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Lessons from the light of a neutron star merger

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A B S T R A C T

The discovery by Advanced LIGO/Virgo of gravitational waves from the binary neutron star merger GW170817, and subsequently by astronomers of transient emission across the electromagnetic spectrum, has initiated a new era of multi-messenger gravitational wave astronomy. Here I summarize the electromagnetic discoveries in the context of theoretical counterpart models and present personal views on the major take-away lessons and outstanding new questions from this watershed event, focused on the implications for nuclear physics. The luminosity and colors of the early optical emission discovered within a day of the merger agree well with predictions for "kilonova" emission, powered by the radioactive decay of light *r*-process nuclei (atomic mass number $A \lesssim 140$). The transition of the spectral energy distribution to near-infrared wavelengths on timescales of days indicates that inner portions of the ejecta contain heavy *r*-process nuclei with high UV/optical opacity due to the presence of at least some lanthanide elements ($A \gtrsim 140$). The "blue" and "red" ejecta components likely possess distinct origins (e.g. dynamical ejecta, magnetar-powered wind, or accretion disk outflow), with implications for the merger process (e.g. the lifetime of the remnant prior to black hole formation) and fundamental properties of neutron stars. I outline the predicted diversity in the electromagnetic emission of future mergers—observed with different ingoing binary masses and/or viewing angles—discovered in the years ahead as LIGO/Virgo reach design sensitivity.

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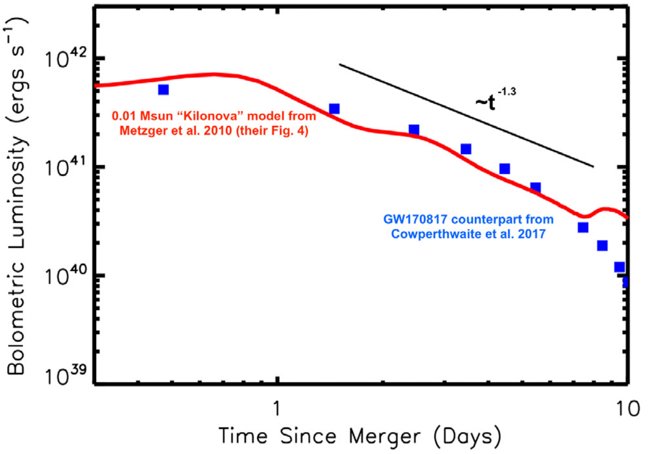

Fig. 1. Bolometric light curve of the optical/infrared counterpart of GW170817 (blue squares) from multi-band photometry [21] compared to the fiducial model of [32] (red line; their Fig. 4) for "kilonova" emission powered by the radioactive decay of $10^{-2}M_{\odot}$ of r-process matter expanding at $v = 0.1$ c, assuming complete thermalization of the radioactive decay products. Shown above for comparison is a line with the approximate power-law decay $\propto t^{-1.3}$ for r-process heating [32,33]. The true ejecta mass required to explain the data exceeds $0.01M_{\odot}$ by a factor of several (Table 1) because the actual thermalization efficiency is less than unity [34–36]. The observed color evolution of the emission from optical to near-infrared wavelengths can also only be understood by accounting for the details of the ejecta structure and the different opacities of light and heavy r-process nuclei (Section 2.2 for details).

1. A big reveal from the cosmos

When a neutron star (NS) binary coalesces into a single object following a prolonged inspiral driven by gravitational wave (GW) radiation, the outcome is a prodigious collision which releases mass and energy into the surrounding environment on a timescale as short as milliseconds. The merger aftermath was predicted to be accompanied by a diverse range of thermal and non-thermal electromagnetic (EM) counterparts from radio to gamma-ray frequencies (e.g. [1–5]). The discovery of the first GW chirp from a binary NS merger GW170817 by the Advanced LIGO and Virgo collaboration [6], and its subsequent localization to a host galaxy at a distance of only $\approx$ 40 Mpc (e.g. [7] and references therein), provided astronomers with a golden opportunity to test theoretical predictions for the EM and nucleosynthetic signatures of these events, as established by the work of theorists over the last 40 years.

The discovery and announcement of GW170817 was followed by the most ambitious campaign of EM follow-up observations ever conducted (see [7] for a summary). Observations covered the gamut of frequencies, including radio (e.g. [8–10]), infrared (e.g. [11,12]), optical/UV (e.g. [13–23]), X-ray (e.g. [24–26]), gamma-ray (e.g. [27–30]), and even neutrinos [31].

Often in astronomy, hints of the underlying nature of a phenomenon build up only gradually as the capabilities of telescopes incrementally improve; and even once a consensus opinion is reached, it is often the product of several pieces of indirect evidence. GW170817 represents a sharp departure from this rule, as the LIGO/Virgo discovery transported us in one quantum leap directly from the dark into the light (the "Big Reveal"), albeit a leap that theorists had long anticipated and given unusually extensive consideration to, despite the lack of observational guidance (e.g. Fig. 1).

