The X-rays Also Rise: *Chandra* Observations of GW170817 Mark the Dawn of X-ray Studies of Gravitational Wave Sources

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The Dawn of a New Era of Exploration

The first extraterrestrial X-ray photons to be detected were those from the Sun in the late 1940s, followed in 1962 by the discovery of the first cosmic X-ray source: Scorpius X-1 (Giacconi, Gursky, Paolini & Rossi 1962). Since then, for ~60 years the X-ray sky has revealed rich and violent phenomena, including jets from accreting black holes (BHs) and neutron stars (NSs), stellar explosions, mergers, eruptions and disruptions (e.g., Seward & Charles 2010). In August 2017, *Chandra* observations of the gravitational wave (GW) event GW170817 marked the beginning of a new field: X-ray studies of sources of gravitational waves (Haggard et al. 2017, Margutti et al. 2017, Troja et al. 2017).

The mergers of the most compact objects in nature (BHs and NSs) emit GWs that are now detectable by the Laser Interferometer Gravitational-wave and Virgo Observatories (LIGO/Virgo). LIGO/Virgo has thus far detected ten BH-BH mergers and one binary neutron star (BNS) merger GW170817 (Abbott et al. 2017c, 2018). The BNS merger GW170817 is the first GW event for which emission has been observed across the entire electromagnetic spectrum, from the gamma-rays to the radio band, including soft X-rays. The X-ray emission from GW170817 was first captured by the sharp eyes of *Chandra*, which continues to provide a detailed view of the rise and fall of the non-thermal (i.e., synchrotron) radiation associated with the fastest material flying out from the merger (Alexander 2018, Haggard et al. 2017, Margutti et al. 2017, 2018, Nynka et al. 2018, Piro et al. 2018, Pooley et al. 2018, Ruan et al. 2018, Troja 2017, 2018).

GW170817 was detected by LIGO/Virgo on 17 August 2017, and localized to within a 28 deg^2 (90% confidence region) area of the sky containing ~40 nearby galaxies at a distance of roughly 40 Mpc (Abbott et al. 2017b,c). The GW detection was followed approximately two seconds later by the detection of gamma-rays from a consistent location in the sky (Abbott et al. 2017b, Goldstein et al. 2017, Savchenko et al, 2017), and roughly half a day later by the detection of a rapidly-evolving transient shining brightly at UV/optical/NIR wavelengths (Arcavi et al. 2017, Chornock et al. 2017, Coulter et al, 2017, Drout et al. 2017, Evans et al, 2017, Kasliwal et al. 2017, Kilpatrick et al. 2017, Lipunov et al. 2017, Nicholl et al. 2017, Pian et al. 2017, Shappee et al. 2017, Smartt et al. 2017, Soares-Santos et al. 2017, Tanvir et al. 2017, Valenti et al, 2017), known as “kilonova” (KN, proposed by Li & Paczyński,1998 see Metzger 2017 for a recent review). The KN emission from GW170817 (and from BNS mergers) is powered by the radioactive decay of heavy chemical elements produced by the merger through “r-process’” nucleosynthesis, and tracks the slower moving material ejected by the collision, with inferred velocities of ~0.1–0.3c (Cowperthwaite et al. 2017, Kasen et al. 2017, Smartt et al. 2017, Villar et al. 2017, Tanvir et al. 2017). The observations of KN emission in GW170817 showed remarkable agreement with theoretical predictions on the luminosity evolution of the kilonova emission at optical/NIR wavelengths (Metzger 2017b). These observations signaled the birth of Multi-Messenger Astrophysics (MMA) with GWs (Abbott et al. 2017a).

Models of compact-object mergers have also proposed that these systems could launch energetic collimated outflows reaching ultra-relativistic speeds (i.e., relativistic jets) and could be the progenitor systems of short gamma-ray bursts (SGRBs, Eichler et al. 1989, Narayan et al. 1992). The interaction of these relativistic outflows with the merger’s environment creates shocks that accelerate particles which then cool by radiating photons. The radiation, produced by electrons gyrating in amplified magnetic fields (i.e., synchrotron), is non-thermal in nature and dominates the observed emission at X-ray and radio wavelengths at all times, where the contribution from the KN is negligible (Fig. 5). The resulting electromagnetic transient is thus an excellent probe of the physics of compact-object mergers and their sub-parsec environments. The evolution of the resulting transient directly depends on the following factors: (i) amount of mass expelled by the catastrophic collision, (ii) speed of expelled material, (iii) collimation and direction with the line of sight, and (iv) density of the circum-merger medium (e.g., Piran 2004). This is where *Chandra*’s observations of GW170817 provided a fundamental contribution to the nascent field of MMA with GWs.

