1 *The ground-based gravitational-wave detectors that make up the global network. Clockwise from top left: LIGO Hanford, an illustration of KAGRA, LIGO Livingston, and Virgo.* (ICRR, Univ. Tokyo/LIGO Lab/Caltech/MIT/Virgo Collab.)

Electromagnetic counterparts of gravitational-wave signals

Laura Nuttall and Christopher Berry review the potential of multimessenger astronomy with gravitational-wave observations.

Over the last several decades, different messengers have emerged as new ways of probing our universe. As well as electromagnetic (EM) waves, there are high-energy particles such as neutrinos and cosmic rays, as well as gravitational waves, all of which can carry different information about their sources. Multi-messenger astronomy, the combination of at least two of these signals, allows us to dig deeper in uncovering the secrets of how the universe works. For example, supernova 1987A saw the first joint neutrino and EM observations of a single event; they confirmed theoretical predictions at the time that the majority of a supernova's energy is released as neutrinos (e.g. Arnett *et al.* 1989).

Gravitational-wave astronomy is still relatively new. The first gravitational-wave signal (GW150914) was observed around six years ago, on 14 September 2015 (Abbott *et al.* 2016a). In the early hours of this historic day, gravitational waves from two stellar-mass black holes (around

Multiple detectors Localizing gravitational-wave sources

Key to the hunt for counterparts to gravitational-wave signals is the localization of the source: both the position on the sky and the distance. This tells telescopes where it is best to point. Additionally, if the telescopes find something intriguing, the source localization can be used to calculate the probability that the observed signal came from the same source as the gravitational waves. To localize the sources of gravitational-wave transients, like binary coalescences, we really need a network of detectors (Abbott *et al.* 2020c).

The most important information comes from the arrival time of the signal at the different detectors (Wen & Chen 2010). Gravitational waves travel at the speed of light, so we can use the time delay between the signal arriving at the different observatories to triangulate the source location (Fairhurst 2011). With two observatories, a time delay measurement leads to a band on the sky; with three observatories, one or two points; and with four, one unique point.

As well as the arrival time of the signal, we can measure its amplitude (Abbott *et al.* 2016c). The amplitude of the signal depends on intrinsic loudness – a function of distance – and the sensitivity of the detectors – a function of position on the sky. The detectors are most sensitive to sources directly above or below them, and least sensitive to sources off to the side. Hence, the relative amplitudes measured by the different detectors can help to provide localization.

The relative amplitudes of the signals were especially important in localizing the source of GW170817 (Abbott *et al.* 2017b). The signal-to-noise ratio for Virgo was about 2, below the threshold needed for confident identification of a signal. From the amplitudes measured by the two LIGO detectors, we knew that the source was close enough that it could have been observed by Virgo. Therefore, the source must be in a position where Virgo is least sensitive. So, even though Virgo did not detect the signal, it was crucial in localizing the source (Abbott *et al.* 2017d; figure 3).

Additional information comes from the phase of the signal. This can help discern the orientation of the binary, which impacts the loudness of the signal. To combine all the timing, amplitude and phase information, our best localization results come from a coherent analysis of the data from all the different detectors (Singer *et al.* 2014, Berry *et al.* 2015).

The full inference of source properties is computationally expensive. We need to simulate millions of different gravitational-wave signals and see how well each matches our observations (Meyer *et al.* 2020). These calculations are lengthy, so techniques have been designed to estimate localizations quickly, giving astronomers the best chance of catching the early phases of any counterpart (Singer & Price 2016). The first localizations are produced within a few seconds of a detection.

"Joint observations can provide insights into the progenitors of phenomena such as gamma-ray bursts"

$36\,M_\odot$ and $31\,M_\odot$, where $1\,M_\odot$ represents a solar mass) that had merged around 1.3 billion years ago (Abbott *et al.* 2019a) were detected by the two LIGO detectors in the USA. These detectors, located in Hanford (Washington) and Livingston (Louisiana), are 4 km long interferometers designed to measure the tiny stretch and squash of a passing gravitational wave (Aasi *et al.* 2015). They act as antennae for gravitational waves travelling from (almost) any direction. Since 2015, the global network has been expanded to include the 3 km Virgo detector near Pisa, Italy (Acernese *et al.* 2015), and the underground 3 km KAGRA detector in Japan (Akutsu *et al.* 2019). These four detectors are shown in figure 1. The more widely separated detectors we have to observe the same gravitational-wave signal, the more confident we can be in the properties of the signal, especially the position of the source on the sky (see box "Localizing gravitational-wave sources").