Here I review theoretical models for the EM counterparts of binary NS mergers in the context of the GW170817 discovery. I focus on the thermal kilonova emission produced by the mildly-relativistic merger ejecta (Section 2), leaving a detailed discussion of the non-thermal emission from the ultra-relativistic gamma-ray burst (GRB) jet and its afterglow to other work. Fig. 2 summarizes a reasonable guess for the origin of the different EM counterparts observed following GW170817. In Section 3, I draw major take-away lessons from the first binary NS merger, and use them to

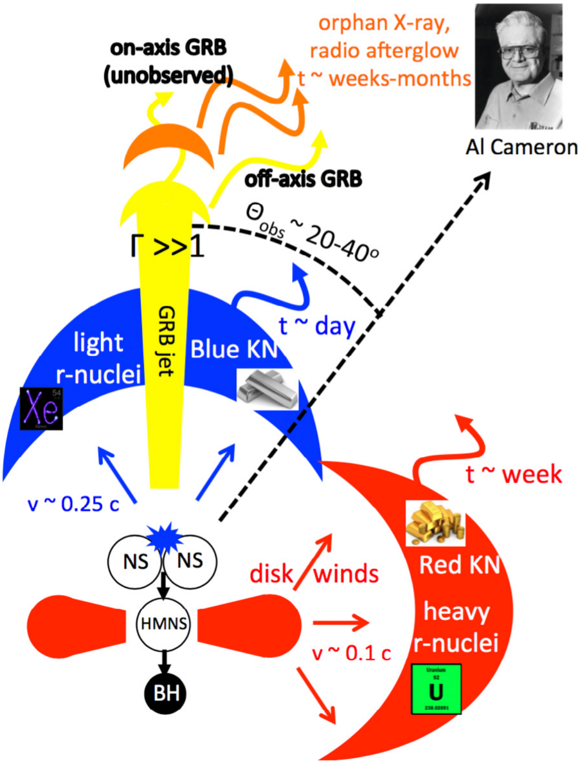

Fig. 2. Scenario for the EM counterparts of GW170817, as viewed by the observer (Al Cameron) from the binary inclination angle $\theta_{\rm obs} \approx 20^\circ$–$40^\circ$ (e.g. [37–39]), consistent with interpretations presented in several papers (e.g. [11,21,25,29,30,40,40,41]). **Timeline:** (1) Two NSs of comparable mass ($q \approx 0.8$–1) coalesce. The dynamical stage of the merger ejects a small mass $\lesssim 10^{-3}$–$10^{-2}M_\odot$ at high velocities $v \approx 0.2$–0.3 c, part of which is shock-heated polar ejecta with a high electron fraction $Y_e > 0.25$, which synthesizes exclusively light r-process nuclei ($A \lesssim 140$; e.g. xenon and silver); (2) The merger product is a temporarily stable HMNS, which generates a large accretion torus $\sim 0.1M_\odot$ as it sheds its angular momentum and collapses into a BH on a timescale of $\lesssim 0.1$–1 s. Winds from this highly-magnetized object also contribute substantially to the high-Y_e fast ejecta [42]; (3) The torus-BH powers a collimated GRB jet, which burrows through the polar ejecta on a timescale of $\lesssim 2$ s; (4) Gamma-rays from the core of the GRB jet are relativistically beamed away from our sight line, but a weaker GRB is nevertheless observed from the off-axis jet or the hot cocoon created as the jet breaks through the polar ejecta (e.g. [10,12,29]); (5) On the same timescale, the accretion disk produces a powerful wind ejecting ≈ 0.03–$0.06M_\odot$ of $Y_e \lesssim 0.25$ matter which expands quasi-spherically at $v \approx 0.1$ c and synthesizes also heavier r-process nuclei with $A \gtrsim 140$ such as gold and uranium; (6) After several hours of expansion, the fast polar ejecta becomes diffusive, powering $\sim$ visual wavelength ("blue") kilonova emission lasting for a few days; (7) over a longer timescale ≈ 1 week, the more deeply embedded disk wind ejecta becomes diffusive, powering red kilonova emission; (8) the GRB/cocoon ejecta decelerates as it shocks the ISM, causing a delayed rise of non-thermal X-ray and radio synchrotron afterglow over several weeks to months.

motivate new questions for scrutiny as the sample of EM/GW events grows over the next several years.

2. Kilonovae and the origin of the heaviest elements

The optical/infrared transient following GW170817 is fully consistent with being powered by the radioactive decay of nuclei synthesized in the NS merger ejecta. Here, I review the history of models for the r-process in binary NS mergers and the expected sources of mass ejection in these events based on numerical simulations (Section 2.1). I then describe the historical development of kilonova models (Section 2.2) in the context of their expected timescales, luminosities and colors;

particular emphasis is placed on the distinction between the emission from ejecta with and without the presence of heavy r-process nuclei. Within this framework, in Section 2.3 I summarize one interpretation for the kilonova from GW170817, and the resulting implications for the fate of the merger remnant and the properties of NSs, and thus of the supranuclear density EOS, more broadly.

2.1. Mass ejection in binary NS mergers and the r-process

Roughly 60 years ago, Burbidge et al. (1957; [43]) and Cameron (1957; [44]) recognized that approximately half of the elements in the Galaxy heavier than iron must have been produced in an environment in which the density of free neutrons was so high that neutron captures on nuclei proceed much faster than $\beta-$decays. Since that time, however, while the astrophysical sites of most of the other nucleosynthesis channels identified in these pioneering works have been identified, the origin of the rapid neutron capture process ("r-process", for short) has remained an enduring mystery. Hot outflows from the newly-formed proto-neutron stars created in core collapse supernovae were at one time considered the most promising contender. However, this model is known to exhibit large theoretical difficulties (e.g. [45]), and several lines of evidence in recent years have pointed towards an r-process source which is much rarer than garden variety supernovae (e.g. [46–49]).