Chandra X-ray observations of GW170817 provided key constraints on the physical properties of the fastest ejecta launched into space by the NS merger and on its environment (Alexander 2018, Haggard et al. 2017, Margutti et al. 2017, 2018, Nynka et al. 2018, Piro et al. 2018, Pooley et al. 2018, Ruan et al. 2018, Troja 2017, 2018). In the following sections we highlight the impact of *Chandra* observations to constrain the nature of the X-ray emission in GW170817. We also consider other potential sources of X-ray emission that did not play a major role in GW170817, but might be relevant for future GW detections. Finally, we discuss other broad areas of astrophysics that can be impacted by X-ray studies of GW sources and we end with our views on discovery frontiers in the field.

Chandra Observations of GW170817 Reveal a Structured, Collimated, Relativistic Outflow in a BNS Merger

It all started with zero photons. The first deep X-ray observation of GW170817 was carried out by *Chandra* ~2 days after the merger and the non-detection provided an upper limit on the flux (Fig. 1, Margutti et al. 2017). This observation was followed on day 9 by the detection of ~14 photons from GW170817 (Fig. 1, Troja et al. 2017). These two *Chandra* observations established, at high statistical confidence, that GW170817 was associated with faint ($L_x \leq 10^{39}$ erg/s at $t < 10$ days) but rising X-ray source of emission (Fig. 2–3), setting GW170817 phenomenologically apart from all X-ray afterglows of Short Gamma-Ray Bursts (SGRBs) observed thus far (Fig. 4, Fong et al. 2017). Yet, accurate modeling of the non-thermal emission from GW170817 over one year of observations demonstrated that its intrinsic nature was similar to SGRBs (Alexander et al. 2018, D'Avanzo et al. 2018, Margutti t al., 2018, Troja et al. 2018b, Wu et al. 2018), and that its different appearance was simply due to a different viewing angle. While SGRBs are typically discovered through their powerful collimated gamma-ray emission and are viewed along the jet axis (see Fong et al. 2015 for a recent review), the GW emission detection of GW170817, whose jet is pointing ~30° away from our line of sight, allowed us to view a BNS merger "from the side" for the first time.

The X-ray emission from GW170817 showed a slow rise to a peak at t~160 days after the merger (Ruan et al. 2018, Margutti et al, 2018, Troja et al. 2018, D'Avanzo et al. 2018). After peaking at $L_x \sim 10^{40}$ erg/s, the X-ray luminosity started a fast decay, as $\sim t^{-2}$ (Alexander et al. 2018, Nynka et al. 2018, Troja et al. 2018b, Fig. 3–4). Meanwhile, the spectrum interestingly showed no evidence for any evolution (Fig. 5). At all times, the X-ray spectrum is well described by a fairly hard power-law model with $F_\nu \sim \nu^{-0.6}$ and no evidence for intrinsic absorption, all of which is consistent with the low densities expected in the immediate environments of BNS mergers and the early-type nature of the host galaxy of GW170817 (Blanchard et al. 2017, Fong et al. 2017, Levan et al. 2017). Indeed, the broad band radio to X-ray spectral energy distribution remarkably also showed no evidence for evolution, and continuously exhibited simple power-law behavior ($F_\nu \sim \nu^{-0.6}$) over nine order of magnitudes in frequency, from the earliest observations at ~9 days, to the most recent observation (~400 days since the merger, Fig. 5).

The combination of the slow rise to peak, the fast decay after peak, and the absence of spectral evolution provided by *Chandra* observations of GW170817 over ~400 days of its evolution, offered key observational evidence that the merger powered a collimated relativistic outflow directed away from our line of sight, i.e., an off-axis relativistic jet (Alexander et al. 2018, Margutti et al. 2018, Troja et al. 2018). Distinct from the on-axis jets of gamma-ray detected SGRBs for which the emission detected by the observer is always dominated by the jet core and decays with time, for off-axis jets the observer initially receives an increasing amount of energy flux as the jet decelerates in the environment and the relativistic beaming of the emitted radiation becomes less and less severe with time. As a result, the observer who does not view the jet along the jet axis detects an outflow carrying an increasing amount of energy with time until the entire jet cone becomes visible and the X-ray light-curve peaks (e.g., Granot et al. 2002). In this off-axis scenario, the apparent increase of energy detected by the observer is not intrinsic to the source but due to the increasing fraction of radiation from the jet that