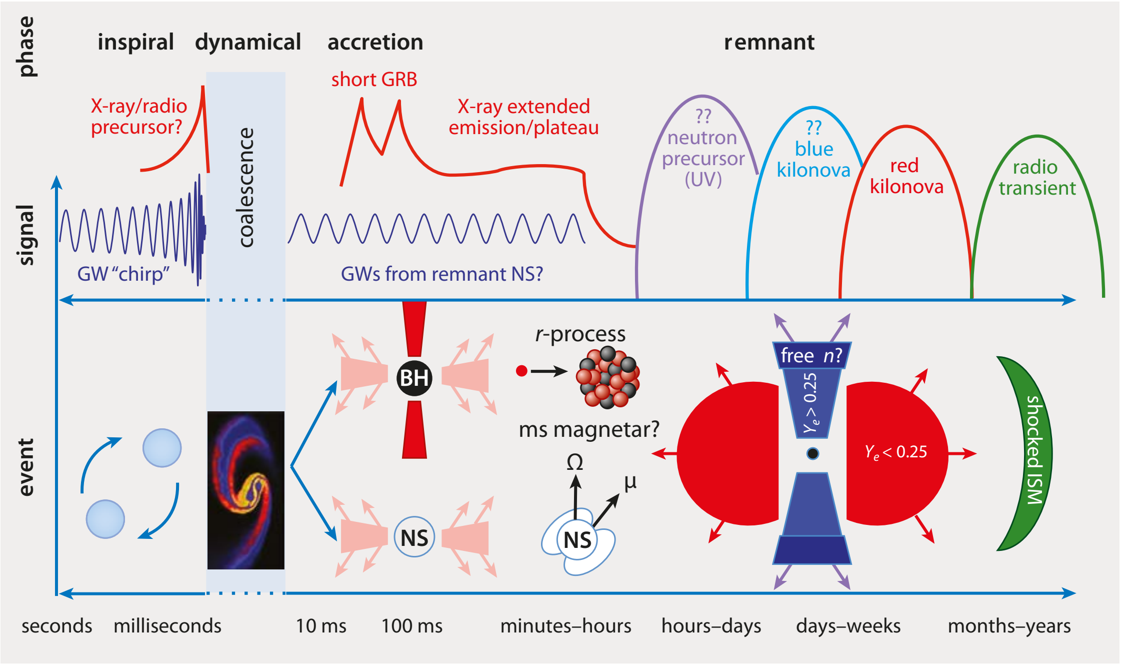
To date, more than 50 candidate gravitational-wave signals have been identified, all from the coalescences of black holes and neutron stars (Abbott *et al.* 2020e). While gravitational-wave observations alone are revealing the population properties of compact objects merging in the local universe (e.g. Abbott *et al.* 2020f, Zevin *et al.* 2021), there is even more to be learnt from multimessenger observations, particularly EM and gravitational waves. In general, gravitational waves trace the bulk motion of mass within a source, while EM waves are typically produced by hot matter (whether heated by nuclear reactions, shocks, friction or other EM emission) or matter interacting with magnetic fields. The two types of observation give complementary information and the combination of these two datasets is powerful. For instance, joint observations can provide insights into the progenitors of astrophysical phenomena, such as gamma-ray bursts (e.g. Burns 2020), and can reveal the origin of some of the heavy elements (e.g. Côté *et al.* 2018, Metzger 2019). Gravitational waves can be used as standard sirens, measuring the distance to a source, and joint EM observations providing a source redshift are ideal for constraining the Hubble constant (Schutz 1986, Abbott *et al.* 2021). Currently, there is a tension between the late and early time measurements of the Hubble constant: there is a 4σ to 6σ disagreement between measurements depending on the dataset considered (e.g. Di Valentino *et al.* 2021). Therefore, having gravitational-wave measurements as a new, independent probe could help to resolve this disagreement: is there a systematic source of error, or is there some undiscovered physics? Additionally, EM and gravitational waves should shed light on the neutron-star equation of state, a relation between their mass and radius, which will increase our understanding of quantum chromodynamics and, ultimately, the standard model of particle physics (e.g. Burns 2020).