Lattimer & Schramm (1974; [50]) proposed that the coalescence of a binary system consisting of a NS and a stellar mass black hole (BH) would provide a promising source of neutron-rich ejecta conducive to the r-process with a very low electron fraction $Y_e = n_{\rm p}/(n_{\rm n} + n_{\rm p})$, where $n_{\rm p}$ and $n_{\rm n}$ are the densities of protons and neutrons, respectively. Following the ejection of NS matter through the outer binary Lagrange points by tidal forces, its rapid decompression from nuclear densities would naturally result in the formation of heavy nuclei through neutron capture [51,52]. Later works [53,54] proposed that a similar mechanism of mass ejection could occur from merging compact binaries consisting of two NSs. The first numerical simulations of binary NS mergers showing tidal mass ejection followed (e.g. [55–57]), with subsequent work establishing that the r-process of this extremely neutron-rich matter ($Y_e \lesssim 0.1$–0.2) would result in an heavy element abundance pattern broadly consistent with that in the solar system [58,59]. Tidally-ejected matter expands away from the merger site primarily in the equatorial plane of the binary at velocities $\sim$0.2–0.3 c, and its quantity $\sim 10^{-4}$–$10^{-2} M_{\odot}$ is a sensitive decreasing function of the binary mass ratio $q = M_2/M_1 < 1$ (e.g. [57,60]), i.e. more asymmetric mergers eject greater mass tidally.

In addition to the tidal ejecta, contemporary numerical simulations have established a separate ejecta source originating from the interface between the merging stars and emerging into the high latitude polar region [60–62]. Heating due to shocks and neutrino-irradiation promote weak interactions (e.g. $n\nu_e \rightarrow pe^-$, $e^+n \rightarrow p\bar{\nu}_e$) which raise the electron fraction of the polar ejecta to values $Y_e \gtrsim 0.25$ well above its initial composition in the neutron star interior [63–66]. Though relatively independent of the binary mass ratio, the quantity of shock-heated polar ejecta instead depends sensitively on the NS radius (see below) and the lifetime of the compact remnant created during the merger. If the baryonic mass of the binary (and thus of its compact central remnant, $M_{\rm rem}$) exceeds the maximum mass of a neutron star, $M_{\rm max}$, by a factor of $f = 1.3$–1.6 (the precise threshold decreases with the NS compactness; [67]), then the merger product promptly collapses to a BH with little or no polar dynamical ejecta [68]. On the other hand, if $M_{\rm rem} \lesssim fM_{\rm max}$ then the merger product is a hypermassive NS (HMNS) or supra-massive NS (SMNS), which is at least temporarily stable to collapse due to its rapid rotation. The quantity of polar dynamical ejecta in this case exceeds the prompt collapse case, varying from $\sim 10^{-3}$–$10^{-2} M_{\odot}$, depending most sensitively on the radii of the NSs; a more compact NS results in the collision occurring deeper in the gravitational potential and thus produces stronger shock-heating and greater mass loss, at least until reaching the prompt collapse threshold (e.g. [62,69,70]).

Debris from the merger which is not immediately unbound can possess enough angular momentum to circularize into an accretion disk around the central remnant, providing an agent to power an ultra-relativistic gamma-ray burst jet (e.g. [71]). Slower expanding outflows from this remnant disk, which occur on timescales of up to seconds post merger, provide another important source of r-process ejecta (e.g. [72,73]). The quantity of mass in the disk outflows $M_{\rm ej}^{\rm disk}$ scales approximately with the original mass of the torus M_t, with $M_{ej}^{disk} \approx 0.2$–$0.4M_t$ [74–80]. Because the mass of the torus increases with both the mass ratio of the binary and the lifetime of the HMNS (e.g. [60]), M_{ej}^{disk} is also a decreasing function of q and M_{rem}/M_{max}, i.e. an asymmetric merger or long-lived NS remnant produces a greater quantity of disk ejecta. For a massive torus $\gtrsim 0.1$–$0.2M_\odot$ the disk ejecta mass $M_{ej}^{disk} \sim 0.05$–$0.1M_\odot$ can greatly exceed that of the dynamical ejecta. The electron fraction distribution of the disk outflows, though potentially broad $Y_e \sim 0.1$–0.4 [76], depends on the lifetime of the central neutron star remnant due to the de-neutronizing impact of its strong electron neutrino luminosity. The average Y_e of the disk outflow grows with the time the HMNS or SMNS survives before collapsing to a BH [75,81]. Disk outflow simulations find that the unbound matter achieves asymptotic speeds $v_{ej} \approx 0.03$–0.1 c which are typically 2–3 times lower than the velocity of the dynamical ejecta.

Fig. 3 and Table 2 summarizes the quantity of lanthanide-poor ("blue") and lanthanide-rich ("red") ejecta from neutron star mergers from both dynamical and disk wind channels, and their dependence on properties of the binary (remnant mass M_{rem}, mass ratio) and neutron star (radius, maximum M_{max}). The disk wind ejecta exhibits a complex behavior with increasing remnant lifetime (decreasing M_{rem}/M_{max}), as outlined schematically by the region between the black solid arrows.

2.2. *Kilonova emission models*

Table 3 summarizes the historical progression of kilonova models and their predictions for the luminosity, timescale, and color of the thermal emission. Although models capable of explaining the detailed color evolution of the emission following GW170817 reached their present mature form just in the last couple of years, many of the basic predictions were in place earlier.

