Searches for Electromagnetic Counterparts to Gravitational Wave Events (pre-2017)

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0.1 Suggested Reading

"What is the Most Promising Electromagnetic Counterpart of a Neutron Star Binary Merger?", B. Metzger and E. Berger, ApJ, **746**, 48, 2012

1 Introduction

The first direct detection of gravitational waves from the merger of two stellar mass black holes (GW150914; Abbott et al. 2016) has opened an entirely new window onto the Universe. The picture from gravitational waves we have seen of compact binary mergers is remarkably rich - gravitational wave measurements provide measurements of individual masses and spins, as well as a distance measurement independent of the cosmic distance ladder. But the full astrophysical context – including the redshift, host galaxy, location within the host, and merger ejecta – is only possible with the joint detection of an electromagnetic counterpart.

The purpose of this lecture is to describe the search for counterparts to gravitational wave sources *prior to the discovery of GW170817*. Given that a) we did not know of any binary stellar mass black holes in the Universe prior to GW150914, and b) we do not expect any electromagnetic signal from the merger of two stellar mass black holes, I will focus here largely on the various predicted signals from the merger of two neutron stars.

Figure 2 shows a cartoon picture of the four primary EM signals that have been previously suggested as potential counterparts to binary neutron star mergers (Metzger and Berger, 2012).

1. Short-Duration Gamma-Ray Burst: Given the plethora of circumstantial evidence connecting short-duration gamma-ray bursts (GRBs) to binary neutron star mergers, this was one of the first proposed counterparts for gravitational wave detections (Eichler et al., 1989).
2. Gamma-Ray Burst Afterglow: Even if the GRB itself is not detected (for instance, due to lack of sky coverage by high-energy satellites at the time of merger), the longer-lived X-ray, optical, and/or radio emission could be detected. This includes both afterglows viewed "on-axis" (within the opening angle of the collimated jet), or even off-axis, when the jet spreads laterally and illuminates an increasing fraction of the sky (so-called "orphan" afterglows; (Rhoads, 1999)).
3. Kilonova (also known as a "macronova"): Resulting from nucleosynthesis in the neutron-rich ejecta, this short-lived transient was predicted to be largely isotropic, and so was posed as a particularly promising counterpart (Li and Paczyński, 1998).
4. Merger Radio Remnant: Analogous to radio emission viewed at late times from supernovae (aka, the "remnant"), when the outgoing blastwave shock heats sufficient material in the circumstellar medium,

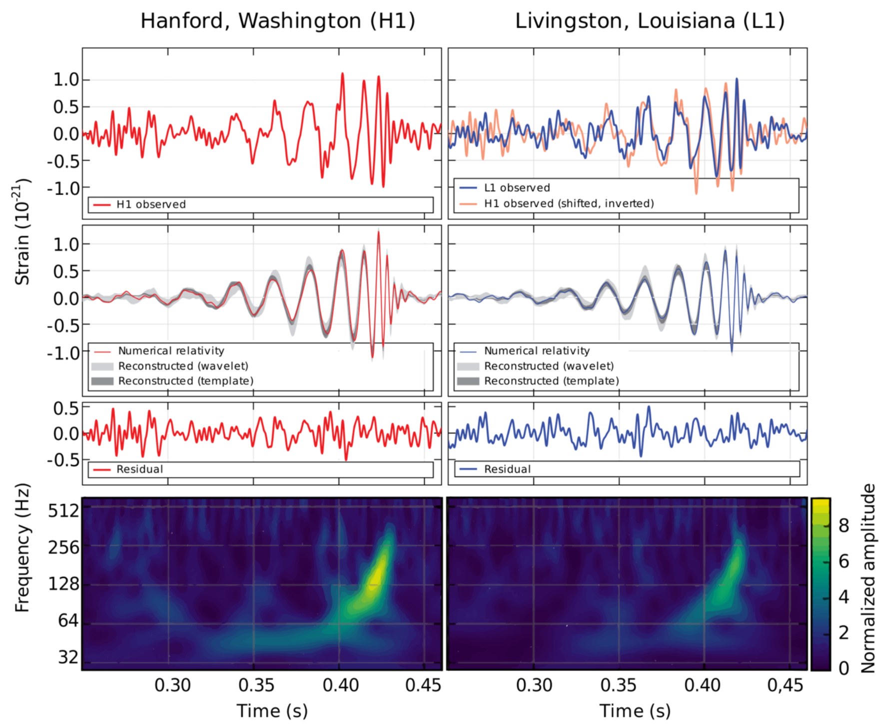

Figure 1: Discovery of gravitational wave emission from the merger of two stellar mass black holes. The gravitational wave strain is plotted in the top two plots, with frequency and amplitude both increasing as the black holes inspiral. The very short time scale in which the signal is in the LIGO bandpass indicates massive compact objects, too large to be neutron stars. From (Abbott et al., 2016).

the neutron-rich ejecta will eventually give rise to radio emission, though on relatively late time scales (˜ years; (Nakar and Piran, 2011)).

I will discuss these potential counterparts in greater detail in the sections that follow.