Mergers of neutron stars and black holes

The coalescences of stellar-mass black holes and neutron stars are the most detectable sources of gravitational waves with ground-based detectors. The gravitational waves emitted from these systems only enter the sensitive region of our detectors in the final part of the system's inspiral, which can last for seconds or minutes, depending on the type of system. The signal chirps upwards in frequency as the binary spirals together, before peaking as the two objects merge. In general, lower mass binaries (i.e. binary neutron stars, or BNSs) are observed for longer. Following the merger, a remnant object is created that is $\gtrsim 90\%$ of the masses of the two individual objects. For binary black holes (BBHs), we have been able to observe the formation of the final black hole and confirm that it behaves as expected from general relativity (Abbott *et al.* 2020g). For binary neutron stars, a search for gravitational waves from the newly formed object has so far failed because they are at too high a frequency and are too faint for our current detectors (e.g. Abbott *et al.* 2017a, Abbott *et al.* 2019b). After the merger product has relaxed to its final state, gravitational waves are undetectable; compact-object coalescences are spectacular, but fleeting.

Despite BBH mergers being the dominant source of detectable gravitational waves, we do not typically expect them to produce EM emission as there is no matter present. However, there are numerous theories that describe how surrounding material, such as an accretion disc, is influenced by the merger, thus allowing the possibility of an EM signal.

The most likely sources to produce both detectable gravitational and EM waves are the collisions of two neutron stars, or a neutron star and black hole (NS–BH). We have now detected a couple of BNS systems with gravitational waves (Abbott *et al.* 2017b, Abbott *et al.* 2020a).



2 *The different phases of a neutron-star merger as a function of time. The top panel illustrates the associated observational signatures and the bottom panel the underlying physical phenomena.*
BH: *black hole*
GRB: *gamma-ray burst*
GW: *gravitational wave*
ISM: *interstellar medium*
n: *neutron*
UV: *ultraviolet*
Y_e: *electron fraction.*
(From Fernandez & Metzger 2016)

NS–BHs have proved more elusive. GW190814 may come from an NS–BH, but the nature of its smaller component is uncertain: at around 2.6$M_\odot$ it may be too big for a neutron star, and it may instead be the smallest black hole discovered in a binary (Abbott *et al.* 2020h). Much of this section is based on the fantastic reviews of Fernandez & Metzger (2016), Burns (2020) and Nakar (2020).

Figure 2, from Fernandez & Metzger (2016), shows the phases of a typical neutron-star merger. At ~100s before the two objects merge, it is possible to get an EM precursor, with emission in gamma-rays, X-rays and radio, with typical luminosities of 10^{42}–10^{47} erg/s. To date, the strongest evidence of this comes from Troja *et al.* (2010), who observed some activity preceding the onset of a short gamma-ray burst. We have yet to observe this for a gravitational-wave source. The ensuing phases of the merger depend on the properties of the system (the type of compact objects, their masses, mass ratio, spins etc). These properties ultimately govern the timescale and the type of object that is created.

For a NS–BH system, a black hole is always formed. A NS–BH system with a large mass will be unlikely to produce any EM signature, as the neutron star will be swallowed entirely by the black hole. For lighter NS–BH systems, however, the neutron star may be tidally disrupted and release a considerable amount of mass before it plunges into the black hole (Foucart *et al.* 2018).

In BNS mergers, the newly created object and subsequent EM emission is governed by the initial masses of the neutron stars. The heaviest neutron stars are expected to collapse to a black hole immediately, whereas slightly lighter neutron stars can form a hypermassive neutron star for a short amount of time (<1 s) before collapsing to form a black hole. A hypermassive neutron star is a neutron star with internal differential rotation that supports it from collapse. Lighter BNS systems could form a supramassive neutron star (i.e. a neutron star supported against collapse by uniform rotation) for hundreds to thousands of seconds, before ultimately resulting in a black hole. For the lowest mass systems, though, it is possible for two neutron stars to merge and form a stable, more massive, neutron star.

When the two objects merge, huge amounts of material are released. For BNSs this is around 10^{-4}–10^{-2} $M_\odot$, travelling up to 30% the speed of light, whereas for NS–BH mergers the ejected mass can be up to ~0.1 $M_\odot$ with similar velocities (Dietrich *et al.* 2017, Foucart *et al.* 2018, Shibata & Hotokezaka 2019, Krüger & Foucart 2020, Fernández *et al.* 2020). There are two main processes that drive mass ejection in a BNS merger. First, tidal forces late in the inspiral can lead to matter being ejected as the neutron stars are pulled apart. This is predominantly ejected in the equatorial plane. Then, hydrodynamical forces at the points where the two neutron stars meet can squeeze out material in a range of directions. Both are known as dynamical mass ejection. The second process is driven by winds that eject material from the accretion disc that forms around the remnant object. Factors such as the neutron-star equation of state, mass ratio and total mass of the system influence the amount of ejecta and the mechanism by which it is produced.