Li & Paczynski (1998; [82]) first proposed that the radioactive ejecta of a NS merger could power a supernova-like thermal transient. Due to the small quantity of ejecta mass and its high expansion speed ~ 0.1 c, they predicted that the ejecta would become diffusive to photon radiation and the emission would peak on a timescale of $\lesssim 1$ day, much shorter than the rise time of a supernova. However, [82] did not possess a physical model for radioactive heating rate $\dot{q}$ (e.g. based on a nuclear reaction network; the term "r-process" does not appear in their paper), which they instead parameterized as $\dot{q} \propto t^{-1}$ with the normalization left as a free parameter. Since the peak luminosity is proportional to the heating rate at the time of peak light, their fiducial model reached extremely high values $\sim 10^{44}$ erg s^{-1}, close to the brightest supernovae ever discovered, with a spectral peak in the ultra-violet. Such luminous transients following NS merger were disfavored based on observations ruling out their presence following short duration GRBs, after they began to be localized to sufficient accuracy for optical follow-up by the *Swift* satellite starting in 2005 (e.g. [83–86]).

Metzger et al. (2010; [32]) were the first to calculate the late-time radioactive heating from decaying r-process nuclei (predicting $\dot{q} \propto t^{-1.3}$ on timescales of hours to days; Fig. 1), which they incorporated self-consistently into the light curve calculation. They also used a more physical model for the opacity, assuming it was provided by the line (bound–bound) opacity of iron versus the (highly sub-dominant) electron scattering opacity assumed in earlier work. They predicted peak luminosities of $\sim 3 \times 10^{41}$ erg s^{-1} for $10^{-2}M_\odot$ of ejecta expanding at $v \sim 0.1$ c and a spectral peak at visual wavelengths. As this was roughly 1000 times more luminous than classical novae (which peak typically close to the Eddington luminosity of a solar mass object of $\sim 10^{38}$ erg s^{-1}), they dubbed these events "kilonovae". Metzger & Berger (2012; [2]) highlighted that the isotropic nature of the kilonova emission, as compared to the tightly collimated and relativistically beamed GRB/afterglow emission, would make them the most promising counterpart for a typical binary NS merger at 200 Mpc, the range of Advanced LIGO/Virgo at design sensitivity. Kasliwal & Nissanke (2014; [87]) emphasized that during the few observing runs with Advanced LIGO, mergers could occur much closer than 200 Mpc and thus kilonovae could be discovered even with 1 m class telescopes (as turned out to be the case for GW170817).

Barnes & Kasen (2013; [88,89]) and subsequently, Tanaka & Hotokezaka (2013; [90]), performed the first kilonova calculations including line opacity data based on atomic data expected for ejecta containing heavy r-process elements. They showed that if the ejecta contains lanthanide or actinide

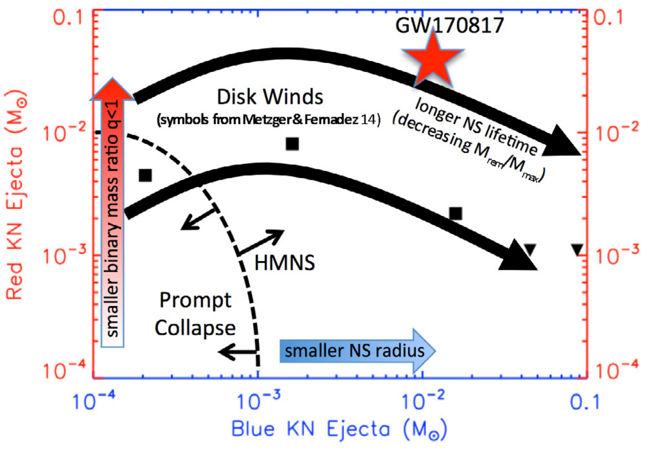

Fig. 3. Quantity of lanthanide-free (light r-process; "blue KN") ejecta and lanthanide-bearing (heavy r-process; "red KN") ejecta from a binary NS merger and its dependence on the properties of the binary (remnant mass $M_{\rm rem}$, NS radius, and maximum mass NS $M_{\rm max}$) in comparison to those inferred from the blue and red kilonova emission of GW170817 (e.g. [11,21,41]). The amount of low-Y_e (red) tidal tail ejecta increases for more asymmetric binaries (decreasing binary mass ratio $q = M_2/M_1 < 1$), while the amount of high-Y_e (blue) shock-heated ejecta ejected dynamically into the polar regions is larger if the colliding NSs possess smaller radii. For a massive binary with a high ratio of $M_{\rm rem}/M_{\rm max}$, the merger product promptly collapses to a BH, producing little blue shock-heated ejecta. The dependence of the disk wind ejecta composition, as approximately delineated as the region between the black arrows, is more complex and depends on the lifetime of the HMNS or supra-massive NS merger remnant, which increases with decreasing $M_{\rm rem}/M_{\rm max}$ [75,94–96]. Not included here are neutrino-irradiated outflows from the **magnetized** HMNS (prior to its collapse), which may have produced most of the blue KN ejecta in GW170817 [42].

Table 1
Key Properties of GW170817.

