

GW170817: Gravitational Waves and Light Together at Last

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1 Introduction

In this lecture, I will try to briefly capture the main observational results surrounding the joint discovery of gravitational waves and electromagnetic radiation from the binary neutron star merger GW170817. Over 100 (I lost count a long time ago) have appeared on the ArXiv dedicated to this event, and so it is impossible for me to capture the entirety here in just a single lecture. Furthermore, while the summer school is focused on the associated r-process kilonova / macronova, I'll try to give a bit broader perspective and at least discuss all the relevant manifestations of electromagnetic radiation from this object. Without wasting any more time, let's dive in.

2 Gravitational Wave Signal

On the morning (US East coast time) of August 17, 2017, the two LIGO gravitational wave detectors registered a signal in both detectors (well, there was a “glitch” in the Livingston strain data that precluded rapid notification, but we'll skip over that for the time being). Thus began a chain of events that would occupy over 70 telescopes on the ground and in space, and several thousand astronomers (both theorists and observers), for the better course of a two months.

The frequency vs. time plot for GW170817, as the event would eventually be dubbed, is shown in Figure 1. The characteristic “chirp” signal is apparent in data from both LIGO detectors – the frequency increases as the objects approach each other, and correspondingly the amplitude of the gravitational wave strain also grows. The duration of the signal in the LIGO bandpass is significantly longer than that observed from binary black hole mergers like GW150914. This indicates a much lower chirp mass for the system (the parameter most precisely measured by gravitational wave detectors), where the chirp mass is given by:

$$M_{ch} \equiv \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \quad (1)$$

By comparing the gravitational wave strain signals with those from a bank of templates (i.e., models), it is possible to constrain the basic parameters of the system. As discussed above, the most precisely measured parameter is the chirp mass, in this case to $\approx 0.03\%$. However due to uncertainties in the distance, inclination, and spins, the masses of the individual components are significantly more uncertain ($\approx 10\%$). Nonetheless, the system is entirely consistent with the merger of two approximately equal neutron stars with $M \approx 1.4 M_\odot$.

Gravitational waves are particularly powerful probes of cosmic sources because they also come with a measurement of the distance to the source that is independent of the cosmic distance ladder. Unfortunately, that distance estimate is highly degenerate with the inclination: smaller inclination events can be seen further

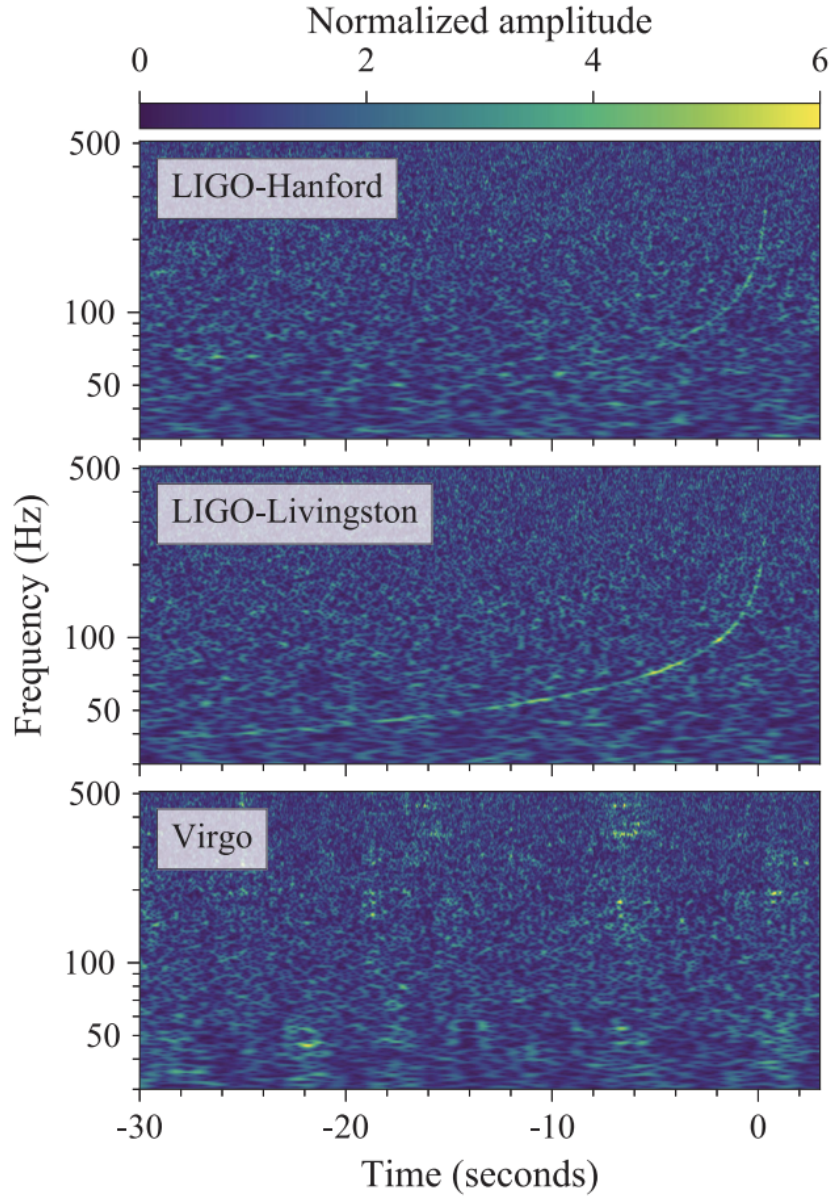


Figure 1: The frequency vs. time plot for GW170817, from the three detectors in the LIGO/Virgo network. The characteristic chirp pattern is apparent in the signal from the two LIGO and Virgo detectors, but no signal was seen in Virgo (which will become important when we start discussing localization). Note that the time scale for which the signal is in the LIGO bandpass is much longer than GW150914 - this is directly indicative of a binary neutron star (rather than binary black hole) origin for this event. From ([Abbott et al., 2017b](#)).

away than mergers viewed at large inclination. In this case the gravitational waves alone imply a distance of ≈ 40 Mpc, with an uncertainty of $\approx 25\%$.

The gravitational wave signal also allows us to constrain the *tidal deformability* of the neutron star, an important quantity that depends on the equation of state of dense matter. In the final orbits before merger,

	Low-spin priors ($ \chi \leq 0.05$)	High-spin priors ($ \chi \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55^\circ$	$\leq 56^\circ$
Using NGC 4993 location	$\leq 28^\circ$	$\leq 28^\circ$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4M_\odot)$	≤ 800	≤ 1400

Figure 2: The parameters of the binary system in GW170817 derived (largely) from the gravitational wave signal. Low spin priors assume the individual neutron stars (pre-merger) are spinning at a rate consistent with observations of Galactic systems. The high-spin priors place a looser constraint, namely that the neutron stars are spinning slow enough that they will not break up. From (Abbott et al., 2017b).

