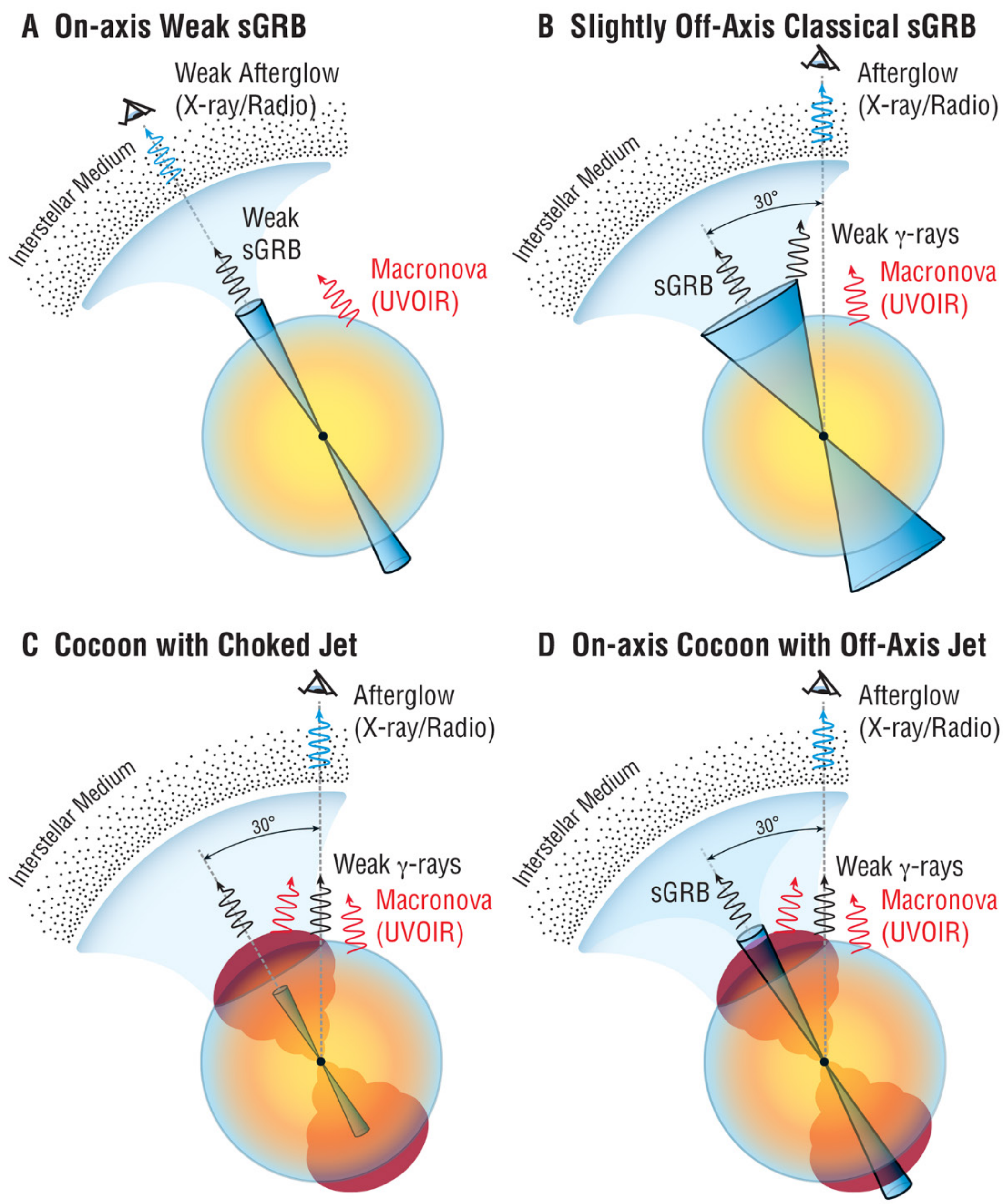

Fig. 5. Model schematics considered in this paper. In each panel, the eye indicates the line of sight to the observer. (**A**) A classical, on-axis, ultra-relativistic, weak short gamma-ray burst (sGRB). (**B**) A classical, slightly off-axis, ultra-relativistic, strong sGRB. (**C**) A wide-angle, mildly-relativistic, strong cocoon with a choked jet. (**D**) A wide-angle, mildly-relativistic, weak cocoon with a successful off-axis jet.