Material that is gravitationally bound either forms into an accretion disc or falls back onto the remnant object. Material that accretes onto the remnant black hole or neutron star may produce a highly collimated, ultra-relativistic jet. This is the source of a short gamma-ray burst. These bursts are some of the most luminous EM events that we know of, with energies typically around 10^{50} erg (Fong *et al.* 2015). The jets subsequently interact with the circum-burst medium and emit synchrotron radiation across the entire EM spectrum, giving rise to a gamma-ray burst afterglow.

The fate of unbound material is quite different. The temperature of the single or double neutron stars is greatly increased in the merger, and as such there is around 10^{-4}–10^{-1} $M_\odot$ of hot neutron-rich matter. As the ejecta expand, they rapidly cool by releasing energy as neutrinos and enter a relatively slow, homologous expansion. At this point only 10–100 ms have passed since the merger. Heavy elements are created rapidly via the rapid neutron capture process (*r*-process), which is responsible for creating around half of elements heavier than iron in our universe; however, this process cannot necessarily account for the *r*-process abundance seen in the Milky Way (Côté *et al.* 2018, Hotokezaka *et al.* 2018), suggesting that other sources (such as supernovae) are required too (Kajino *et al.* 2019). These nuclei decay radioactively to stability over time, releasing energy via beta decay and fission, which can power a thermal transient, or kilonova, that lasts days to weeks after the merger. Kilonovae emission is approximately isotropic and can peak in the optical band. The characteristics of a kilonova, such as its

Apps, texts and notices Gravitational-wave alerts

To enable the best chance of finding emission from a gravitational-wave counterpart, we analyse the gravitational-wave data as it is acquired and produce an alert as soon as a candidate is identified (Abbott *et al*. 2019c).

Searching for gravitational waves takes lots of computing power. However, many years have been invested in optimizing our algorithms so that they can produce initial results in a few seconds (Dal Canton *et al*. 2020, Chu *et al*. 2020, Drago *et al*. 2021, Aubin *et al*. 2021, Cannon *et al*. 2021). As the low-frequency sensitivity of our detectors improves, we can see signals from binary mergers earlier in their inspiral. This has enabled recent work to try to identify the signals before the actual merger (e.g. Magee *et al*. 2021), and such detections may be made in observing run O4, due in 2022.

Once a candidate is found, it is uploaded to a database and alerts are sent out. People working on the instruments, experts in data quality, and those running the search algorithms can expect a phone call or text alert to start reviewing the candidate; astronomers can expect to be notified via a Notice sent out using the Gamma-ray Coordinates Network (GCN) service originally created to alert them of gamma-ray bursts, and anyone can get a notification via the Chirp app (chirp.sr.bham.ac.uk). The initial alert will indicate the likely type of signal and a potential sky location; it is now possible to hunt for counterparts.

Analysis of the gravitational-wave data continues after the initial alert is sent. Top priority is to check the validity of the detection. One of the great challenges in gravitational-wave astronomy is distinguishing between a real signal and a burst of noise (a glitch) in the detectors (Nuttall 2018, Abbott *et al*. 2020d). Given the sensitivity and complexity of gravitational-wave detectors, there are many potential sources of noise (Davis *et al*. 2021). If something changes in the detector or its environment, or a new source of noise appears, this may lead to a false alarm. In some cases, like GW170817 (Abbott *et al*. 2017b), we may have both a signal and a glitch, which means the inferred source localization may be incorrect (Pankow *et al*. 2018). Hence, the state of the detectors and their surrounding environments are carefully assessed (Abbott *et al*. 2016d). If the signal is a false alarm, a retraction is sent, otherwise a reaffirmation is sent. Some astronomers may wait for the reaffirmation before dedicating actual telescope time.

Additional gravitational-wave data analysis may also produce a refined source-localization, or understanding of the nature of the source. The initial estimates come from the search algorithms, which are optimized to detect signals rather than to get the source properties correct. Therefore, something initially classified as an exciting NS–BH may be revised to being a more typical BBH, or vice versa. These more in-depth analyses are computationally expensive, and may take some time to complete, but important updates are shared once they become available.