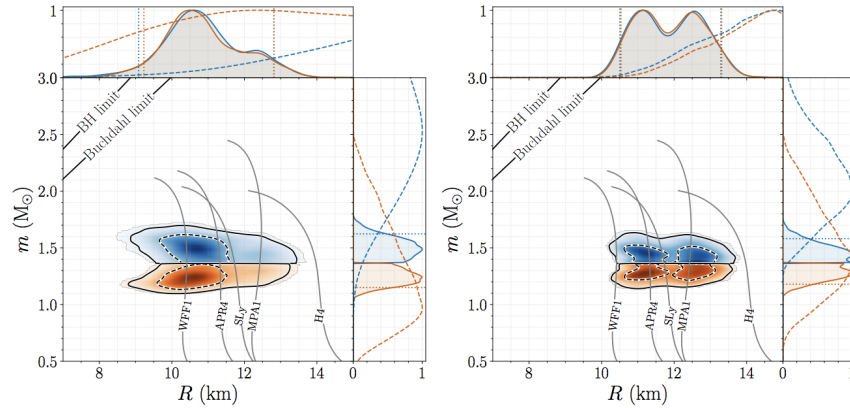


Figure 3: Constraints on the masses and radii of the two neutron stars (more massive in blue, less massive in red). The left panel imposes no constraints on the equation of state, while in the right panel the maximum mass of a neutron star is assumed to be > 1.97 solar masses (from dynamical neutron star mass measurements). Some equations of state are ruled out in this case. From Abbott 2018.

tidal forces stretch and squeeze the neutron stars, and the strength of that force a) depends on the equation of state, and b) will result in subtle differences in the gravitational wave strain signal. Assuming that both neutron stars have the same equation of state, the results are shown in Figure 3. Some of the most and least stiff equations of state are ruled out – however most of the “preferred” models remain viable.

3 GRB170817A

Just 1.7 s after the neutron star merger, the Gamma-Ray Burst Monitor on the *Fermi* satellite triggered on a short-duration gamma-ray burst. The existence of the trigger and the sky localization were automatically sent to the worldwide community of GRB astronomers, as is done hundreds of times each year. Obviously this GRB (dubbed GRB170817A) would, however, turn out to be slightly more special than the typical *Fermi* GRB.

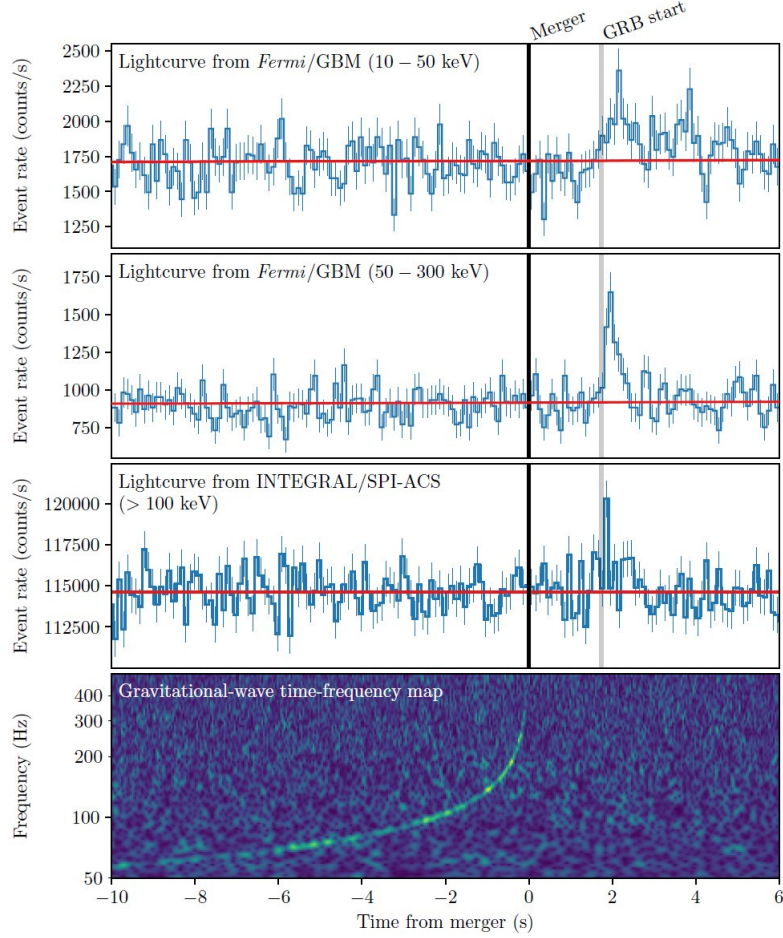


Figure 4: Simultaneous discovery of a gamma-ray burst (GRB170817A) consistent in time and location with GW170817. From (Goldstein et al., 2017).

The high-energy emission was also (weakly) detected by the SPI-ACS instrument on-board the ESA *INTEGRAL* satellite (Figure 4). However, the signal to noise ratio is somewhat lower, and the SPI-ACS has no localization capabilities on its own.

The duration ($t_{90} \approx 2$ s) and spectrum (peak energy ≈ 200 keV) place GRB170817A in the category of short-duration GRBs (Figure 5). In fact, in nearly all observer-frame properties, GRB170817A appears like a pretty ordinary short-duration GRB: the fluence is typical, while the peak flux and spectral peak are low but consistent with the distribution. Absent the gravitational wave signal, this GRB would likely have gone by completely unnoticed by the community – because of their large localizations (hundreds to thousands of square degrees), *Fermi*-GBM GRBs are rarely (if ever) followed-up by ground-based observers.

However, given that the distance to the binary neutron star merger is known from gravitational waves ($d \approx 40$ Mpc), GRB170817A is actually a very unusual GRB when considering its *rest-frame* properties. In particular, the isotropic energy release is 2–5 orders of magnitude less than the known population of short-duration GRBs. This presents a very basic puzzle that I will return to at the end of this lecture: why is the gamma-ray emission associated with GW170817 so faint?

This also raises another very important question – are we missing such faint gamma-ray events in the nearby

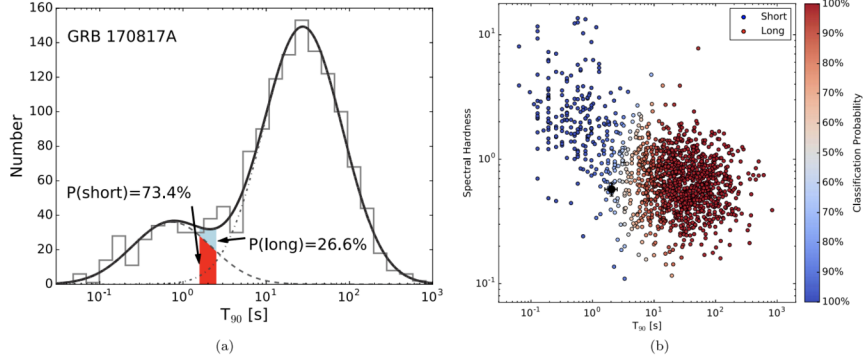


Figure 5: The duration and spectrum of GRB170817A place it (mostly) in the category of short-duration GRBs. From (Goldstein et al., 2017).