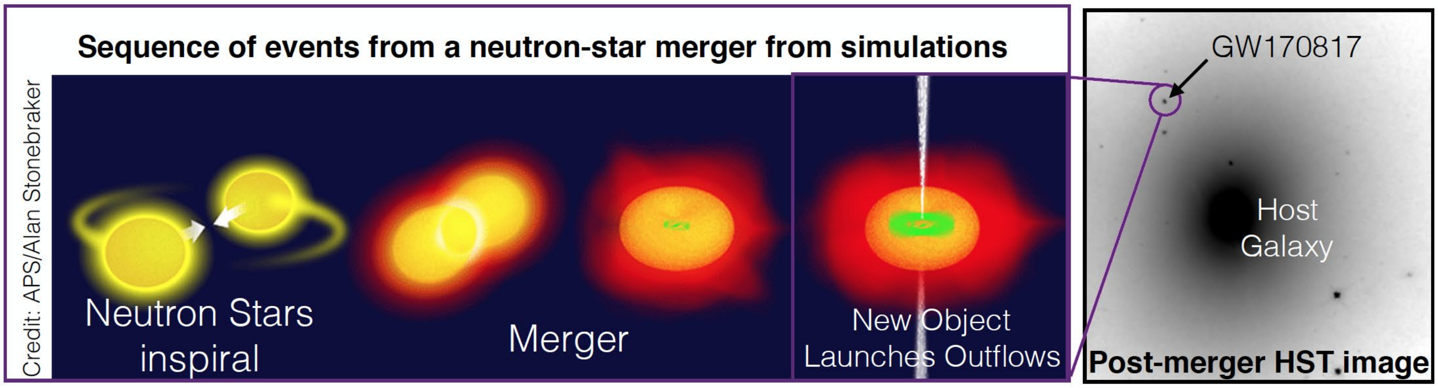

Figure 1 Left: Neutron-star merger from computer simulations (Baiotti et al. 2017). The collision creates a more massive neutron star or a black hole, and launches powerful outflows of material into the environment (white jet-like streams). These outflows are the primary source of radiation (i.e., they produce electromagnetic radiation). Such a source was detected on August 17, 2017 from GW170817. Right: Hubble Space Telescope image of GW170817 from Margutti et al. 2017; Blanchard et al. 2017.

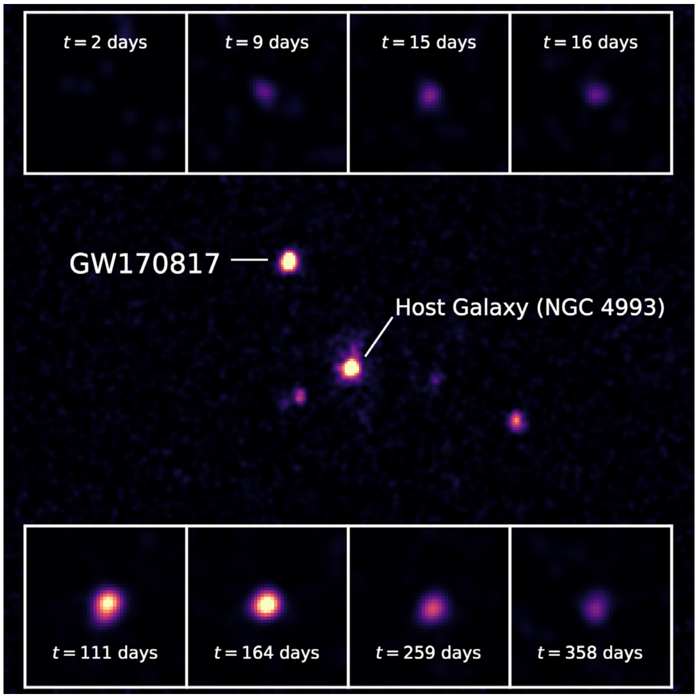

Figure 2: Deep Chandra 0.3-10 keV X-ray image of GW170817 and its host galaxy (main panel, 450 ks). Insets: zoom into the evolution of the X-ray emission from GW170817 in the first 400 days, from the first non-detection at ~2 days, its peak around ~160 days and the subsequent steep decline.

intercepts the observer's line of sight with time. After the peak, the emission detected by an on-axis and an off-axis observer evolves similarly, as both observers effectively "see" the entire jet cone (e.g., van Eerten et al. 2010, 2012). No spectral evolution is expected to accompany the rise and fall of the observed emission due to the off-axis location of the observer.