"Magnetars are another promising source of both EM and gravitational-wave messengers"

colour, brightness and duration, indicate the processes that took place during the merger. For instance, blue kilonovae, which peak on the timescale of around a day, are indicative of ejecta that had a relatively high electron fraction ($Y_e>0.3$) and produced mostly lanthanide-free material (e.g. Metzger *et al.* 2010). Low electron fraction ($Y_e<0.3$) ejecta that produces material rich in lanthanides creates a red kilonova, which peaks in luminosity on the order of about a week (e.g. Barnes & Kasen 2013).

It can take weeks for the kilonova signal to fade as the material cools. This material will continue to move away from the remnant, and over the course of months and years it will interact with the interstellar medium, releasing synchrotron radiation across the EM spectrum. This can be referred to as a kilonova afterglow. Over the course of many, many years, a kilonova remnant forms. This may be similar to a supernova remnant, but with some key differences: a kilonova remnant will have lower total kinetic energies and the emission will be dominated by isotopes with half-lives similar in age to the remnant. When this kinetic energy is used up, the shock wave will dissipate and bound material will become part of the diffuse galactic material that may eventually make up new stars (Wu *et al.* 2019).

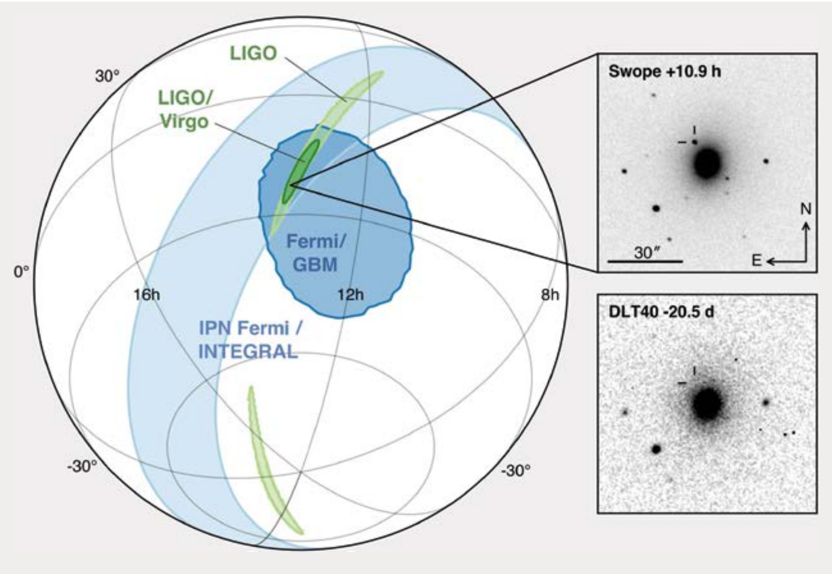
Serendipity

There are many more sources that should produce both detectable gravitational waves and EM emission. The most obvious may arguably be core-collapse supernovae. Some of the most promising gravitational-wave signals may originate from the newly formed compact object. For the current ground-based detectors (Abbott *et al.* 2020b), gravitational waves emitted from core-collapse supernovae should be detectable to a distance of a few tens of kiloparsecs to a few megaparsecs, depending on which theoretical supernova model is considered. As for an EM signal, supernovae are spectacular in the optical band. We also know long gamma-ray bursts are associated with the collapse of massive stars. This includes both prompt and afterglow emission. Other types of gamma-ray bursts may also be associated with core-collapse supernovae that a multimessenger detection may help to associate, such as low-luminosity gamma-ray bursts and X-ray flashes, as well as ultra-long gamma-ray bursts. Supernovae are also a source of neutrinos, and for any supernova from which we can detect gravitational waves, we should also be able to observe neutrinos. A supernova may be the first source from which we detect EM emission, gravitational waves and neutrinos!

Magnetars, or highly magnetized neutron stars, are another promising source of both EM and gravitational-wave messengers. They will produce high-frequency gravitational waves and in the EM window their bursting activity manifests as soft gamma-ray repeaters or anomalous X-ray pulsars. This bursting activity is likely due to the neutron-star magnetic field readjusting, potentially resulting in cracks in the surface. Giant flares have already been observed from three soft gamma-ray repeaters (Turolla *et al.* 2015, Svinkin *et al.* 2021).