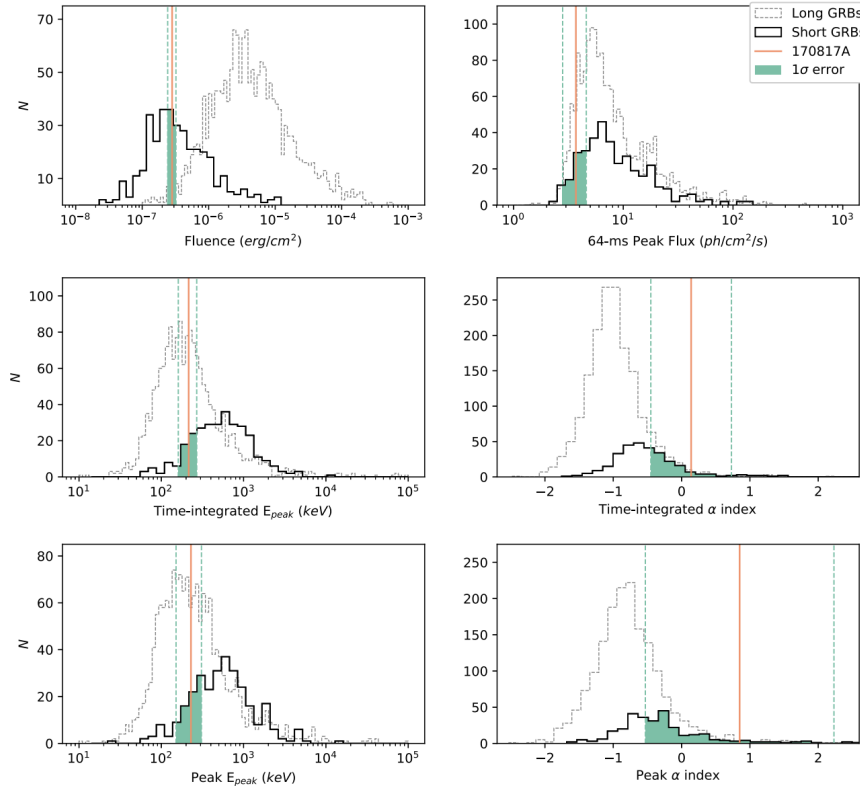


Figure 6: Observer frame properties of GRB170817A, compared with the population of short (dark histogram) and long (light histogram) GRBs. Based only on the properties, GRB170817A looks like an entirely ordinary GRB. From (Goldstein et al., 2017).

universe? Prior to GW170817, no short-duration GRB had been demonstrated to lie within the LIGO horizon distance of 200 Mpc ($z \approx 0.05$). Since most short-duration GRBs found by *Swift* have X-ray counterparts, and thus precise (few arcsecond) localizations that lack local galaxies nearby, we can definitively conclude that the large majority of *observed* short-duration GRBs are not like GW170817A. However, the intrinsic rate of such low-luminosity short-duration GRBs is largely unconstrained by observations to date, and so

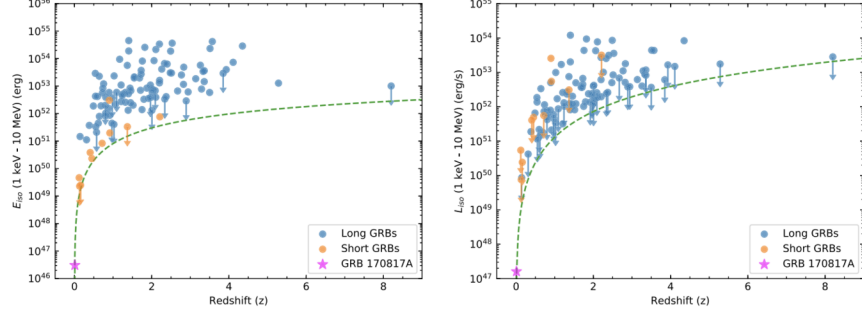


Figure 7: The isotropic energy release and luminosity of GRB170817A, compared with the population of short- and long-duration GRBs. GRB170817A is highly sub-luminous compared with the “classical” population of short-duration GRBs. From (Abbott et al., 2017a).

there may be a sub-dominant population that we are missing by not following up *Fermi*-GBM events.

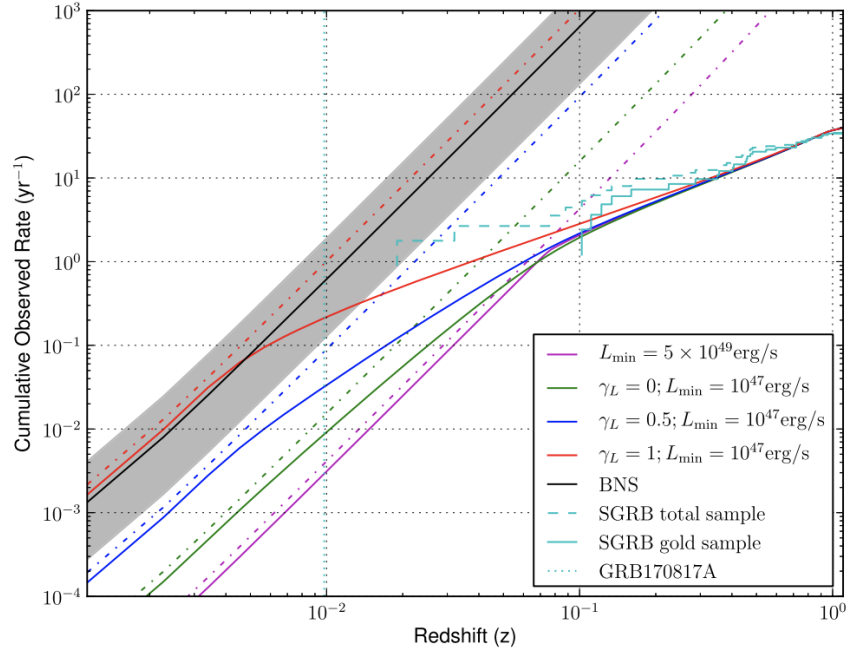


Figure 8: The rate of short-duration GRBs, making different assumptions about their luminosity function. The known population does not extend down to the LIGO horizon distance, meaning that extrapolations to the very nearby universe are highly uncertain. From (Abbott et al., 2017a).

3.1 Exercise 1: The delay between the neutron star merger and the gamma-ray burst is interesting, for a variety of reasons. Calculate the precision with which we can measure the speed of the graviton (compared to the speed of light).