2 Short-Duration GRBs

The singular advantage in short-duration GRBs as potential gravitational wave counterparts is that they are remarkably bright. Outshining the entire gamma-ray sky for their brief durations, they can be detected with modest collecting areas and relatively old technologies (e.g., NaI scintillators). Currently there are a large number of gamma-ray facilities sensitive to GRBs operating in orbit:

- The Burst Alert Telescope (BAT; Barthelmy et al. 2005) on *Swift*: The most sensitive GRB detector ever flown, the BAT can detect GRBs down to fluences of $\sim 10^{-9}\,\mathrm{erg\,cm^{-2}}$, but "only" images $\approx 1/6$ of the sky at any given time.
- The Gamma-Ray Burst Monitor (GBM; Meegan et al. 2009) on *Fermi*: Less sensitive than the BAT, the GBM can detect GRBs down to fluences of $\sim 10^{-8}\,\mathrm{erg\,cm^{-2}}$ (though for short-duration GRBs it partially compensates for this with its higher-energy bandpass than the BAT). However, can view the entire sky that is not occulted by the Earth (in its low-Earth orbit), or $\approx 85\%$ of the sky.
- The InterPlanetary Network (IPN; Hurley et al. 2005): The IPN consists of a series of spacecraft with gamma-ray detectors distributed throughout the Solar System. Noteable members include the

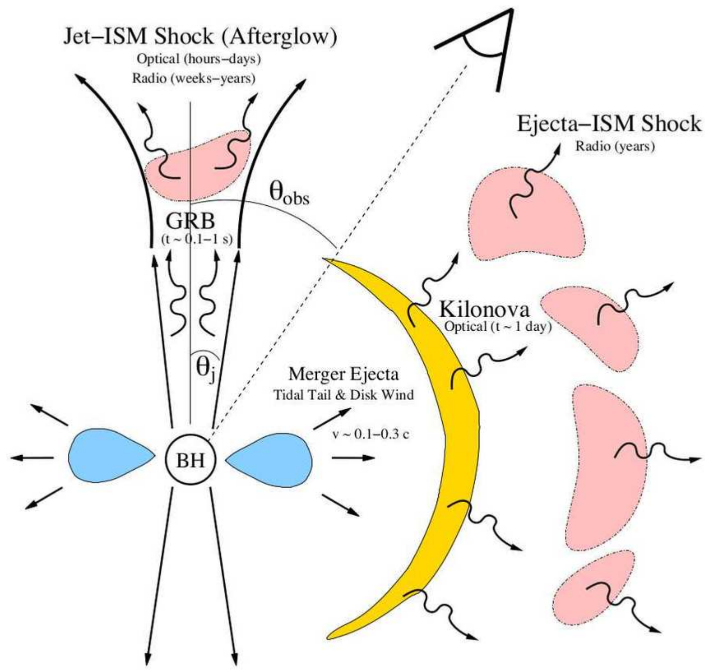

Figure 2: A cartoon schematic of the various electromagnetic counterparts to binary neutron star mergers. From (Metzger and Berger, 2012).

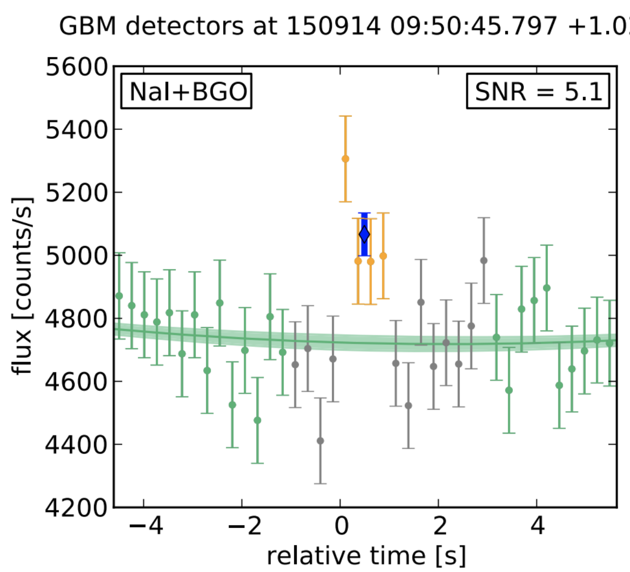

Figure 3: The gamma-ray light curve from the *Fermi*-GBM at the time of the binary black hole merger GW150914. A short-duration, faint transient is detected ˜ 0.4 s after the merger time. From (Connaughton et al., 2016).

European *INTEGRAL* mission and the Russian KONUS instrument on the NASA WIND satellite. While few of these facilities have any localization capabilities alone, they can use "triangulation" (like GPS satellites) to provide positions for GRBs when multiple detections are made. And while most of the individual instruments are less sensitive than both the BAT and GBM, because the IPN facilities are so widely distributed they have effectively no down time (c.f., *Swift* and *Fermi*, both of which pass through the South Atlantic Anomaly).

2.0.1 Exercise 1: Calculate the likelihood of a binary neutron star merger having a GRB visible here on Earth.

Despite the relatively small likelihood calculated above, a number of searches have been conducted for coincident gamma-ray and gravitational wave signals. By far the most intriguing result from this search was the discovery of a weak, short-duration gamma-ray transient coincident spatially and temporally coincident with the first binary black hole merger, GW150914 (Figure 3; Connaughton et al. 2016). The significance of this excess emission has generated spirited discussion within the gamma-ray community over the last several years (Greiner et al., 2016; Connaughton et al., 2018). It's worth emphasizing that even if the gamma-ray excess is astrophysical, it is not necessarily associated with the binary black hole merger. No significant gamma-ray emission has been seen in coincidence with any subsequent binary black hole merger.