Fast radio bursts (FRBs) are another possible candidate for multimessenger observations, although little is known about them (Petroff *et al.* 2019, Chatterjee 2021). They are millisecond-duration pulses that (mostly) originate outside of our galaxy, occurring thousands of times per day over the entire sky. In 2020, an FRB was observed from a galactic magnetar (Andersen *et al.* 2020, Bochenek *et al.* 2020). This event looks like other extragalactic FRBs, albeit less energetic, which implies that active magnetars could be responsible for more of the FRB population. However, a recent discovery found an FRB in a globular cluster, which is not where you would expect to find a young, highly magnetized neutron star (Kirsten *et al.* 2021). There are also plenty of theoretical models of FRBs, which tend toward sources involving isolated or binary compact objects (white dwarfs, neutron stars and black holes) and active galactic nuclei (AGN), perhaps interacting with neutron stars (e.g. Cordes & Chatterjee 2019). If any FRBs are associated with a compact binary coalescence, then we may be able to pick up their gravitational-wave signature.

LIGO, Virgo and KAGRA search for gravitational waves associated with these different types of sources. EM observatories can alert the gravitational-wave community to when such events have taken place, and archival gravitational-wave data can then be reanalysed with the increased knowledge of the sky location of a potential



3 *The localization of the gravitational-wave (GW170817), gamma-ray burst (GRB170817A) and optical (AT2017gfo) signals. The left panel shows the 90% credible localization of the gravitational-wave signal using just the two LIGO detectors (light green) with the addition of Virgo (dark green). Triangulation from the time delay between Fermi and the INTEGRAL satellite (light blue) is shown with the Fermi Gamma-ray Burst Monitor localization (dark blue). The right panel shows the optical transient observed by Swope 10.9 hours after the merger in galaxy NGC4993 (top right) with the pre-discovery image taken 20.5 days before the merger (bottom right).* (From Abbott *et al.* 2017d)

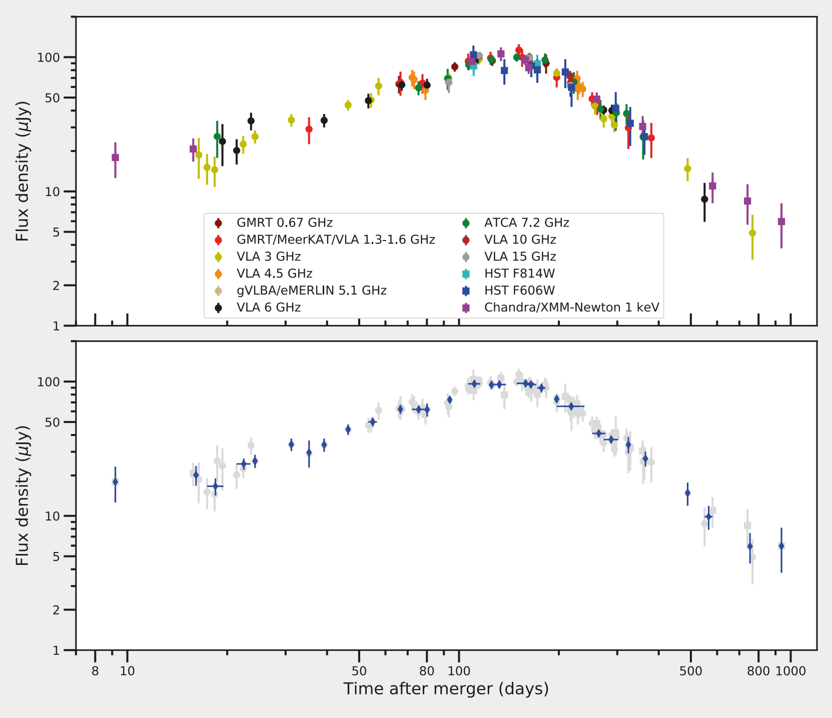
gravitational-wave source. These are referred to as externally triggered searches. For example, an archival search was performed for gravitational waves associated with FRBs detected between 2007 and 2013 (Abbott *et al.* 2016b). This, as well as other such searches, has not yet revealed an associated gravitational-wave signature.