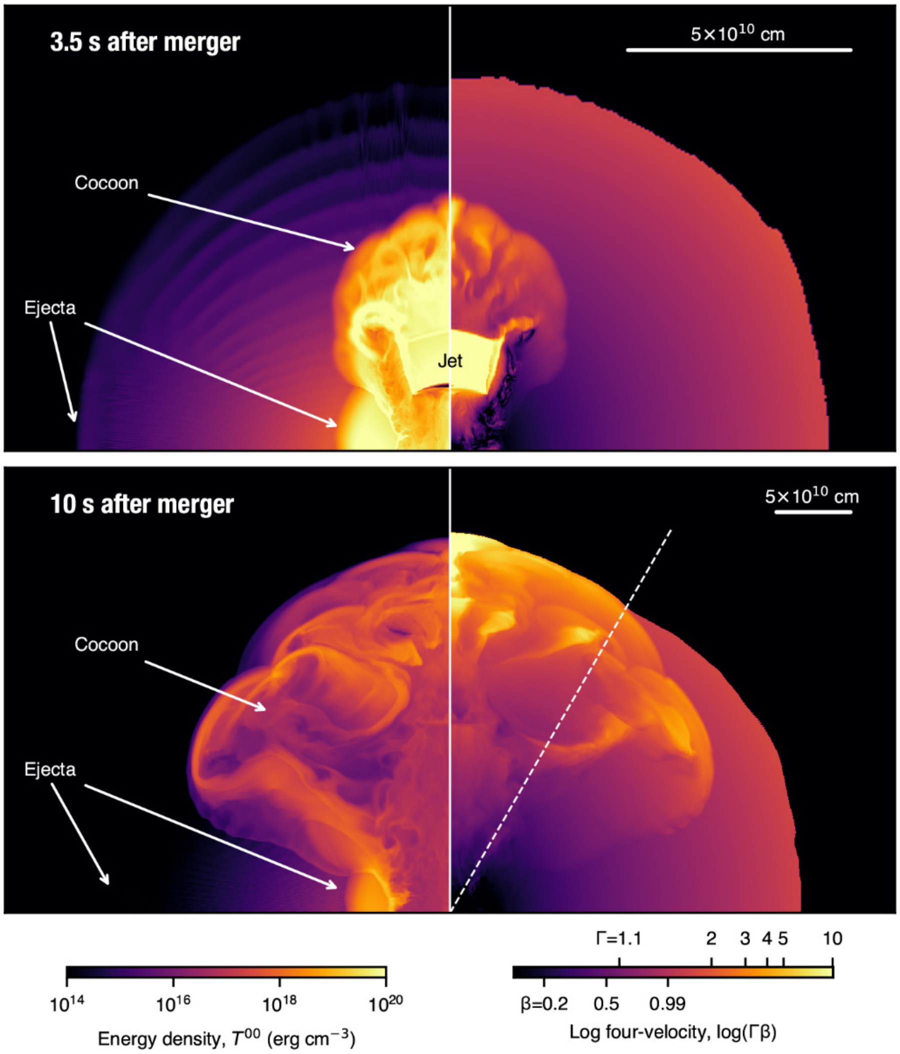

Fig. 6. Snapshots from a hydrodynamic simulation of a cocoon generated by a choked jet with emission consistent with EM170817 (see (*10*) for details). The left half-plane is color-coded by logarithmic energy density (erg cm^{-3}) and depicts the energetics. The right half-plane is color-coded by logarithmic four-velocity ($\Gamma\beta$) and depicts the kinematics. The observer is at an angle of 40°, the ejecta mass is 0.1 $M_{\odot}$ and the jet luminosity is 2.6×10^{51} erg s^{-1}. Based on this simulation, a bolometric light curve is calculated and shown in Fig. 2. (**A**) This snapshot is taken at 3.5 s, shortly after the jet injection stops. The jet is fully choked by 4s. (**B**) This snapshot is taken at 10 s when the cocoon breaks out. The breakout radius is 2.4×10^{11} cm which corresponds to 8 light-seconds. Thus, the delay between the observed γ-ray photons and the NS-NS merger is the difference in these times, 2 s. The Lorentz factor of the shock upon breakout is between 2 and 3.

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