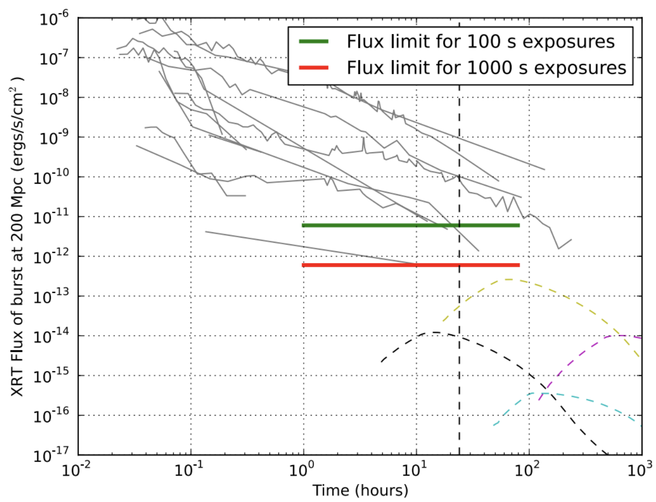

Figure 4: The X-ray afterglow light curves of short-duration GRBs, shifted to a distance of 200 Mpc (the horizon distance for binary neutron star mergers from Advanced LIGO at design sensitivity). The (on-axis) afterglows would be extremely bright, and could be easily detected by the *Swift*-XRT as late as several days after the burst. From (Kanner et al., 2012).

3 Afterglow

Like the prompt gamma-ray emission itself, afterglow emission from a binary neutron star merger detected via gravitational waves, when viewed from within the opening angle of the ultra-relativistic jet ("on-axis" afterglows), will be extremely bright. The horizon distance of 200 Mpc for binary neutron star mergers from Advanced LIGO is much more nearby than any known short-duration GRB. In Figure 4, I show a plot of X-ray afterglows of known short-duration GRBs as they would appear at a distance of 200 Mpc (Kanner et al., 2012). The green line shows the sensitivity of the X-Ray Telescope (XRT) on *Swift* in a 100 s exposure, indicating that most afterglows could be easily detected even a day after that neutron star merger.

For essentially the same reasons as described above for the prompt gamma-ray emission, such on-axis afterglows will be relatively rare, certainly a small minority of the binary neutron star mergers discovered by gravitational wave detectors. Thus, there is strong motivation to search for alternative counterparts.

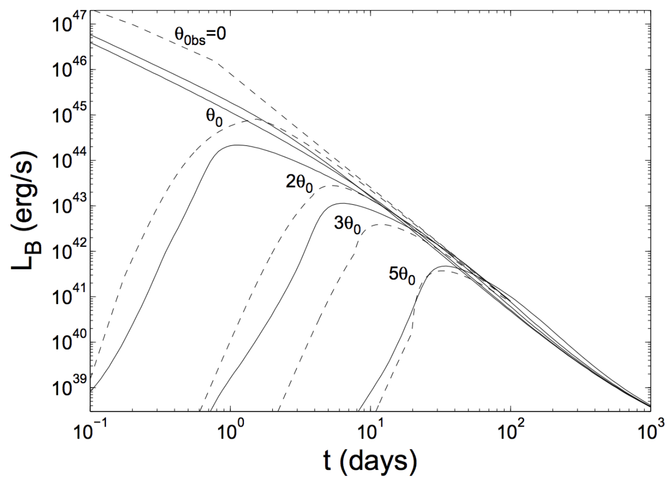

Figure 5: The optical (B-band) light curve a long-duration gamma-ray burst, for different viewing angles. For viewing angles outside the opening angle of the jet, the emission rises rapidly as the jet spreads laterally and illuminates an increasing fraction of the sky. Eventually the decay resembles that seen by an on-axis observer. From (Granot et al., 2002).

However, unlike the prompt emission, which was (until GW170817) expected to be visible only within the narrow jet opening angle, the afterglow emission from "off-axis" events will become visible at late times (Rhoads, 1999). As the outward expansion of the jet slows around the time of the jet break, the outflow will begin to expand laterally. Off-axis observers will see rapidly rising emission until the jet illuminates the entire sky, at which point the decay will resemble that seen at late-times from on-axis GRBs (Figure 5).

At first blush, this seems a very promising candidate for an electromagnetic counterpart to a binary neutron star merger, since it does not suffer from the same beaming constraints as the prompt emission. However, how bright do we expect this emission to be?

Hint: For a fixed opening angle, the time of the jet break can be written as:

$$t_{\rm jet} = \left(\frac{17E\theta^8}{1024\pi n m_p c^5}\right)^{1/3}$$

3.0.1 Exercise 1: Using the relations from last lecture, calculate the X-ray, optical, and radio flux density at the time of the jet break for an opening angle of 15 degrees at a distance of 200 Mpc (take other parameters as having standard values). This is the maximal possible flux for an off-axis afterglow - how does it compare to current observational capabilities?

The identification of such "orphan" afterglow, either for a long- or short-duration GRB, is one of the few remaining prizes for GRB observers, as this would instantly confirm our picture of GRBs as highly collimated explosions. Most of the effort in this area has been undertaken at optical (because of the availability of wide-area optical imaging facilities) and radio (because the peak time scale in the radio is the longest) wavelengths.

Optical searches with the Palomar Transient Factory (PTF) have yielded two candidates of interest. The first, iPTF14yb, was discovered as a rapidly fading optical transient with no apparent host galaxy. A prompt spectroscopic redshift of $z = 1.97$ made this source the most luminous transient discovered by PTF over the course of its nearly 10 years of operations. However, several days following discovery, a long-duration GRB consistent temporally and spatially with iPTF14yb was identified by the InterPlanetary Network. Thus