4 Kilonova

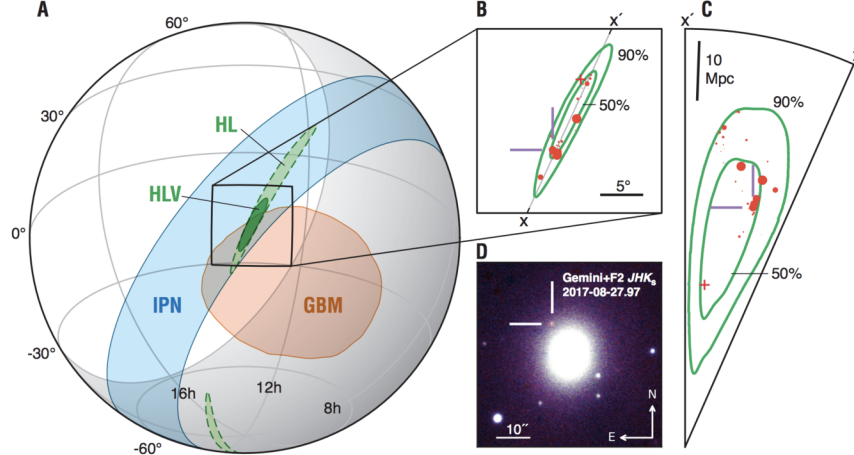


Figure 9: The 3D localization of GW170817. By combining the distance information from gravitational waves with the 2D sky position, it is possible even for telescopes with small fields of view to efficiently search for the counterpart. From (Kasliwal et al., 2017).

With the joint discovery of gravitational waves and a gamma-ray burst from a binary neutron star merger, the hunt for emission at longer wavelengths (X-ray, optical, and radio) quickly swung into action. GW170817 was particularly well localized for a gravitational wave event - when including the fact that Virgo did *not* detect any emission from the source (and thus the localization was in one of the four null points of the interferometer), the final localization had an area on the sky of 31 deg^2 (Figure 9).

This is still a large area on the sky (compared to most radio, optical, and X-ray telescopes). But the problem is greatly simplified by the fact that gravitational waves also encode distance. Within this 31 deg^2 , there are only ≈ 50 galaxies that lie at a distance of $\approx 40 \text{ Mpc}$ (Figure 9). By weighting these galaxies by either stellar mass or star formation, and convolving with the gravitational wave localization, the search becomes possible even for telescopes with small fields of view (Gehrels et al., 2016).

After the field became visible in Chile for the first time, at least 6 groups independently discovered a bright optical counterpart in the outskirts of the S0 galaxy NGC4993, first imaged and reported by the 1M2H collaboration with the Swope telescope (Coulter et al., 2017). Once this source was identified, over 70 telescopes across the globe and in space began observing the location of the counterpart over the course the next several weeks. Unfortunately due to its location on the sky, after a few weeks it got too close to the Sun for follow-up at UV/optical/near-infrared wavelengths.

The UV/optical/near-infrared light curve is shown in Figure 11. The source is relatively bright at early times, with strong emission detected at near-UV wavelengths. This UV emission fades away extremely quickly, however, and after $\sim 1 \text{ d}$ the color becomes relatively red. The near-infrared light emission is much longer-lived, peaking on a time scale of $\approx 4 \text{ d}$ at K -band ($2.2 \mu\text{m}$). Does this light curve look familiar to you?

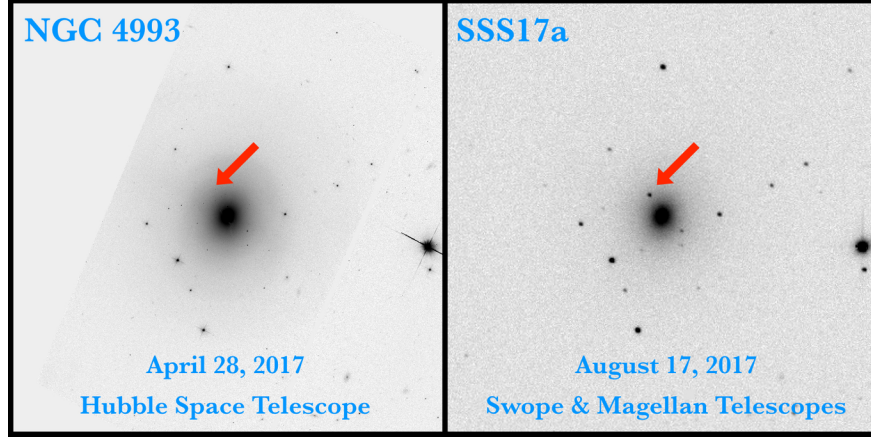


Figure 10: Discovery of the optical counterpart of GW170817 by the Swope telescope at Las Campanas Observatory. From (Coulter et al., 2017).

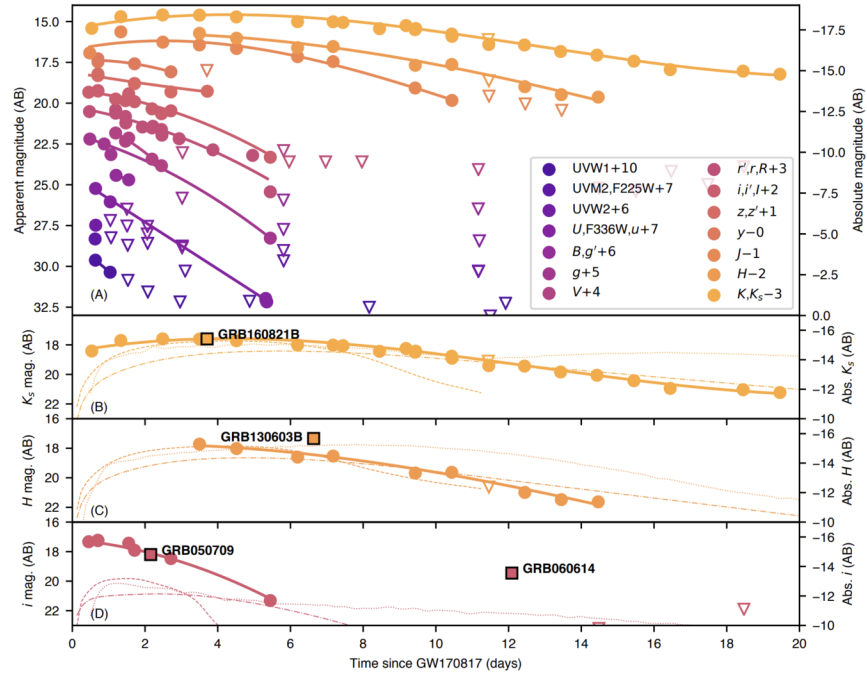


Figure 11: The UV/optical/near-infrared evolution of the transient associated with GW170817. The source is relatively blue at early times, but the UV emission fades rapidly. The NIR on the other hand, is much longer lived, with a peak on a time scale of several days. From (Kasliwal et al., 2017).