Property	Value	References
Chirp mass, $\mathcal{M}$ (rest frame)	$1.188^{+0.004}_{-0.002} M_\odot$	[97]
First NS mass, M_1	1.36–$1.60 M_\odot$ (90%)	[97]
Second NS mass, M_2	1.17–$1.36 M_\odot$ (90%)	[97]
Total binary mass, $M_{\rm tot} = M_1 + M_2$	$\approx 2.74^{0.04}_{-0.01} M_\odot$	[97]
Observer angle to orbital axis, $\theta_{\rm obs}$	19–42° (90%)	e.g., [37–39]
Blue KN ejecta ($A_{\rm max} \lesssim 140$)	≈ 0.01–$0.02 M_\odot$	e.g., [21,40,41]
Red KN ejecta ($A_{\rm max} \gtrsim 140$)	≈ 0.03–$0.06 M_\odot$	[11,21,40]
Light r-process yield ($A \lesssim 140$)	≈ 0.04–$0.07 M_\odot$	
Heavy r-process yield ($A \gtrsim 140$)	$\approx 0.01 M_\odot$	
Energy of GRB jet	$\sim 10^{49}$–10^{50} erg	e.g., [8–10,98]
ISM density	$\sim 10^{-5}$–10^{-3} cm^{-3}	e.g., [8–10,98]

nuclei with partially-filled f-shell valence electron shells, as occurs if the r-process passes the second abundance peak at atomic mass number $A \approx 130$, then the resulting photon opacity at UV and optical wavelengths is $\gtrsim$10–100 times greater than if the ejecta were composed of iron-like nuclei with partial d-shell valence electrons. This high optical opacity delays the evolution timescale of the light curve from $\sim$1 day to $\sim$1 week and pushes the spectral peak from visual frequencies predicted by earlier work (e.g. [32,91]) to near-infrared wavelengths [89,90,92,93].

Although lanthanide opacities move the kilonova emission to the infrared, ***not all portions of the NS merger ejecta necessarily produce such heavy nuclei***. In particular, ejecta with $Y_e \gtrsim 0.25$ lacks sufficient neutrons for neutron-capture reactions to push the nuclear flow past the second r-process peak at $A \approx 130$ [81]. In such a case, the lanthanides are not produced, and the ejecta would produce a "blue" and fast-evolving kilonova similar to original expectations [32] because the opacity of light r-process nuclei is only moderately higher than that of iron [40,102].

Table 2
Sources of r-Process Ejecta in Binary Neutron Star Mergers.

Ejecta Type	$M_{ej}(M_\odot)$	$v_{ej}(c)$	Color	M_{ej} decreases with	References
Tidal Tails	$\sim 10^{-4}$–10^{-2}	0.15–0.35	Red (NIR)	$q = M_2/M_1$	e.g., [57,60]
Polar Shocked	$\sim 10^{-4}$–10^{-2}	0.15–0.35	Blue (visual)	M_{rem}/M_{max}, R_{ns}	e.g., [62,65,66]
Magnetar Wind	$\sim 10^{-2}$	0.2–1	Blue (visual)	M_{rem}/M_{max}	[42,99]
Disk Outflows	10^{-3}–0.1	0.03–0.1	Blue+Red	M_{rem}/M_{max}	[74–76,78–80]

Table 3
Historical Development of Kilonova Models.

Model	Opacity	L_{peak} (erg s^{-1})	t_{peak}	SED Peak	Ref.
Parameterized heating	e-scattering	10^{43}–10^{44}	$\sim$1 day	UV	[100]
r-process heating	Iron	10^{41}–10^{42}	$\sim$1 day	visual	[32,91]
La opacities	Heavy r	10^{40}–10^{41}	$\sim$1 week	NIR	[89,90]
"Blue" + "Red"	light + heavy r	10^{40}–10^{42}	1 day $\rightarrow$ 1 week	Visual $\rightarrow$ NIR	[81,101,102]

At least a small quantity of ejecta with $Y_e \lesssim 0.2$ will be present in any merger from the tidal tail ejecta or disk winds, making "red" kilonova emission a ubiquitous feature. However, outflows from the accretion disk are more isotropic and thus should expand also into the lanthanide-poor polar regions [75,81,101], powering a separate component of "blue" emission similar to original kilonova models [32]. In original hybrid "blue" + "red" scenarios, the quantity of red versus blue kilonova emission originates from the disk outflows and is diagnostic of the lifetime of the central merger remnant (Fig. 3; [81,101]). However, Wanajo et al. (2014; [63]) first showed that when neutrino transport effects are included, the shock-heated polar dynamical ejecta may also be lanthanide-free with $Y_e \gtrsim 0.25$ (see also [64,65]), in which case it could also contribute to—or even dominate—the early-time blue kilonova emission. A potentially even larger source of high-Y_e ejecta is the neutrino-irradiated, magnetized outflow driven from the rapidly spinning HMNS remnant prior to its collapse to a black hole [42]. Depending on the velocity of the red ejecta relative to the blue and the observer viewing angle, the blue emission may be at least partially blocked by the higher-opacity red ejecta (e.g. [95]).

2.3. *Interpreting the Kilonova following GW170817*

The thermal spectrum of the optical counterpart of GW170817 (e.g. [11,41]) strongly supported the kilonova model (e.g. as compared to the power-law spectrum expected for non-thermal GRB afterglow emission). The shape of the bolometric light curve following peak is broadly consistent with the $\propto t^{-1.3}$ radioactive heating rate from freshly synthesized r-process nuclei (Fig. 1; [32]). Over the first few days the transient colors were blue and rapidly-evolving with a spectral peak at visual wavelengths (e.g. [16,17,19,21–24,41,103]). At later times, the colors became substantially redder and more slowly-evolving on timescales of several days to a week, with a spectral peak around 1.5 μm (e.g. [11,12,17,23]). The lack of well-defined spectral features is suggestive of line blending due to the photosphere expanding at speeds up to several tenths of the speed of light [41], though broad undulations in the NIR spectra predicted from lanthanide absorption [88] were possibly observed in GW170817 (e.g. [11,24]). As pointed out by several works (e.g. [11,12,16–18,21,22,24,40,104]), these properties are consistent with the two-component blue+red kilonova picture discussed above (e.g. [81,102,105]; however, see [106,107] for perturbations on this picture).