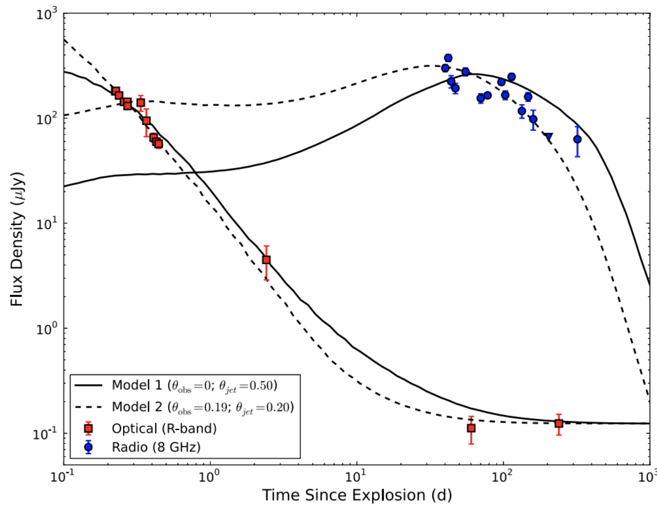

Figure 6: The optical (red) and radio (blue) light curves of PTF11agg. The rapidly fading optical emission, together with the long-lived radio flux, indicates the presence of at least mildly relativistic ejecta. However, no high-energy counterpart (i.e., GRB) was discovered. As such, it is one of the best candidates for an "orphan" afterglow to date. From (Cenko et al., 2013).

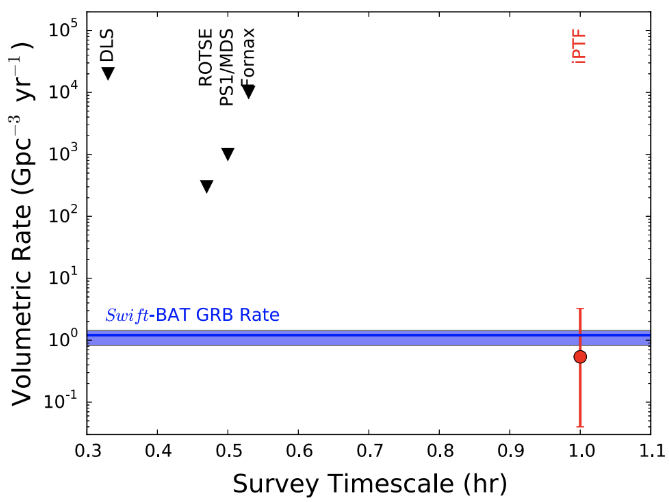

Figure 7: The rate of "fast" optical transients (defined as sources that fade by more than 1 magnitude within an hour), in several surveys searching for orphan afterglow emission. The volumetric rate of such events is entirely consistent with the rate of on-axis GRB optical afterglows, bounding the rate of "orphan" events from off-axis or "cloaked" fireballs. From (Cenko et al., 2015).

the source turned out to be an "ordinary" long-duration GRB (i.e., viwed on-axis), just for the first time identified independent of any high-energy trigger (Cenko et al., 2015).

A more intriguing, though not as well characterized event, was discovered several years earlier: PTF11agg (Figure 6; Cenko et al. 2013). The transient exhibited a rapid decline in the optical, but had a long-lived and scintillating radio counterpart. A very faint host galaxy is present underlying the source, but no emission lines were detected despite extensive efforts at measuring a redshift. While the rapid fading at early times seems more consistent with an on-axis relativistic explosion, no gamma-ray burst was reported by any detector in the relevant time window. Thus we speculated that this may be a new type of "dirty fireball" explosion, where the jet was sufficiently baryon-loaded to suppress any gamma-ray emission (due to pair-production). However, other authors have suggested a potential association with a binary neutron star merger (Wu et al., 2013).

Taken together, we have calculated the rate of "fast" optical transients from the Palmoar Transient Factory data set, where by fast we mean fading by ≥ 1 mag in ≤ 1 hour of time (i.e., much faster than a supernova or any other known extragalctic transient). The rate, shown in Figure 7, is entirely consistent with the rate of (on-axis) long-duration GRBs from *Swift*, indicating that a substantial population of orphan events (either off-axis or dirty fireballs) is unlikely to exist (Cenko et al., 2015).

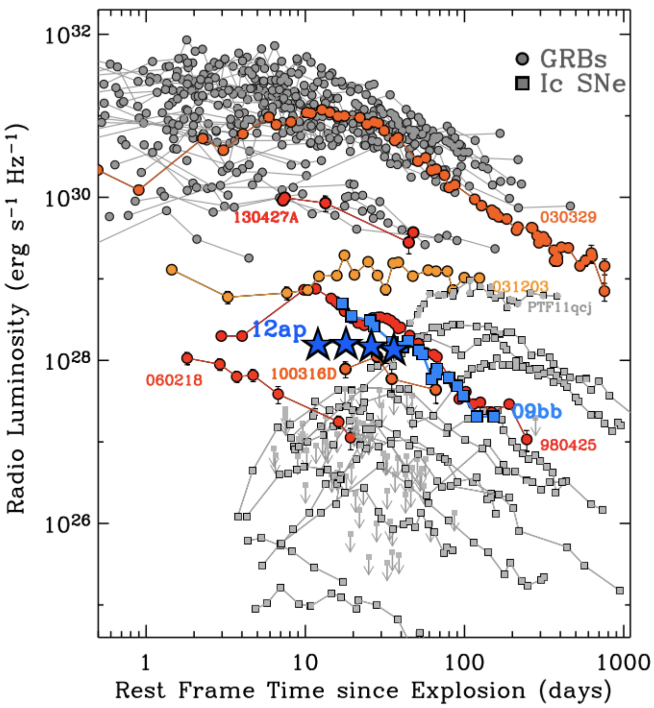

Figure 8: The radio luminosity evolution of gamma-ray bursts (circles) and ordinary stripped envelope supernovae (squares). A new population of intermediate events, with evidence for mildly relativistic ejecta, have been identified both in targeted radio follow-up of optically discovered supernovae, as well as in the class of low-luminosity (and thus nearby) long-duration GRBs. From (Margutti et al., 2014a).