4.1 Exercise 2: For the provided data points, calculate the blackbody luminosity, temperature, and radius for the UV/optical counterpart at a time of $\Delta t = 0.6$ d after the merger. Is this consistent with “afterglow” emission? What can we infer about the ejecta velocity from this measurement?

$$\begin{aligned}
 f_{\lambda}(1928 \text{ \AA}) &= (1.68 \pm 0.38) \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1} \\
 f_{\lambda}(2246 \text{ \AA}) &= (1.59 \pm 0.32) \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1} \\
 f_{\lambda}(2600 \text{ \AA}) &= (4.35 \pm 0.44) \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1} \\
 f_{\lambda}(3465 \text{ \AA}) &= (7.57 \pm 0.59) \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1} \\
 f_{\lambda}(7485 \text{ \AA}) &= (2.99 \pm 0.17) \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1} \\
 f_{\lambda}(8658 \text{ \AA}) &= (2.10 \pm 0.12) \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1} \\
 f_{\lambda}(9603 \text{ \AA}) &= (1.48 \pm 0.14) \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}
 \end{aligned}$$

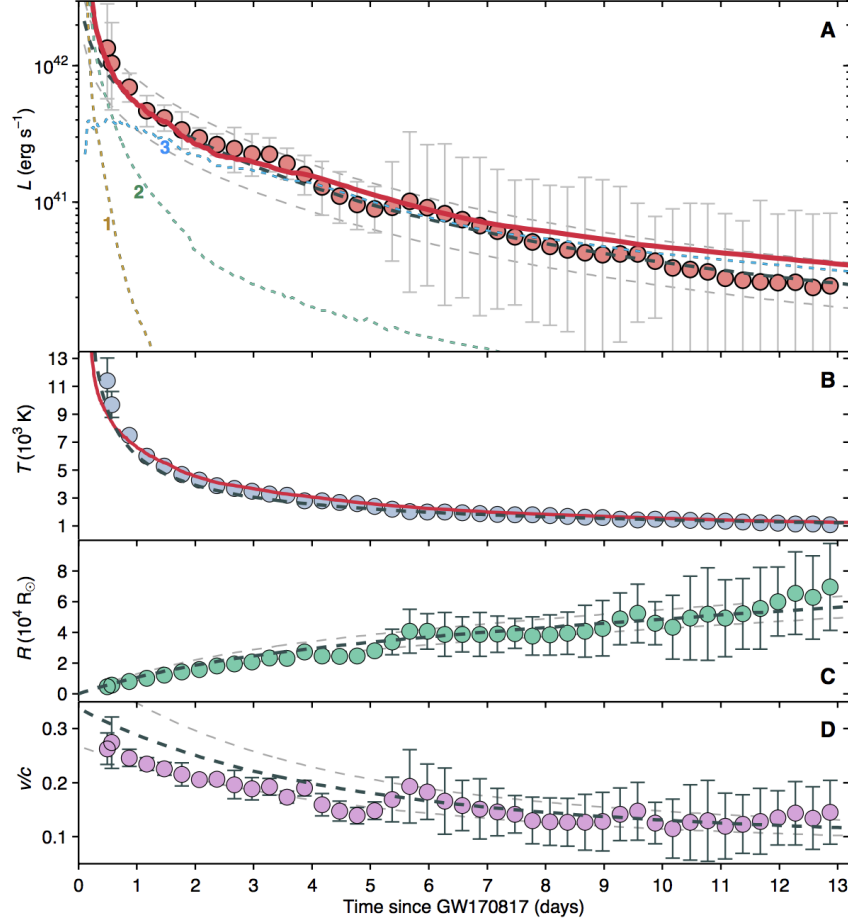


Figure 12: The evolution of the blackbody luminosity, temperature, radius, and (inferred) velocity of the transient associated with GW170817. From (Kasliwal et al., 2017).

The evolution of the counterpart based on blackbody fits to the UV/optical/NIR light curve is shown in Figure 12. As was apparent from Figure 12, the transient cooled extremely rapidly, from a temperature of $\approx 10,000$ K at $\Delta t = 0.5$ d, to ≈ 1500 K only a few days after the merger. Perhaps most interesting, associating the merger time with the start of the explosion (corresponding to zero size), the ejecta velocity

must be quite large initially, $\approx 0.3c$. Such behavior (very large velocity, rapid cooling of ejecta) have never before been seen in any (well-studied) optical transient.

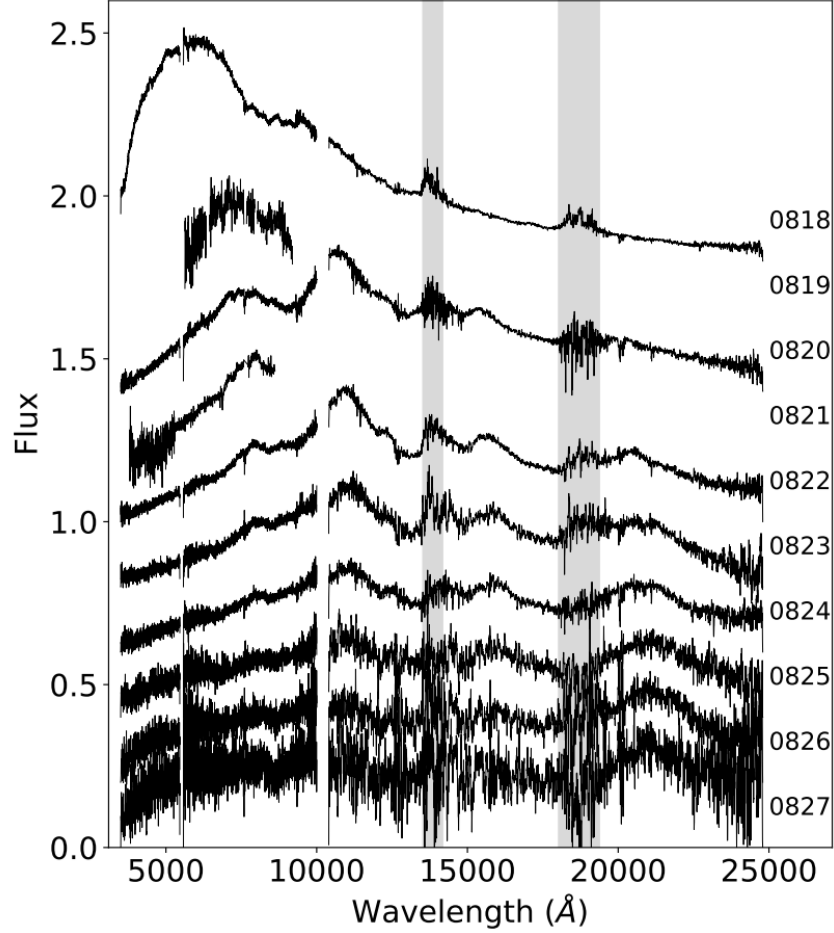


Figure 13: The spectroscopic evolution of the counterpart of GW170817. From (Pian et al., 2017).

The evolution of the optical and NIR spectra of the counterpart are (not surprisingly) also similar to this picture (Figure 13). The early spectra are dominated by a large blue hump, with extremely broad features consistent with Doppler broadening of very high velocity ejecta. Rapidly the ejecta cool, but broad (tens of thousands of km s^{-1}) undulations remain in the spectra, most prominently around 1.2 and $2.2 \mu\text{m}$.