What part of the merger or its aftermath created most of the ejecta we observe? Both the dynamical merger phase, as well as the subsequent HMNS and accretion disk wind phases can contribute to the ejecta (Section 2.1, Table 2), making it important to carefully assess the origin of the dominant contribution to the blue and red ejecta components (see also [21,40]). The quantity of blue (lanthanide-free) ejecta from GW170817 was estimated to be $\approx$1–2 $\times$ $10^{-2} M_\odot$ with a mean velocity of $v_{ej} \approx 0.2$ c [21,41], based on fitting the observed light curves to kilonova models [108] and the spectra to more detailed radiative transfer calculations [40]. Comparing these measurements to the results of numerical simulations (Section 2.1), the high velocity tentatively supports an origin associated with the shock-heated dynamical ejecta [63–65] or a magnetized wind from the HMNS remnant [42] rather than a disk wind. If dynamical in origin, such a large *quantity* of the ejecta would favor relatively small neutron star radii $\lesssim$11 km [41] a result that would have key implications for the equation of state (e.g. [109]).

The total mass of the red (lanthanide-bearing) ejecta was $\approx 4 \times 10^{-2} M_{\odot}$ with a somewhat lower expansion velocity $v \approx 0.1$ c than the blue ejecta (e.g. [11,21,41]). Such a large quantity of ejecta, if originating from the tidal tail, would require an extremely asymmetric merger (e.g. [60]); however, this would not explain the low ejecta velocity, which based on numerical simulations is expected to be ≈0.2–0.3 c. Accretion disk winds provide a more natural explanation, as several $10^{-2} M_{\odot}$ expanding at $v \approx 0.1$ c matches theoretical expectations for the outflow from a massive torus $\gtrsim 0.1 M_{\odot}$ (e.g. [72,74,76,78,80,110]).

Such a large torus is not expected if the merger event resulted in the prompt collapse to a BH, but instead suggests that at least a temporarily-stable HMNS formed in GW170817 (e.g. [68]). On the other hand, the fact that the disk outflows produced at least some ejecta with $Y_e \lesssim 0.25$ (as needed to synthesize lanthanides) would, based on the results of numerical simulations of the disk evolution [94–96,111], implicate a relatively short HMNS lifetime, $\lesssim$100 ms (see Fig. 2 of [111]). This is consistent with the moderate kinetic energy of the kilonova ejecta $\approx 10^{51}$ erg, which does not require substantial rotational energy input from a long-lived stable NS remnant [112,113]. The requirement to form a HMNS with a massive accretion disk has been used to place constraints on the properties of the NS equation of state (e.g. [105,114]).

The kilonova emission from GW170817 probes the merger ejecta structure for one particular viewing angle and set of initial binary parameters. Future NS mergers observed from different viewing angles, or with a different total binary mass or binary asymmetry, could produce a quantitatively or qualitatively different signal. Some of these possibilities are described in Section 3.

How uncertain are the ejecta masses? Uncertainties enter estimates of the kilonova ejecta mass from at least three sources: geometry, the radioactive heating rate, and the thermalization efficiency of the decay products. While the thermalization efficiency of the early-time blue kilonova is relatively robust [32], the total radioactive heating rate of $Y_e \gtrsim 0.25$ matter is uncertain at the factor of a few level [115]. By contrast, while for the red kilonova emission the total radioactive heating rate of $Y_e \lesssim 0.25$ matter is robust to within a factor $\lesssim$2 [32,116], the thermalization efficiency is less certain because it depends on the distribution of heating between $\beta-$decays, α-particle decay and fission [34–36,117], which depend on the unknown masses of nuclei well off the valley of nuclear stability [47,118]. Geometric effects also typically enter at the factor ≈2 level [40,91,92,104]. A reasonable guess is that the kilonova ejecta masses are accurate to a factor of $\lesssim$2–3. Even given these uncertainties, and those on the overall rate of binary NS mergers, the discovery of GW170817 makes it likely that binary NS mergers are an important, if not dominant, site of r-process nuclei in the universe (e.g. [50,53,54,58]; however, see [119]).

3. Lessons learned and open questions

Taking at face value the unified scenario for the multi-wavelength counterparts to GW170817 summarized by Fig. 2, I now summarize the major take-away lessons from the first joint GW- and EM-detected binary neutron star merger. I also address how "typical" we should expect the EM signal from GW170817 to be, and, conversely, what counterpart diversity is expected as we move ahead to the era in which LIGO/Virgo approach design sensitivity and the NS mergers may be detected as frequently as once per week.

- **A triumph for theory.** While the detection of gamma-ray emission from an off-axis jet was surprising to many (however, see [122–124]), perhaps the biggest take-away from GW170817 is that theorists predicted the observed EM signals more or less accurately; the merger was surprisingly ***well-behaved***. The discovery of both blue [32] and red [125,126] kilonova emission was observed with the timescale, luminosity, and colors predicted by theory (Fig. 1) for an ejecta mass and velocity broadly consistent with those predicted by numerical