Similar searches for relativistic explosions independent of any high-energy trigger have been undertaken over the years at radio wavelengths. The most intriguing candidates have come from *targeted* searches - in particular by following up broad-lined type Ib/c supernovae discovered at optical wavelengths. Since these are the (relatively rare) sub-type of core-collapse supernovae that have been exclusively associated with long-duration GRBs, late-time follow-up can probe the presence of relativistic ejecta, even for off-axis events. After more than a decade of such efforts, two supernovae have been identified with mildly relativistic ejecta from radio observations: SN2009bb (Soderberg et al., 2010) and SN2012ap (Chakraborti et al., 2015; Margutti et al., 2014b). Both sources are indicative of a new population of sources that bridge the gap between the ultra-relativistic jets seen in GRBs and the dominant class of supernovae lacking any relativistic ejecta (Figure 8).

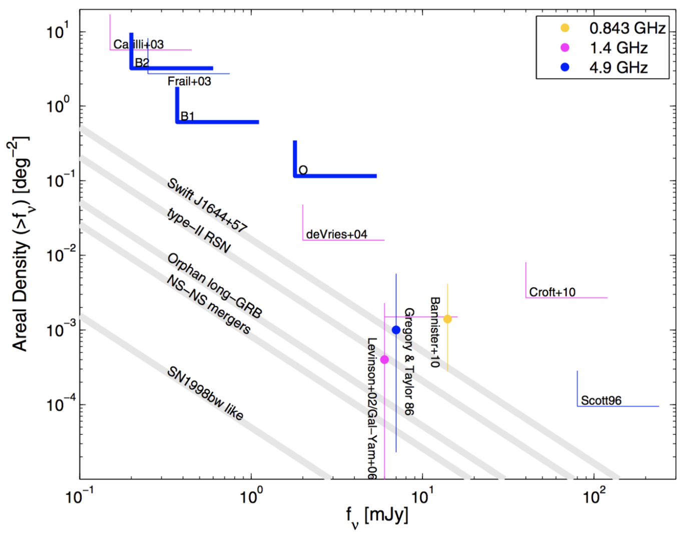

Figure 9: A summary of blind searches for radio transients. Given the relatively small fields of view or low sensitivities of radio facilities, most surveys were not sufficient to probe the known populations of extragalactic transients. The few blindly discovered candidates that have been identified are consistent with being ordinary (i.e., non-relativistic) radio supernovae. From (Frail et al., 2012).

In contrast to targeted radio searches, few if any other transient candidates have been identified in blind radio transient surveys. In large part this reflects the relatively small fields of view of the most sensitive radio interferometers - as can be seen from Figure 9, the limits to date are largely not constraining given the expected rates of orphan GRBs and binary neutron star mergers (the few blind candidates identified are consistent with being ordinary core-collapse supernovae; Frail et al. 2012). This is likely to change in the upcoming years, as more sensitive wide-area telescopes begin to become operation (MeerKAT, LWA, ultimately SKA).

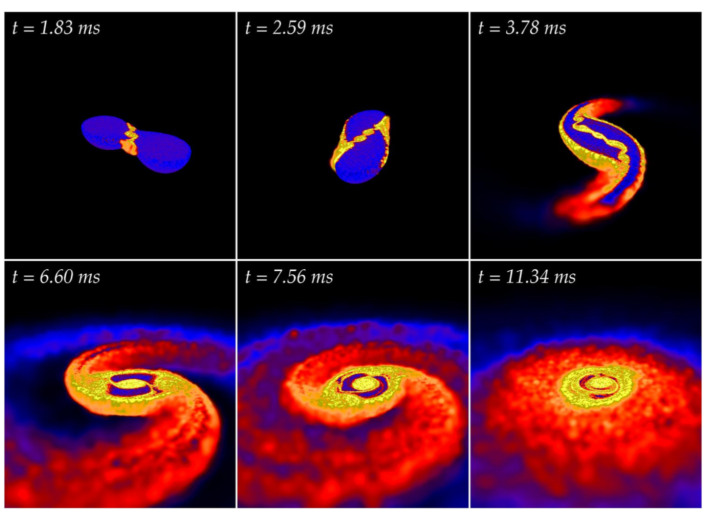

Figure 10: A magnetohydrodynamic simulation of the merger of two neutron stars. In the final orbits before merger, material is tidally stripped from the outer layers and dynamically ejected from the system with high velocities. A remnant accretion disk is also visible. From (Price, 2006).

4 Kilonova

Given the difficulties of detecting GRB and afterglow counterparts to binary neutron star mergers, the attention of the community turned towards a more *isotropic* signal. The details of what has come to be called a **kilonova** (or macronova, or merger-nova, or ...) will be discussed in great detail for the entirety of this summer school. Here I will give a (very) brief overview of the theory behind kilonova emission (or at least an observers perspective), and describe some of the observational constraints that existed prior to the discovery of GW170817.

The merger of two neutron stars is a complex process. In the final orbits prior to the merger, tidal forces (the difference in gravity between the near and far side of the neutron star) will act to *disrupt* the individual neutron stars. If sufficiently strong, these tidal forces can strip material from the outer layers of one (or possibly both) neutron stars, dynamically ejecting it from the system with high velocities ($v \approx 0.2c$; Figure 10; (Rosswog, 1999)). Alternatively, *after* the merger, viscous, magnetic, and/or neutrino-driven outflows from a hyper-massive neutron star and accretion disc may also eject mass from the system (Metzger et al., 2009). Such ejecta is often collectively referred to as a "disk" wind.