Broadly speaking, the properties of the UV/optical/near-infrared match well with the *predictions* for a kilonova - the radioactively powered transient we discussed yesterday. The presence of bright blue emission at early times was somewhat of a surprise (at least to me), but the time scale, luminosity, and color of the radiation at late times was precisely what was predicted by radiative transfer calculations.

A large variety of attempts have been made to model the UV/optical/NIR light curves of GW170817, and the results largely (though not completely) agree:

- To simultaneously explain both the early blue emission and the longer-lived red emission, it is necessary to invoke a *two component* model, where the blue emission is resulting from ejecta with a high velocity

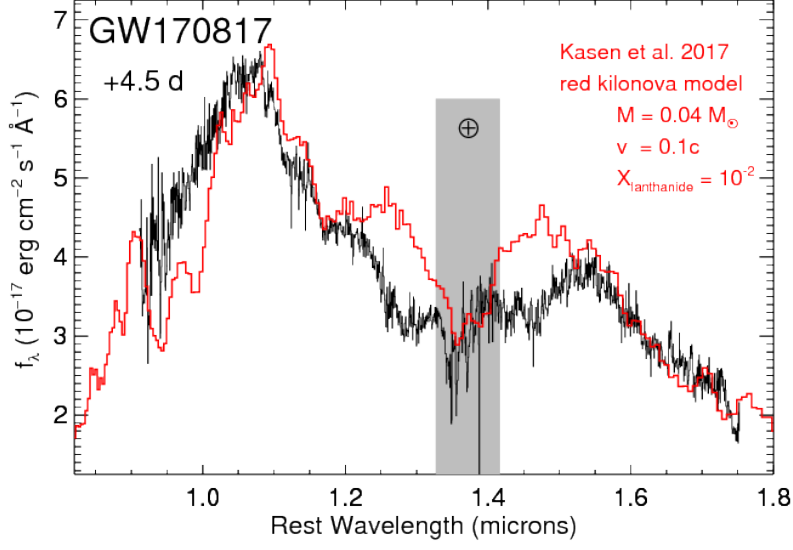


Figure 14: Comparison of the NIR spectrum of GW170817 with a kilonova model, showing a remarkable level of agreement. From (Chornock et al., 2017).

and low Lanthanide fraction, while the red component arises from ejecta with a lower (though still large) velocity and a high Lanthanide fraction (Figure 15).

- Identifying individual lines in the spectra is difficult, due to the large number of transitions and the Doppler broadening of the lines. However, even with relatively simplistic calculations, the spectra show a remarkable degree of similarity to the models (Figure 14).

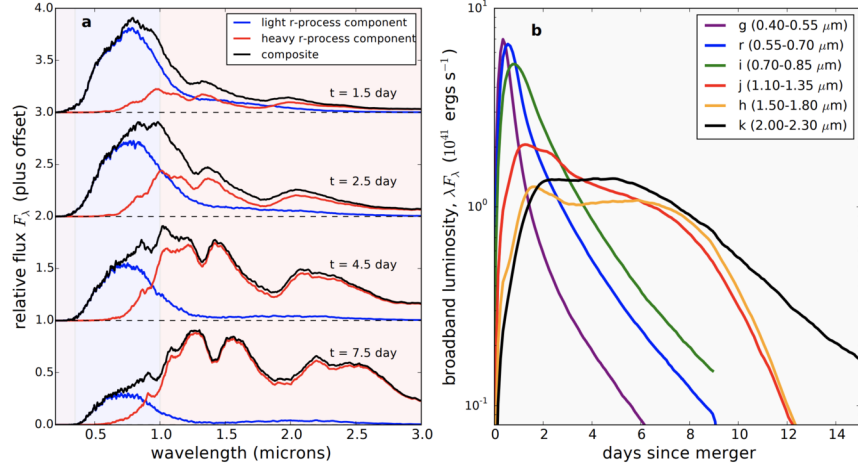


Figure 15: A two component model for GW170817, with a blue component dominant at early times and a red component dominant at late times. From (Kasen et al., 2017).

To summarize, for GW170817 the observations imply a total ejecta mass (both red and blue components) of $\approx 0.05 M_{\odot}$. This is at the high end (though not totally incompatible) with numerical simulations of binary

neutron star mergers). Combined with the rate of binary neutron star mergers derived from the gravitational wave detectors, the rate of generation of heavy r -process elements *that can explain the total abundance of heavy elements in the Solar System neighborhood!* What a remarkable result!

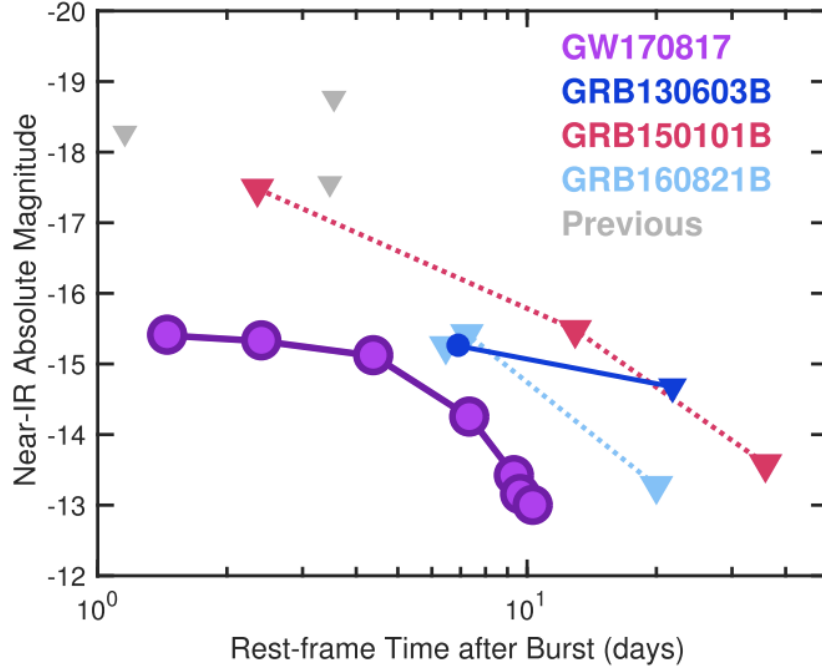


Figure 16: A comparison of GW170817 with previous kilonova searches in short-duration GRBs. From (Fong et al., 2017).

However, there are many questions that remain to be answered from future events. First and foremost, it is not obvious that *all* binary neutron star mergers have such large eject masses. Figure 16 compares the detection of a claimed kilonova signature in GRB130603B, along with upper limits from other events. GRB130603B is slightly more luminous than GW170817, implying perhaps an even larger ejecta mass. The other measurements are typically less constraining.

An equally important lingering question is the *composition* of the ejecta. It is not clear that the relative ratio of blue (Lanthanide-free) to red (Lanthanide-rich) ejecta can reproduce the *relative ratio* of light and heavy r -process elements. Future events (and modeling) will clearly be needed to address this issue.