The basic framework of an outflow with an energetic relativistic core that is directed away from our line of sight successfully explains the non-thermal emission detected from GW170817 (Fig. 3). Our off-axis location is not surprising, as GW170817 was detected through its GW emission, which is not strongly beamed along the jet axis like it is for SGRBs. From probabilistic considerations it is significantly more likely for any observer to reside outside the jet cone than for the jet cone to be aligned with any observer's line of sight. The detection of very weak gamma-ray emission from GW170817 with an isotropic-equivalent energy a factor ~1000 smaller than the weakest SGRBs is consistent with this scenario, and provides important independent observational evidence that supports our off-axis perspective with respect to the jet. Future GW events are also likely to be detected from an off-axis perspective.

The detailed temporal evolution of the X-ray and radio emission before peak in GW170817 provided key information on the angular structure of the relativistic outflow (e.g., Lazzati et al. 2018, Wu et al. 2018) launched by a BNS merger for the first time. In the simplest incarnation of jet models invoked for SGRBs all the jet energy is confined within a cone of angular size θ_{jet}, and no energy is distributed at angles $\theta > \theta_{jet}$ (i.e., the jet has no "wings"). These models are referred to in the literature as "top-hat" jets, and successfully explain the observed phenomenology in SGRBs across the electromagnetic spectrum (Fong et al. 2015). SGRBs are preferentially viewed on-axis, as they are detected through their luminous, collimated gamma-rays. In this on-axis configuration the detected emission is dominated by the more energetic jet core, while radiation from the less energetic jet wings, when present, is always fainter. Hence, it is not surprising that top-hat jets have been successful at explaining SGRBs (Fong et al. 2015)—even though departures from the top-hat jet structure have been suggested in the GRB literature (e.g., Rossi et al. 2002)—and provide realistic expectations for jets that originate from BNS mergers. However, it was not until GW170817, that a clear "need" arose to invoke structured outflows to explain SGRBs afterglows, since there was no observationally-based method to quantitatively constrain the properties of the on-axis outflows beyond the ultra-relativistic jet core. For these reasons, structured outflows in SGRBs remained an intriguing, but difficult to constrain, theoretical possibility.

GW170817 offered the first observational evidence for a clear deviation from a top-hat jet structure. GW170817 showed a slow rise to peak compared with the expectations from top-hat jets viewed off-axis, suggesting the presence of mildly-relativistic jet "wings" around a collimated ultra-relativistic core. These wings of less collimated material are a direct product of the merger dynamics and jet launching process in NS mergers, and pre-peak observations of GW sources can constraint the physical properties of the angular structure of the outflow.

Modeling of the pre-peak X-ray to radio emission in GW170817 constrained the jet-wing's expansion velocity to be mildly relativistic with $\gamma \sim 3$ (e.g., Wu et al. 2018). As a comparison, modeling of the broad-band radio to X-ray emission demonstrates that the ultra-relativistic jet core was highly collimated (jet opening angle of ~5°), highly energetic ($E_k \sim 10^{50}$ erg), and expanding into a low-density medium with $n \leq 0.01$ cm^{-3}. The properties of the highly-relativistic outflow and the inferred properties of the environment of GW170817 are consistent with findings from cosmological SGRBs (Fong et al. 2015, 2017, Troja et al. 2018b).

After ~400 days of data acquisition, analysis and modeling across the electromagnetic spectrum and a strong debate amongst the astronomical community, we can now conclude with confidence that GW170817 shows all the