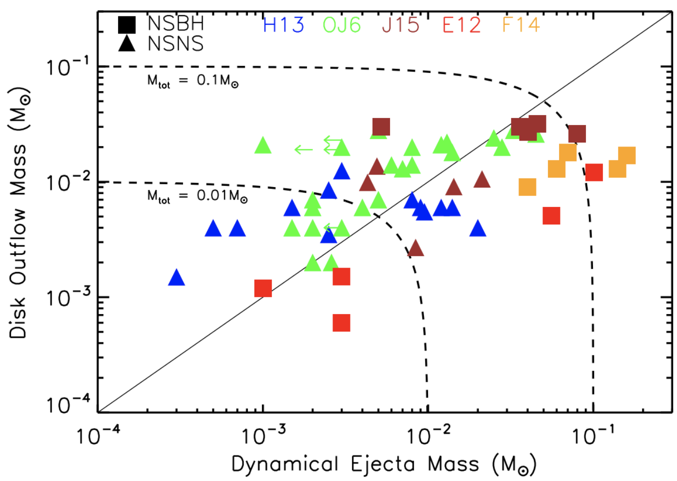

Figure 11: The mass ejected dynamically (x-axis) and via a disk outflow (y-axis) for various models of binary neutron star (triangles) and neutron star - black hole (squares) mergers. Typical values of order 1% the mass of the Sun are commonly achieved for binary neutron star mergers (more for some neutron star - black hole mergers). From (Fernandez 2016).

The amount of material ejected from the system depends senstively on a variety of parameters: the equation of state of the dense material in a neutron star, the parameters of the merging objects (masses, spins, orientation), as well as the details of the physics included in the calculation. Regardless, most recent numerical simulations find that a total ejecta mass of $M \approx 0.01\,M_\odot$ is unbound in a binary neutron star merger (neutron star – black hole mergers can eject even more mass). Figure 11 plots the results from recent numerical simulations (Fernández and Metzger, 2016).

Regardless of the origin of the material (dynamical vs. disk wind), binary neutron stars appear capable of generating significant amounts of *neutron-rich ejecta*. Such systems are extremely rare in the Universe, and early on it was realized that these mergers were prime sites for the formation of many of the heaviest elements via the r (rapid) process (Lattimer and Schramm, 1974). Given the temperatures and densities involved, neutrons are able to be captured rapidly by seed nuclei in these outflows, generating progressively heavier and heavier isotopes (Figure 12). Eventually these heavy isotopes decay to the isle of stability via

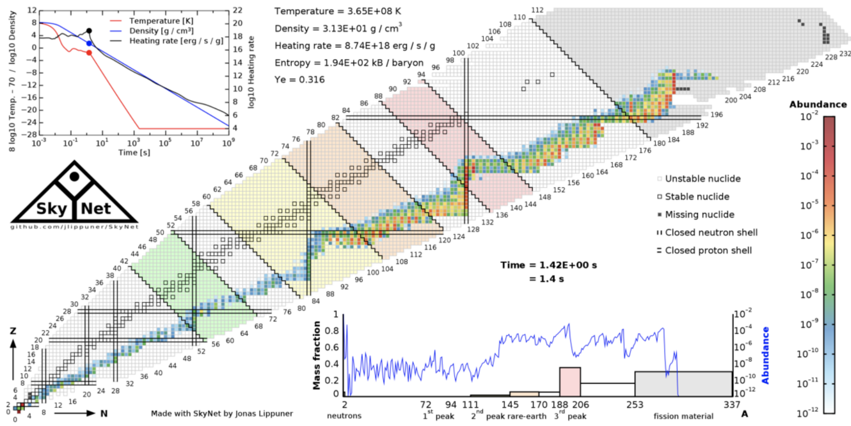

Figure 12: Numerical simulation of the r-process nucleosynthesis in the ejecta of a neutron star merger. Very rapidly heavy isotopes are synthesized from the capture of free neutrons, which eventually decay to stable elements via beta decay. The simulated abundances can nicely match that observed for heavy elements in the Solar neighborhood. From (Lippuner and Roberts, 2015).

beta decay, generating an abundance pattern that can accurately reproduce the observed distribution of heavy elements in the Solar neighborhood.

In analogy with type Ia supernovae, the radioactive decay of these heavy isotopes acts as a heat source energizing the expanding ejecta. The high-energy photons generated by these nuclear transitions are initially trapped in the dense ejecta, but eventually as the ejecta expand more and more radiation (both re-processed and direct) is able to leak out. The result is an electromagnetic transient that should be largely isotropic, and thus has long been viewed as a promising candidate for a counterpart to a binary neutron star merger detected via gravitational waves known as a kilonova (Li and Paczyński, 1998).

4.0.1 Exercise 3: We can approximately estimate the peak time of the associated transient by taking the geometric mean of the expansion time of the ejecta (assumed to be homologous) and the diffusion time for a static medium. Using values derived from the numerical simulations above (M ˜ 0.01 solar masses, v ˜ 0.2c) and an opacity analogous to type Ia supernovae (˜ 0.2), what is the characteristic peak time scale for a kilonova? Can you guess at any limitations in this back of the envelope calculation?

The fundamental limitation of the calculation you performed above is that we assumed the opacity was dominated by Fe-group elements, as is typically the case for type Ia supernovae. Fe-group elements typically have large opacities at wavelengths $\leq 4000\,\mathring{A}$, resulting in significant line blanketing in the rest frame UV spectra of type Ia supernovae around peak.

However, unlike type Ia supernovae, the dominant source of opacity in kilonova is the heavy r-process elements formed in the ejecta (Kasen et al., 2013). Because Lanthanide and Actinide-group elements may be formed in the ejecta (depending on how large the initial neutron fraction is), the opacity at optical (and even near-infrared) wavelengths can be orders of magnitude larger than that seen in supernovae. Lanthanide and Actinide-group elements have electrons in their f shells, which results in a dramatic increase in the number of line transitions available to the outer electrons. Since the opacity in these systems is largely dictated by the number of line transitions in any given bandpass, the result is a greatly increased opacity in kilonova (compared to type Ia supernovae).