4.2 Exercise 3: Calculate the monetary value of the gold synthesized in GW170817.

5 Non-Thermal X-ray and Radio Counterpart

The previous section describes the discovery and characterization of the “thermal” (or at least quasi-thermal) emission associated with GW170817. Here we describe the search for *non-thermal* emission, predominantly performed at X-ray and radio wavelengths.

X-ray and radio observations of GW170817 began promptly after the discovery of the optical counterpart. No X-ray emission was seen over the course of the first $\sim$ week. The lack of X-ray emission ruled out typical short-duration GRB afterglows (after accounting for the much smaller distance to GW170817; Figure 17).

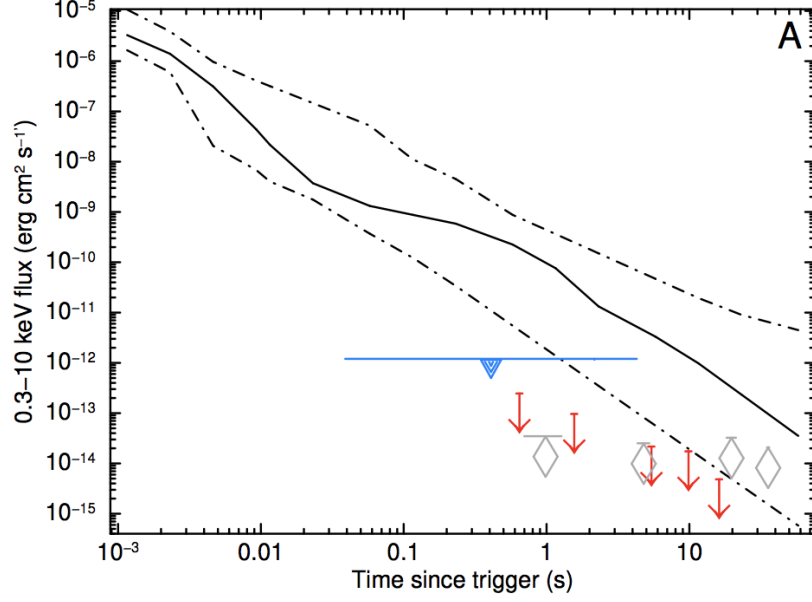


Figure 17: Early X-ray limits from GW170817 (red is Swift, gray is NuSTAR), compared with the population of short-duration GRB afterglows placed at a distance of 40 Mpc (note the x-axis should be in days). From (Evans et al., 2017).

A similar story played out at radio wavelengths, where no emission was detected for the first week (aside from a radio source consistent with the nucleus of NGC4993, and thus unrelated to GW170817).

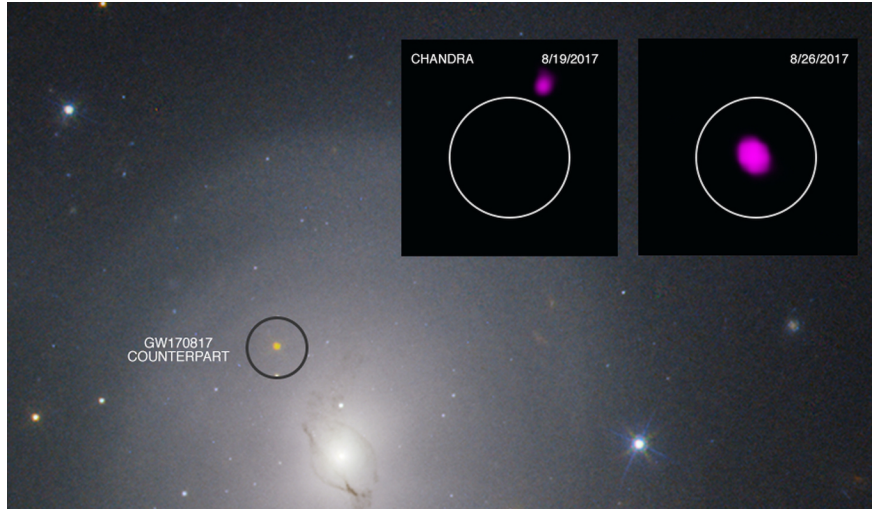


Figure 18: Discovery of the X-ray counterpart of GW170817, at 9 days after the merger.

However, for the X-ray and radio emission from GW170817, good things came to those who waited. At 9 days after the merger, X-ray emission was detected by *Chandra* (Figure 18), and at 16 days after the merger radio emission was detected by the VLA (Figure 19). In both cases, the emission was clearly *rising* for the first month or two after the merger. The broadband spectrum is well described by a single power-law across

the entire X-ray to radio regime, which has (within errors) remained constant over the entire evolution of the source.

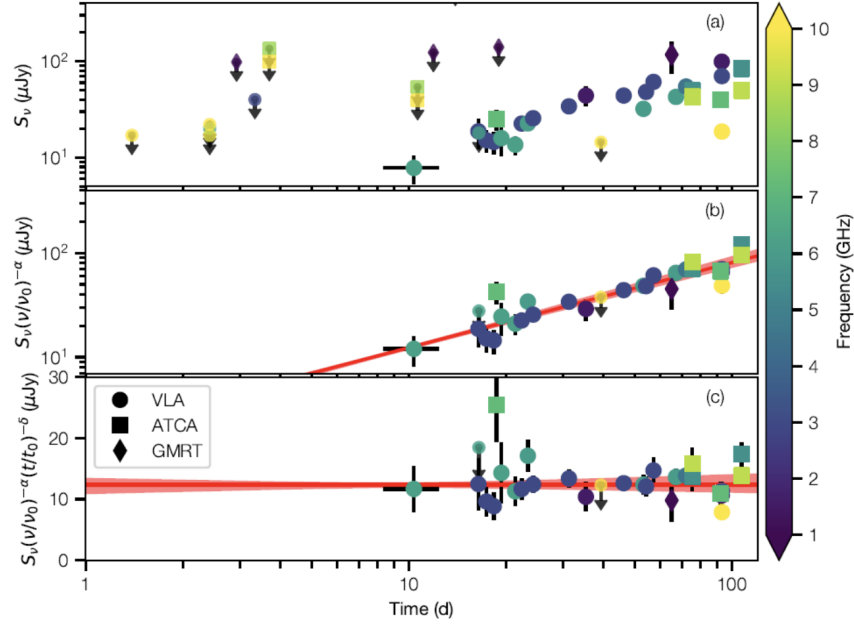


Figure 19: Early radio light curves of GW170817. For the first ~ 100 days after the merger, the source rose steadily in flux (after accounting for the power-law spectrum). From (Mooley et al., 2017).

After more than 100 days of steadily rising with a constant spectrum, the most recent observations show a declining behavior (Figure 20). This is most pronounced at X-ray and radio wavelengths, but appears consistent with the optical behavior as well.