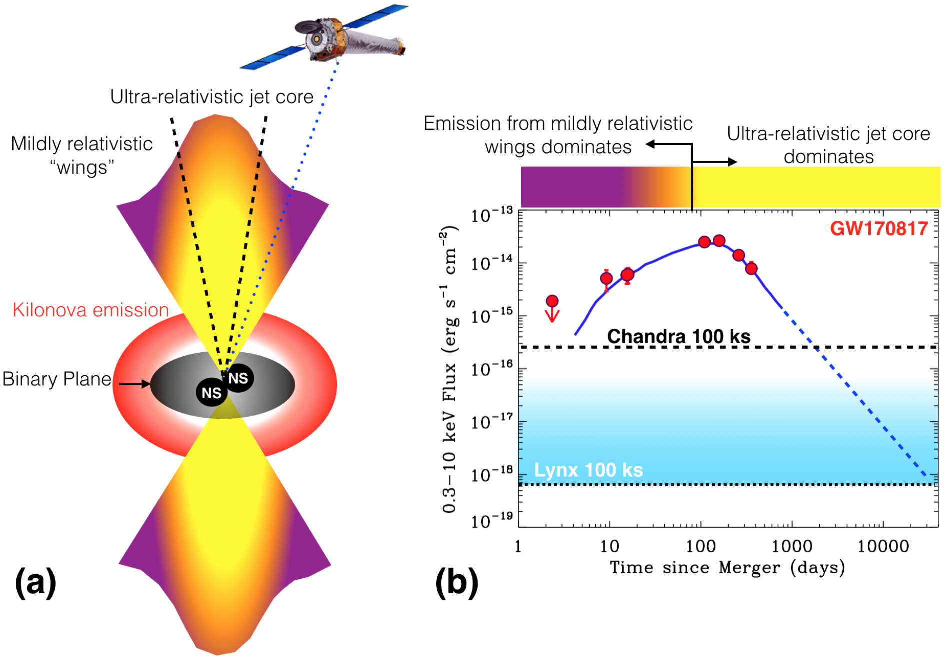

Figure 3: Panel (a): Cartoon showing the geometry of the outflows in GW170817 that give rise to the quasi-isotropic emission from the kilonova (red) and a collimated jet of ultra-relativistic material carrying $E \sim 10^{50}$ erg of energy. The collimated jet is characterized by a narrow cone ($\theta_{jet} < 5°$) with "wings" of mildly relativistic material with Lorentz factor $\Gamma \sim 3$ extending to wider angles. The observer is located ~30° off-axis. Panel (b): X-ray emission from GW170817 as captured by Chandra (red points), with best fitting off-axis relativistic jet model superimposed (thick blue line, from Wu & MacFadyen 2018). Before the peak, the detected emission was dominated by radiation coming from mildly relativistic material at large angles (i.e., the "wings"). At the peak, the jet core came into view and dominated the observed emission. Extrapolating the current flux decay rate, Chandra will be able to detect GW170817 for ~5 yrs after the merger, while with Lynx, the proposed successor to Chandra, we could monitor the evolution of GW170817-like systems for ~30 yrs after the merger.

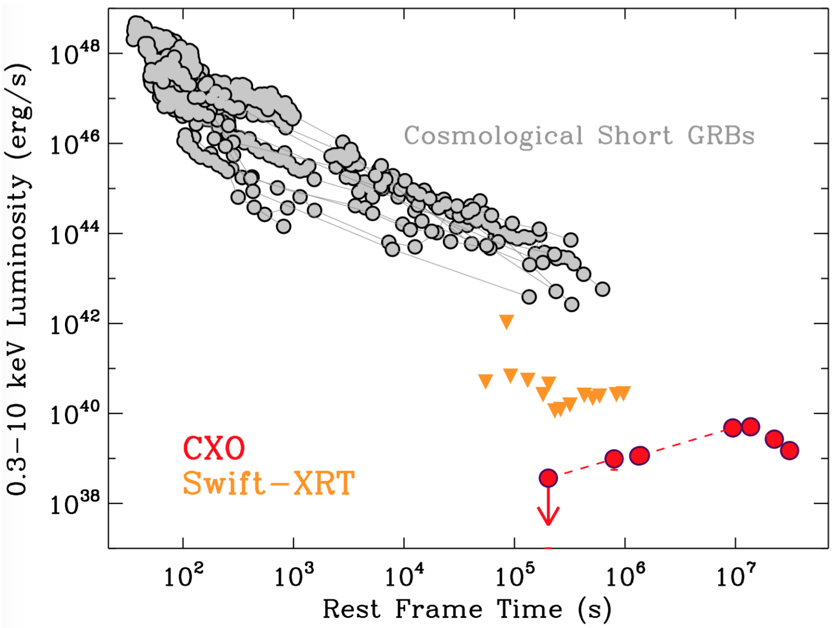

Figure 4: Comparison of the X-ray emission from GW170817 detected by Chandra (red filled circles, Alexander 2018; Haggard et al. 2017; Margutti et al. 2017, 2018; Nynka et al. 2018; Ruan et al. 2018; Troja 2017, 2018) with X-ray afterglows from cosmological short GRBs (Fong et al. 2015). The rising X-ray emission from GW170817 up to t<150 days and its low luminosity (despite being significantly closer than all previously detected SGRBs) sets GW170817 apart from all SGRB afterglows observed thus far. After the peak, the decline of the emission from GW170817 is consistent with SGRB afterglows extrapolated to later times. This phenomenology is expected from emission due to a jet pointed away from our line of sight. The entire jet becomes visible to the observer around the time of the peak. At this point the observed evolution of an off-axis jet (like the one in GW170817) and on-axis jet (like those of SGRBs) is similar. The proximity of GW170817 has allowed us to monitor the emission from a relativistic jet launched by a BNS merger to an unprecedented epoch of ~400 days. Further Chandra observations are ongoing.