The result of the larger opacity has a profound impact on the predicted light curves of kilonovae (Barnes and Kasen, 2013). The left plot in Figure 14 shows the expected light curves for Fe-like opacity (i.e.,

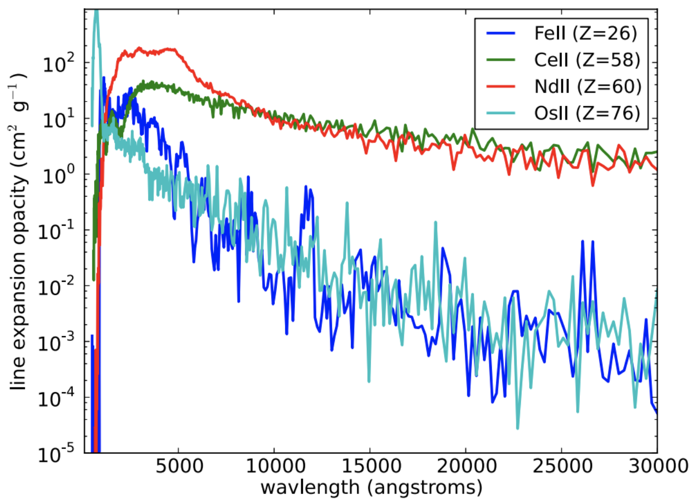

Figure 13: The opacity of different elements as a function of wavelength. Elements lacking f-shell electrons (Fe, Os) have a relatively small number of atomic transitions, and so their opacity is not large. Lathanide and Actinide elements, with their populated f shells, have many more transitions and so a much larger opacity in the optical and near-infrared bandpasses. From (Kasen et al., 2013).

supernova-like): a peak time scale of a few days and most of the luminosity is coming out at (redder) optical wavelengths. The right plot shows the significant difference when incorporating opacities from r-process elements. The time scale to peak of the bolometric light curve is significantly longer ($\approx$ 1 week). And the transient is significantly redder, as radiation is reprocessed to longer wavelengths. Thus a clear prediction came from theorists for observers hunting kilonovae: sensitive searches on time scales of ~ 1 week at *near-infrared* wavelengths would provide the best hope of a "smoking gun" signature of a binary neutron star merger.

Given the predicted brightnesses, the kilonova signature would only be detectable in events at $z \lesssim 0.3$. For gravitational wave detections, this is not an issue, as the Advanced LIGO network is limited to events at $d \leq 200$ Mpc. However, while waiting for Advanced LIGO to come online, GRB astronomers began actively searching for near-infrared excesses in nearby (by GRB standards) short-duration GRBs. Lo and behold, after the predictions in (Barnes and Kasen, 2013) and (Kasen et al., 2013), the first nearby $z = 0.36$ short-duration GRB, GRB130603B, had a prominent near-infrared excess at just the time, magnitude, and color predicted (Figure 15; Tanvir et al. 2013! At long last it seemed like GRB astronomers had the smoking gun signature linking binary neutron star mergers to short-duration GRBs we had long been seeking.

Despite the tantalizing nature of this discovery, a few important caveats are important to keep in mind. First, the sampling of the light curve (at both optical and near-infrared wavelengths) leaves something to be desired. The early decay is not well-sampled in the near-infrared, and with only a single point at late times calling this a "light curve" is perhaps an exaggeration. Surprisingly, the X-ray light curve of GRB130603B also shows an excess at late times that looks remarkably like that seen at near-infrared wavelengths, which is *not* expected for an r-process kilonova. (Figure 16; Fong et al. 2014). Furthermore, deep K-band observations of the more recent (and more nearby) GRB160821B do not show evidence for a prominent near-infrared excess, at a level that is below the emission seen from GRB130603B (Figure 17; Kasliwal et al. 2017).

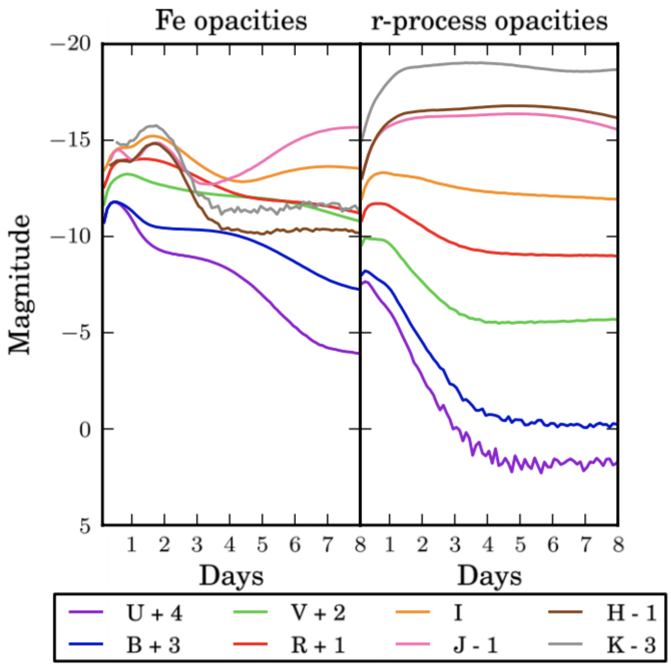

Figure 14: The result of increased opacities due to heavy element formation in kilonovae. The left plot shows the expected light curves for Fe-like opacity (i.e., supernova-like): a peak time scale of a few days and most of the luminosity is coming out at (redder) optical wavelengths. The right plot shows the significant difference when incorporating opacities from r-process elements. The time scale to peak of the bolometric light curve is significantly longer (˜ 1 week). And the transient is significantly redder, as radiation is reprocessed to longer wavelengths. From (Barnes and Kasen, 2013).