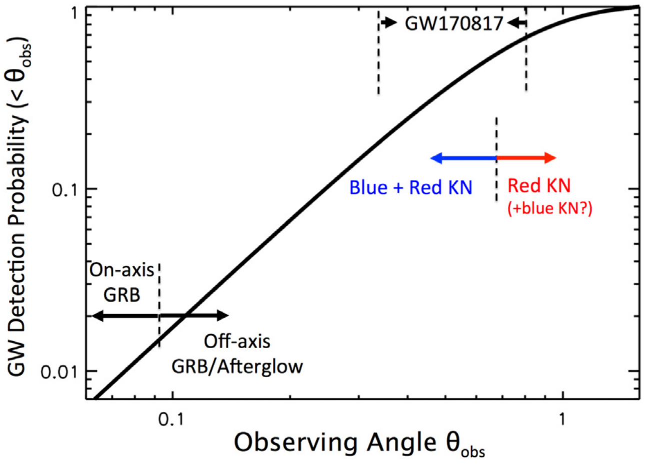

Fig. 4. Probability of detecting GWs from a binary NS merger at an observing angle (as measured from the binary orbital axis) less than a value θ_{obs} [2,120]. Shown for comparison are (1) the 1σ range of inclination angles inferred for GW170817 (when the degeneracy with distance is broken by the host galaxy distance; [37,38]), values consistent with modeling of the multi-wavelength afterglow (e.g. [121]) and VLBI imaging [39]; (2) the approximate angle separating viewers within the lanthanide-free polar funnel of the dynamical ejecta [65], which observe both a blue and red kilonova signature, from those more equatorial viewers who might observe only the red kilonova component (**if** the blue kilonova is obscured by e.g. a faster expanding red tidal tail); (3) the approximate angle $\theta_{obs} \lesssim \theta_j \approx 0.05$–$0.2$ separating mergers which produce on-axis cosmological short GRBs with prompt X-ray afterglows, from mergers viewed outside the jet axis who instead observe a weaker GRB and delayed orphan afterglow emission, observed in GW170817. Adapted from a similar figure in Margutti et al. (2017; [25]).

simulations of the merger (e.g. [57,61,65]) and the post-merger accretion flow (e.g. [74]). Likewise, the predictions for an off-axis afterglow of an otherwise successful GRB jet are broadly consistent with the observed non-thermal X-ray and radio emission for an observer situated at an angle relative to the binary axis [127,128] when the energy and angular structure of the jet-shocked merger ejecta is taken into account [10,121,129,130]. Additional evidence for a tightly collimated ultra-relativistic outflow comes from the VLBI radio interferometric detection of superluminal motion of the centroid of the radio emission [10]. Together, these provide the most direct evidence yet that binary NS mergers are the source of most or all classical short GRBs observed at cosmological distances (e.g. [54]).

- **An abundance of riches.** Given the significant quantity of r-process nuclei produced in GW170817, along with the relatively high implied merger rate, this strongly supports binary NS mergers as a major source of heavy r-process nuclei in the galaxy (e.g. [11,21,40,131]), confirming long-standing theoretical ideas [50,53,54,58]. The red kilonova emitting ejecta component dominates the total ejecta mass and thus likely also dominates the yield of both light and heavy r-process nuclei (Table 1). Assuming an r-process abundance pattern matching the solar one, one infers that over ten Earth masses of gold was created within a few seconds following GW170817.
- **Similar event, but different viewing angle?** GW170817's relatively face-on orientation of $\theta_{obs} \lesssim 0.4$ will be shared by roughly one third of GW-discovered mergers (Fig. 4). For larger inclination angles and/or greater source distances, theory suggests the GRB and afterglow emission will be dimmer and are unlikely to be sufficiently luminous to be detected [29]. The kilonova is predicted to be relatively isotropic and thus in principle should be visible with a similar luminosity (to within a factor of $\approx$2) for viewers observing the event closer to the binary plane. However, if the speed of the high-opacity lanthanide-rich equatorial tidal matter exceeds the speed of the blue polar ejecta, then the blue emission could be blocked or at least partially suppressed for the roughly half of the mergers viewed at $\theta_{obs} \gtrsim 0.6$ [95].

The origin of the large quantity of fast blue kilonova ejecta is not entirely settled, as it could be either dynamical in origin (e.g. [41]), or the result of a powerful wind from the magnetized HMNS remnant [42]. Much will be learned about the source and geometry of the kilonova ejecta from the luminosity of the early blue emission for the next NS merger observed at a higher inclination angle, closer to within the binary plane. Observations taken at earlier times than for GW170817 (e.g. the first hours after the merger) will also shed light on the composition of the fastest layers of the ejecta [132] and to what extent those layers have been shock-heated (e.g. by the GRB jet [129] or the HMNS magnetar wind [42]).