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properties of a relativistic jet similar to those observed from SGRBs. However, for the first time, thanks to our off-axis perspective, in GW170817 we can appreciate the presence of angular structure in the outflow outside the jet core, imprinted by the BNS collision. The major conclusion from this effort is that at least some SGRBs are indeed the result of the merger of NSs, as predicted ~30 years ago (Eichler et al. 1989, Narayan et al, 1992).

Other Sources of X-ray Emission in Compact Object Mergers

In GW170817 all of the X-ray emission detected thus far (~400 days since merger) is dominated by radiation from the deceleration of a relativistic outflow in the BNS environment that is directed away from our line of sight. However, there are other potential sources of X-ray emission that might be relevant in other GW events, or even manifest in the future evolution of GW170817. Here we discuss two other possible sources of X-ray emission in BNS mergers: (i) X-ray emission from the KN ejecta interacting with the medium; (ii) direct emission from the compact object formed by the merger.

In analogy with supernovae (e.g., Chevalier & Fransson 2006), the propagation of the KN ejecta in the BNS merger environment is expected to transfer kinetic energy to the circum-binary medium, and accelerate particles and electrons, which will radiate through synchrotron emission. The emission is expected to be brighter and peak when a sizable fraction of the kinetic energy of the ejecta has been transferred to the medium, and the ejecta are decelerating. This process has been investigated in the specific context of KNe at radio wavelengths (Nakar 2011) where, due to the typically low densities expected in BNS merger environments ($n < 1$ cm^{-3}), deceleration happens on long time scales. In the specific case of GW170817, the inferred density $n \sim 0.01$ cm^{-3} and KN ejecta mass of the order of 10^{-2} $M_\odot$ (e.g., Villar et al. 2017), imply a deceleration timescale of years.

Yet another source of X-rays in BNS mergers can be radiation coming directly from the newly formed compact object, either emission from an accretion disk around a BH, or spin-down radiation from a long-lived magnetar formed by the BNS merger. At early times $t<50$ days, for reasonable BNS ejecta mass and expansion velocities, the large optical depth of the BNS ejecta to X-ray radiation prevents the escape of X-ray photons potentially produced by an inner engine (Metzger 2017, Margutti et al. 2017, 2018). This implies that early X-ray observations are unlikely to be able to probe the intrinsic nature of the compact remnant, as X-ray photons from the remnant are unlikely to escape from the dense BNS merger ejecta and reach the observer, unless the X-ray source was powerful enough to fully photo-ionize the KN ejecta ($L_x>10^{44}$ erg/s; Margutti et al. 2017, much larger than observed in GW170817). However, it should be noted that such a large optical depth is not necessarily expected for on-axis viewers of SGRBs, since in those cases the relativistic jet can clear a low-density funnel through the ejecta perpendicular to the binary orbital plane. Our orientation to GW170817, argues against a central engine as the origin of the early X-ray emission in GW170817. In future GW events we might probe different configurations, where X-ray photons from the remnant do break out at early times.

At later times, however, the BNS merger ejecta expands and becomes transparent to X-ray photons. For standard KN ejecta parameters (mass of the order of M_{ej}~0.01 $M_\odot$ and expansion velocity $v \sim 0.1$–$0.3c$) and chemical composition, the optical depth to soft X-ray radiation is ~1 at ~100 days, thus allowing the X-ray photons produced deep inside the KN ejecta to escape and reach the observer. If the remnant object is a BH, then a possible source of long-lived X-ray emission is fallback accretion. The current X-ray luminosity of GW170817, L_X~10^{40} erg/s, is well above the Eddington limit for a stellar mass BH, and thus far outshines X-ray emission expected from an accreting BH remnant. The constant radio to X-ray flux ratio over ~400 days of monitoring provides an independent line of evidence against the fall back accretion luminosity dominating the X-ray energy release at late times.