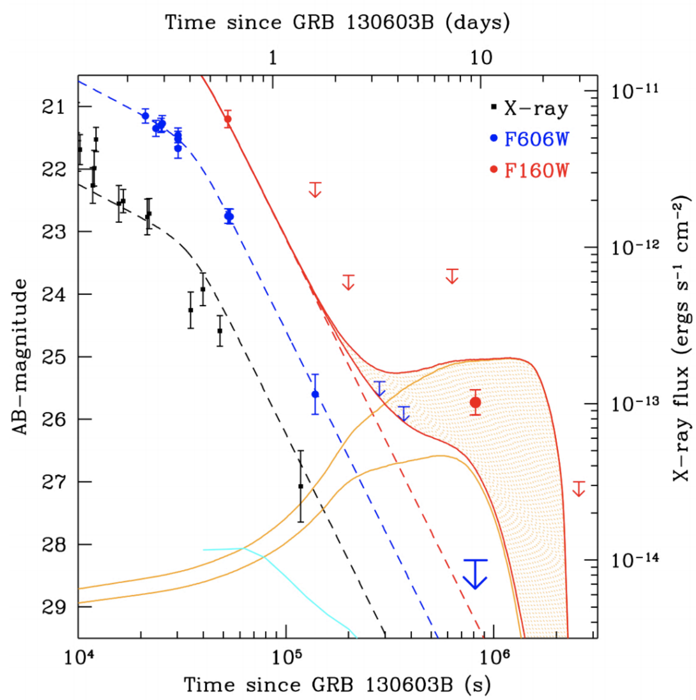

Figure 15: The X-ray (black), optical (blue) and near-infrared (red) light curves of the short-duration GRB130603B. The early emission at all wavelengths is dominated by the bright but rapidly fading afterglow. Extrapolating this forward to ˜ 10 days post trigger, an excess is seen at near-infrared but not optical wavelengths, consistent with theoretical predictions for a kilonova. From (Tanvir et al., 2013).

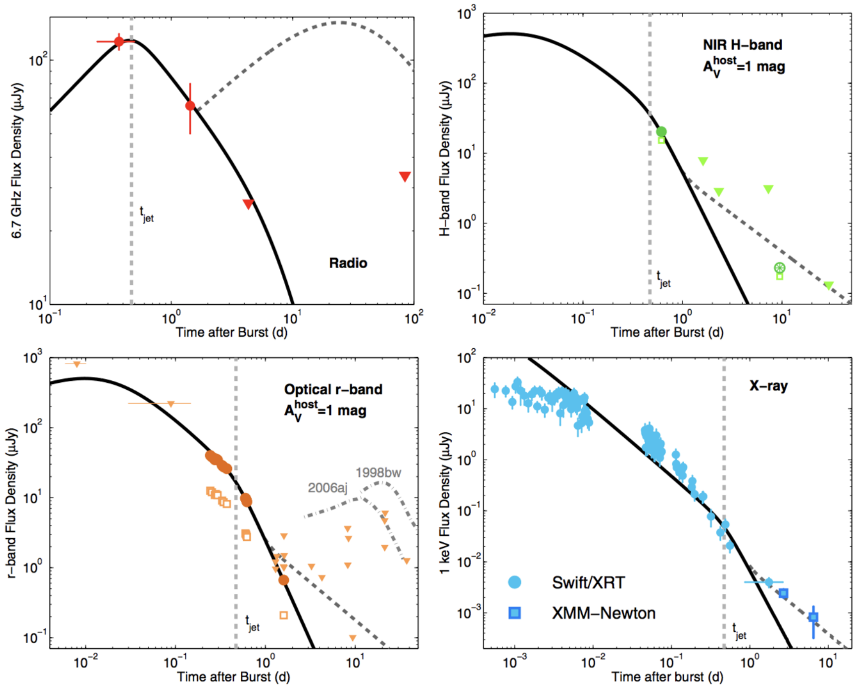

Figure 16: Radio, near-infrared, optical, and X-ray light curves of GRB130603B (same GRB as Figure 15). The X-ray emission also shows a clear excess at ˜ 10 days after the merger, which is **not** expected in (most) kilonova models. The nature of this X-ray excess remains largely unexplained to this day. From (Fong et al., 2014).

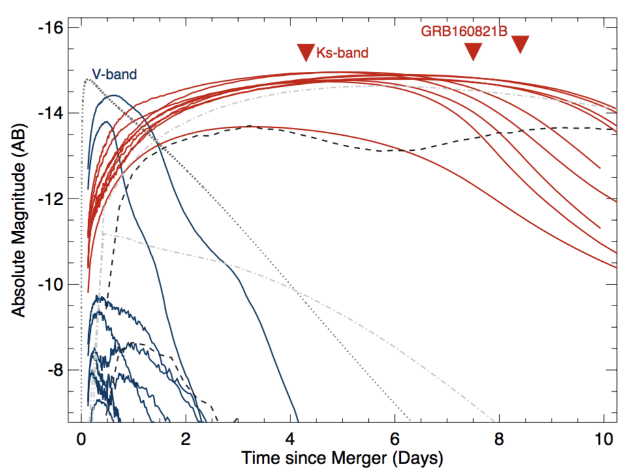

Figure 17: Near-infrared (K-band) limits on late-time emission from the nearby (z = 0.16) short-duration GRB160821B. The lack of a late-time near-infrared excess is not consistent with the behavior observed from GRB130603B. From Kasliwal_2017.

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