Conversely, multimessenger counterparts to gravitational-wave candidates can be sought. To enable this, data from gravitational-wave detectors are analysed in close to real time by numerous analyses looking for signals from both modelled (i.e. compact binary mergers) or unmodelled sources (i.e. bursts of loud gravitational waves, potentially from a source such as a supernova). The aim of these searches (Abbott *et al.* 2019c) is to find the tantalizing signatures of gravitational waves and alert the wider astronomical community as soon as possible to a new candidate (see box "Gravitational-wave alerts").

GW170817

On 17 August 2017, everything changed. At 12:41:04UTC, the LIGO and Virgo detectors picked up the longest and loudest signal they had ever seen: a binary neutron-star signal named GW170817 (Abbott *et al.* 2017b). Independently, the Fermi Gamma-ray Burst Monitor observed a weak signal around 1.7s after the merger time, which was later classified as GRB170817A (Goldstein *et al.* 2017, Abbott *et al.* 2017c). It takes minutes for low-latency gravitational-wave analyses to find and confirm a signal. Therefore, by the time gravitational-wave scientists knew of the binary neutron-star signal, there was an exciting note which indicated that a signal had been seen by Fermi very close in time. Around 40 minutes after the gravitational waves were detected, the LIGO Scientific and Virgo Collaborations issued an alert to the wider scientific community, reporting that a binary neutron-star signal had been detected with an associated gamma-ray burst signal. However, due to an unfortunately timed glitch in the Livingston data (Abbott *et al.* 2017b), it took several hours for LIGO and Virgo to issue a position for the detection (Abbott *et al.* 2017d).

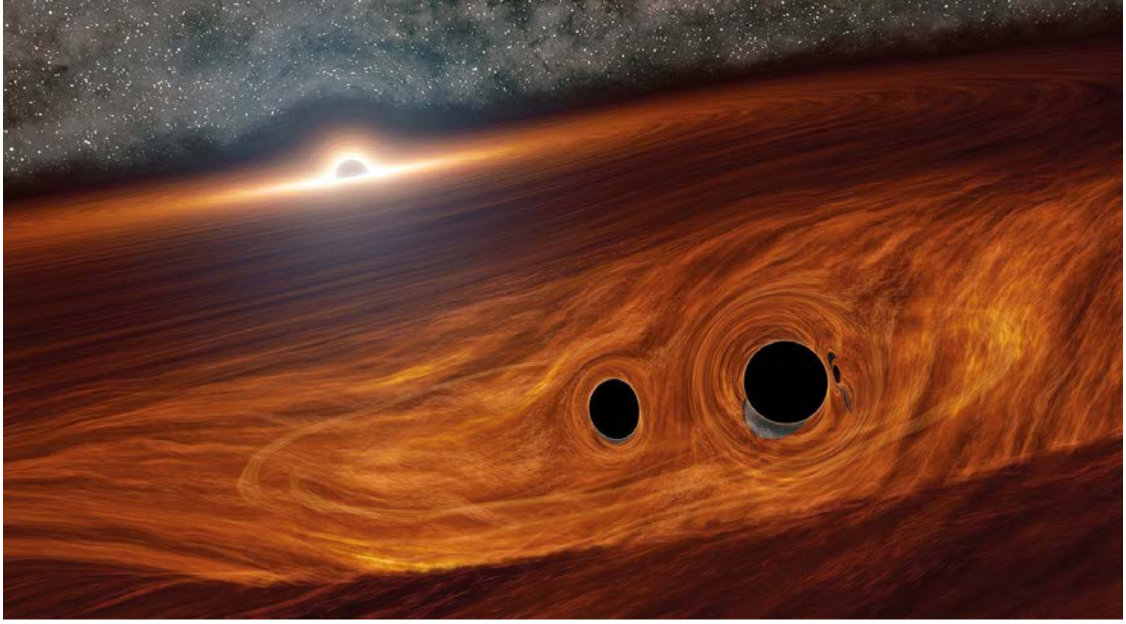
The initial report declared that the gravitational-wave signal most likely occurred within an area of ~30 square degrees (90% probability), as shown in figure 3. This was actually an amazingly small area for a gravitational-wave localization, helped by the binary merging only around 40Mpc away. Unfortunately, by the time the sky localization was released it was a really inconvenient time of day: the Sun was up in South America and several hours elapsed before some of the most powerful telescopes in the world could hunt for the elusive EM counterpart.