How do we interpret this non-thermal emission. Generally speaking, the flux, time scale, and spectrum require the presence of at least mildly relativistic (Lorentz factor of a few) ejecta from a wide-angle outflow. The most pertinent question that remains to be answered is this: is there a viewing angle for which an observer would have seen a “classical” (i.e., high-luminosity) gamma-ray burst? This question unfortunately is not yet possible to answer - the data to date are largely consistent with two possibilities: 1) a spherical, mildly relativistic outflow (e.g., which could be generated if the jet fails to break out of the massive neutron-star ejecta that powers the kilonova), though this requires that the ejecta has a broad distribution of Lorentz factors; 2) A jet with an angular structure, such that the most ultra-relativistic material were in a narrow cone (pointed away from our line of sight), but a wide tail at larger angles with slower moving material. Both models make predictions for how the light curves should evolve in the coming months - hopefully we will be able to discriminate between them with continued monitoring.

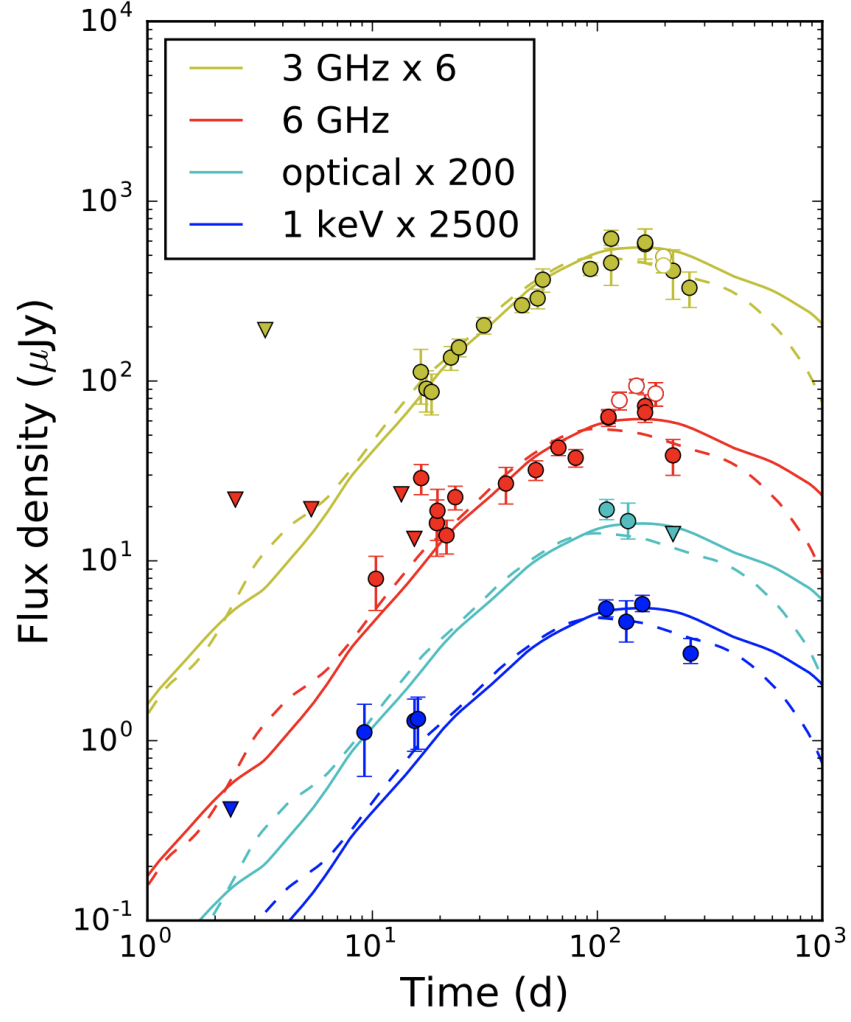


Figure 20: An up-to-date broadband light curve of the non-thermal emission from GW170817. After ~ 150 days the emission has finally started to turn over. From Alexander 2018.

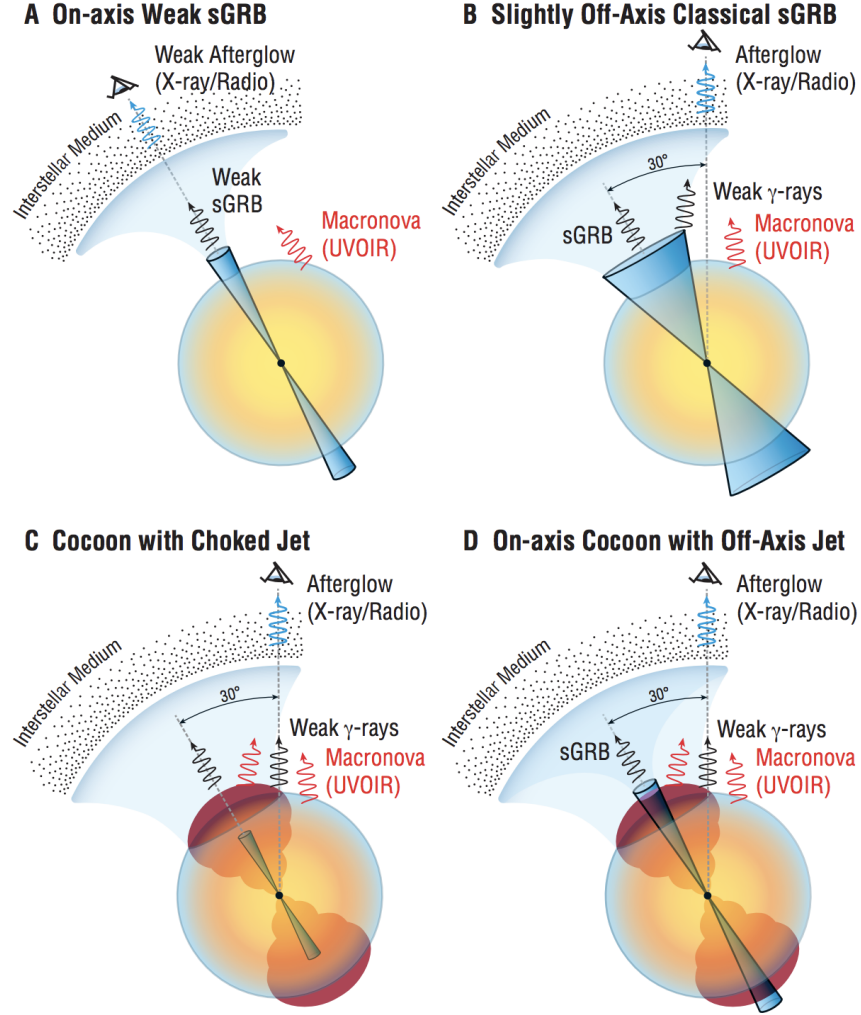


Figure 21: Cartoon explanations for the entire suite of electromagnetic observations from GW170817. Both a) (on-axis weak GRB) and b) (slightly off-axis classical short GRB) are ruled out. But a cocoon with a choked jet and structured jet both remain viable. From (Kasliwal et al., 2017).

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