Alternatively, the remnant of a merger event can be a long-lived magnetar. The spin-down luminosity from a magnetar remnant is another potential source of X-ray radiation at late times. In the case of GW170817 the same magnetar engine required to explain the detected X-ray emission around 100 days would produce luminous optical emission at early times (Metzger & Piro 2014) above the observed bolometric luminosity of GW170817 (Margutti et al. 2018). The late-time *Chandra* monitoring of GW170817 emission also provides evidence against the formation of a long-lived magnetar in GW170817 (Pooley et al. 2018), which is also consistent with the inferences made from the blue colors of the early KN emission (e.g., Villar et al. 2017).

Fundamental Physics with Compact Object Mergers

Electromagnetic (EM) observations of GW events will advance our understanding of compact-object mergers, such as the physical conditions at the time of merger, and their exact locations within their host galaxies. GW observations will also shed light on the properties of their cosmic environments. EM observations of GW events may also enable potentially transformative applications outside the field of compact-object mergers, such as the equation of state of dense matter, shocks physics, and cosmology.

The amount of matter ejected by the merger and its velocity distribution are sensitive to the physical proper-

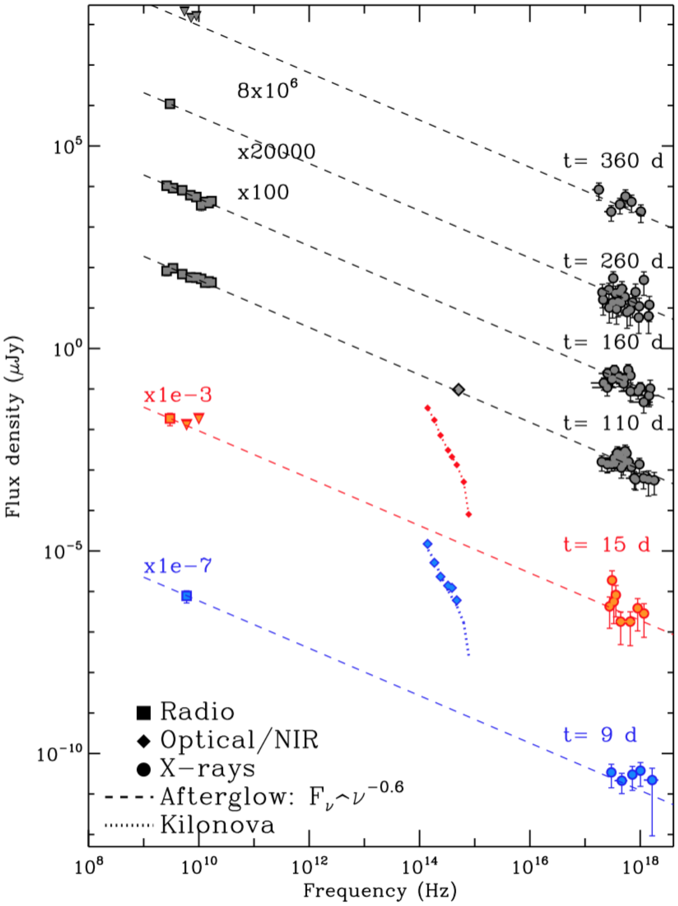

Figure 5: Broad band radio-to-X-ray spectral energy distribution of GW170817 and its (lack of) evolution in the first ~360 days after merger. The radio and X-ray data are dominated by non-thermal synchrotron emission from the GW170817 afterglow at all times and mutually consistent with $F_\nu \sim \nu^{-0.6}$ *spectral power-law. Emission from the kilonova dominates in the UV/optical/NIR in the first 2 weeks, until ~100 days after merger, when the emission from the relativistic outflow dominates UV/optical/NIR. Updated from Margutti et al. 2018.*

ties of the neutron stars, and, ultimately on the neutron star equation of state through their dependency on the NS radius (Metzger 2017). Astrophysical information about location within the host galaxy, an accurate distance, the inclination of the merging binary, and amount of matter ejected by the merger, all of which are derived from the analysis of electromagnetic data, can be combined with the GW strain data to produce tight constraints on the physical properties of the system, including the tidal deformability of neutron stars (e.g., Coughlin et al. 2018).