- **Similar event, but greater distance?** Luck may have played some role in the first NS merger discovery occurring at only 40 Mpc. For the same merger viewed at a distance more typical of those expected during LIGO/Virgo's O3 science run next spring ($\gtrsim$100 Mpc), the gamma-ray, X-ray and radio luminosities observed in GW170817 are probably too dim to be detected with current facilities. By contrast, the early blue kilonova observed on timescales of $\lesssim$1 day would still reach a visual magnitude of $R = 19.5$ at 100 Mpc or $R = 21$ at 200 Mpc, within the reach of moderate-sized wide-field follow-up telescopes, such as the Zwicky Transient Facility [133] and the BlackGEM array [134]. Even kilonovae for which the early blue emission is blocked or suppressed would be detectable to 200 Mpc distances by more sensitive telescopes such as DECam [135]. With a magnitude depth of $R = 25$–26, the Large Synoptic Survey Telescope (LSST) could detect a similar blue kilonova to distances $\gtrsim$1 Gpc! Kilonovae still represent the counterpart most likely to accompany the majority of mergers [2].
- **Similar event, but greater binary mass?** The large quantity of ejecta from GW170817 suggests that a temporarily stable HMNS remnant was created during the merger. The total binary mass $\approx$2.73–2.78$M_{\odot}$ (Table 1) is broadly consistent with that expected by drawing two stars from the Galactic NS population (well-described by a Gaussian of mean $\mu = 1.32M_{\odot}$ and standard deviation $\sigma = 0.11M_{\odot}$; [136]). For more massive binaries (with precisely how massive— and thus how rare —depending sensitively on the maximum NS mass), a prompt collapse would occur instead of the formation of a HMNS [67]. In such a case the blue kilonova would be strongly suppressed, especially the shocked polar dynamical component. The disk mass being much smaller, the red kilonova also could now be dominated by the tidal tail ejecta and thus would also be dimmer. All else being equal (e.g. similar inclination angle of observation), ***an inverse relationship is predicted between the kilonova luminosity and the total binary mass***.
- **Similar event, but lower binary mass?** For less massive binaries, a long-lived SMNS or stable NS remnant could form instead of a short-lived HMNS (e.g. [137,138]). In such cases, a fraction of the substantial rotational energy of the remnant (communicated, e.g., by magnetic spin-down) is likely to be transferred to the kilonova ejecta [139], accelerating it to higher speeds $v \sim c$ than inferred for GW170817. This additional source of acceleration and rotational energy input may power a signal with an optical and X-ray luminosity much higher than what is possible from r-process heating alone [112,140,141] and a faster evolution timescale. An ultra-relativistic outflow from a long-lived remnant may also power the mysterious variable X-ray/gamma-ray emission observed for hundreds or thousands of seconds following some short GRBs [142,143]. No evidence for such "extended emission" was observed at hard X-ray/gamma-ray energies following GW170817 [29]. Still, it would not be surprisingly to see qualitatively different EM behavior from the low mass tail of the NS binary merger population.
- **BH-NS instead of NS-NS?** What if GW170817 had been the merger between a NS and a spinning stellar-mass BH ($\sim$5–15$M_{\odot}$) instead of a NS-NS? If GW170817's blue kilonova was indeed the result of matter squeezed out of the polar region by the colliding NSs, then a similar component of fast high-Y_e ejecta and its concomitant blue kilonova emission will not be present for BH-NS mergers. If the mass of the BH is sufficiently low, and/or its spin sufficiently high, to disrupt the NS outside of the BH innermost stable circular orbit, then the tidal ejecta mass is typically $\sim$0.1$M_{\odot}$ [144], much higher than that in NS-NS mergers. Although this is consistent with the higher red ejecta mass inferred for GW170817, the average velocity of the tidal ejecta from a NS-BH will be higher, closer to $\approx$0.2–0.3 c, than inferred for GW170817.[1]

[1] However, this appears to not be the case for nearly equal mass binaries, e.g. if low mass BHs with masses overlapping the NS population exist in Nature; e.g. Foucart et al. [145].

A disrupted NS will also produce a massive accretion torus as in the NS-NS case, potentially capable of powering a GRB jet. A moderate quantity of blue kilonova ejecta from the accretion disk outflows are expected in this case (e.g. [146] finds $\lesssim 8 \times 10^{-3} M_{\odot}$ in $Y_e \gtrsim 0.25$ disk wind ejecta; [147]). Again, however, the velocity of the disk outflow is predicted to be lower $\lesssim 0.1$ c than that inferred for GW170817, and thus it may be easily blocked by the lanthanide-rich tidal ejecta for equatorial viewers.

- **Implications for the maximum NS mass.** The lack of evidence for either a prompt collapse (from the large inferred quantity of kilonova ejecta) or the formation of a SMNS remnant (from the prompt GRB and moderate kinetic energy of the kilonova ejecta) points to the formation of a HMNS remnant in GW170817. Using a suite of representative NS equations of state, the gravitational masses of the NS-NS binary measured by Advanced LIGO/Virgo, Margalit & Metzger (2017; [113]) place an upper limit on the maximum stable mass of a slowly-rotating NS of $M_{\rm max} \lesssim 2.17 M_{\odot}$ at 90% confidence (see also [148,149]). The essential argument is as follows: while a HMNS can dissipate its supporting differential rotational energy as heat and thus as (effectively invisible) neutrino emission, a long-lived SMNS remnant is stabilized by more persistent ***solid body*** rotation. A large reservoir of rotational energy $\sim 10^{52}$–10^{53} erg must necessarily be released into the environment of the merger to destabilize the star enough to permit black hole. This "energy cost" greatly exceeds the measured GRB/kilonova energy in GW170817 of $\sim 10^{51}$ erg, thereby disfavoring a long-lived remnant. These constraints will be strengthened or tightened with the discovery of additional mergers with EM counterparts, particularly if a SMNS remnant can also be ruled out for lower-mass binaries.

Acknowledgments

This summary, mostly written in the immediate aftermath of GW170817, is dedicated to Alastair (Al) Cameron (1925–2005). Cameron discovered the r-process in 1957 contemporaneously with B^2FH and deciphering its astrophysical origin remained a passion throughout his career. One of Al's last publications, around the time I entered graduate school, hypothesized an r-process origin in magnetized jets from compact object accretion disks created in core collapse supernovae [150]. Similar magnetized outflows from the post-merger accretion disk (e.g. [78,80]) may have provided the dominant source of the heavy r-process inferred from the kilonova emission in GW170817 and thus, as far as we can presently discern, the universe as a whole. I thank Gabriel Martinez-Pinedo for comments on this draft. I also thank my observational collaborators in the DECam GW follow-up team. This work was supported by NASA, USA [grant number NNX16AB30G].

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