Additionally, the fastest relativistic outflows from mergers of compact objects constitute unparalleled physical laboratories for matter under extreme conditions that cannot be tested on Earth. While shocks (and the particle acceleration that follows) are ubiquitous phenomena in our Universe and regulate the emission that we observe from stellar explosions to disruptions of stars by supermassive black holes, fundamental questions remain unanswered. Among the most interesting are: (i) What is the maximum energy of particles accelerated by shocks?, (ii) What is the decay rate of the magnetic field behind the shock?, and (iii) What is the contribution of upstream particles to the observed emission? (Sironi et al. 2015). Addressing these questions will profoundly impact our understanding of the physics of particle acceleration. From an observational perspective, the key advantage of GW170817 has been an extremely well behaved simple power-law spectrum extending for more than nine orders of magnitude in frequency across the electromagnetic spectrum (Fig. 5) for ~400 days since the merger. This enabled the most precise spectral slope measurement of radiation due to particle acceleration from a relativistic outflow ($F_\nu \sim \nu^{-0.585}$; Alexander et al. 2018, Margutti et al. 2018, Troja et al. 2018). This precise measurement allowed us to estimate the shock Lorentz factor (Γ=3–10) — independent from the assumptions on the geometry of the outflow (Γ~3). Future GW events can be fashioned into real-time probes of relativistic shock acceleration.

Finally, joint studies of GW and EM radiation can provide independent constraints on cosmology. Significant disagreement remains between the expansion rates of the universe inferred from supernovae and from the cosmic microwave background (Riess et al. 2016, The Planck Collaboration 2016). This disagreement might signify the failure of the standard cosmological model and hint at new cosmological physics. GWs can provide a third independent measurement through the use of GW sources as standard sirens (Schutz 1986), i.e., sources that can be used to measure distances in our Universe. However, standard GW-based approaches suffer from degeneracies with other parameters (e.g., the inclination of the initial orbit of the two merging objects with respect to the observer) that limit their impact on cosmology. The inclination-distance degeneracy that is inherent in GW studies can be broken by the independent inclination measurement derived from modeling the electromagnetic emission from the merger's outflows, as shown for GW170817 in the pilot study by Guidorzi et al. 2017. In GW170817, based on modeling of the non-thermal radio and X-ray emission, a number of independent studies concluded that the jet launched by the merger was oriented ~30° away from our line of sight (e.g., Wu et al. 2018). The combined GW and electromagnetic observing program can significantly enhance the scientific impact of compact-object mergers on cosmology, and has the potential to solve one of the most challenging riddles posed by the cosmos: how fast is the Universe expanding?

The Future: Discovery Frontiers

Multi-messenger Astrophysics with GWs is a young and rapidly-evolving field. Although there is uncertainty about the future of a field wherein only one astrophysical object has been studied, some aspects of the future landscape are predictable.

First, among the list of potential MMA discoveries is the merger of a neutron star with a black hole. Black hole mergers are now routinely detected by LIGO/Virgo (Abbott et al. 2018); yet, unambiguous evidence for electromagnetic counterparts is still missing. The Fermi detection of gamma-rays associated with the binary black hole merger GW150914 (Connaughton et al. 2016) was very intriguing. A major future discovery will be the detection of radiation from a binary BH merger at multiple wavelengths. Finally, establishing the distribution of the intrinsic properties (ejecta masses, colors, energetics) from a population of BNS mergers may be within reach by the end of the next LIGO/Virgo observing run in 2019/2020.

The expected increase in the number of functional GW interferometers in the next decade (Abbott et al. 2018b) will substantially increase the localization accuracy of sources and, thus, improve the identification of electromagnetic counterparts. However, with the increased sensitivity, future GW interferometers will probe more distant populations of sources since GW interferometers are sensitive to the gravitational strain h, which scales as ~1/d (where d is the distance to a source), while EM telescopes are sensitive to the energy flux, which is proportional to $\sim 1/d^2$. The proposed A+ upgrades (*https://dcc.ligo.org/LIGO-T1800042/public/*) to Advanced LIGO (as early as 2025) will be sensitive to BNS mergers up to ~400 Mpc, which is a factor ~10 more distant than GW170817. At such a large distance, even the peak X-ray emission detected from GW170817 would fall below the *Chandra* detection threshold. Improved GW interferometers lead to farther GW sources with exceedingly faint X-ray counterparts, necessitating the need for larger collecting areas in future generation X-ray telescopes, such as Lynx (*https://www.lynxobservatory.com/*).

Meanwhile, if no additional GW+EM detections are made, *Chandra* and its successors will keep us busy monitoring the X-ray emission from GW170817 for the next 30 years (Fig. 3).

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