4 (Upper panel) *Radio, optical and X-ray observations of GW170817 up to 940 days post-merger. The data are colour-coded to show which telescopes obtained the respective data. All data points have a 1σ error bar. The afterglow light curve is scaled to 3 GHz derived using methods presented in Makhathini* et al. *(2020).* **(Lower)** *The averaged light curve (blue data points) shows a general trend that is consistent with a power-law rise and decline. The same data points as shown in the top panel are overlaid in grey.* (From Makhathini *et al.* 2020)

Around 11 hours after the initial gravitational-wave detection, a bright optical transient called AT2017gfo, hiding in galaxy NGC4993, was found by the OneMeter, Two Hemisphere (1M2H) team using the 1m Swope Telescope (Coulter *et al.* 2017). The image they captured is shown in figure 3. Multiple teams detected this signal independently within an hour (Abbott *et al.* 2017c). This was the first confirmed detection of a kilonova, adding weight to earlier candidates such as the association of a faint red transient with GRB130603B (Tanvir *et al.* 2013, Berger *et al.* 2013).

AT2017gfo was observed across the electromagnetic spectrum, with more than 200 circulars reporting observations by various teams. The kilonova signature dominated early on. This was observed for almost a month in the ultraviolet, optical and infrared before the signal faded. It took a little time, but around 9 days and 15 days after the merger an X-ray and radio afterglow, respectively, were detected (Troja *et al.* 2017, Margutti *et al.* 2017, Hallinan *et al.* 2017). These signatures were just beginning to brighten. It took around 150 days before these signals peaked in the X-ray and radio (e.g. Dobie *et al.* 2018, Lamb *et al.* 2019). The afterglow also became visible in the optical band around 100 days post-merger (Lyman *et al.* 2018, Margutti *et al.* 2018); early on it was masked by the bright kilonova. Astronomers have continued to study



5 *An artist's impression of a binary black-hole system within a disc of gas that surrounds a supermassive black hole. When the two smaller black holes merge, they form a larger black hole. The merger could cause the remnant black hole to move in one direction within the disc, interacting with the gas that creates a flare, perhaps like that identified by ZTF.* (Caltech/R Hurt [IPAC])

the afterglow to the present day. The optical afterglow was observed until almost 600 days post-merger (Fong *et al*. 2019), and the radio and X-ray observations extend beyond the 1000-day mark (Balasubramanian *et al*. 2021, Hajela *et al*. 2021, Troja *et al*. 2021). This wonderful dataset tells an amazing story. Figure 4 shows the panchromatic (radio, optical and X-ray) afterglow light curve of GW170817 up to 940 days post-merger.

In a nutshell, we have learned that two balls of nuclear density material collided at around a third of the speed of light, roughly at the time of the Cretaceous or late Jurassic period on Earth. Almost at the same time we get a blast of gravitational waves and a jet of gamma rays. The ejected, neutron-rich matter synthesizes to form new material which subsequently decays, releasing a kilonova emission. The X-ray and radio emission may then be the afterglow formed by the bubble of ejected material pushing into the surrounding interstellar medium.

There are many amazing things that we can learn from these joint gravitational-wave and EM observations; here we give just a couple of examples. First, from the gravitational-wave signal we can infer the source distance. If we combine this with the redshift of the galaxy, found by EM observations, we can estimate the Hubble constant (Abbott *et al*. 2017e). With GW170817 being the only gravitational-wave signal having a confidently identified source galaxy, the uncertainties on the gravitational-wave Hubble constant measurement are too large to solve the current discrepancy over its true value (Abbott *et al*. 2021). However, over the coming years this will change as we collect more detections (Chen *et al*. 2018, Mortlock *et al*. 2019). Even when an EM counterpart is not identified, we can still consider all potential host galaxies in the immediate field (Schutz 1986, Gray *et al*. 2020, Abbott *et al*. 2021).

Second, the gravitational-wave and gamma-ray burst signal can be used to constrain the difference between the speed of gravity and light. We don't expect the gamma-rays to be emitted at the same time as the strongest gravitational waves, i.e. at the time of merger, because it takes some time for the jet to establish itself and blast its way out of the surrounding material. Hence, if we allow for a sensible range of emission times, we can measure the arrival time difference between the two messengers to constrain their relative speeds. In general relativity, the speed of gravity and light should be the same. With the joint gravitational-wave and gamma-ray observations, this difference was found to be no more than three parts in 10^{15} (Abbott *et al*. 2017b).

Binary black holes?

Given the nature of black holes, a merger of two of them does not seem a good candidate for EM follow-up. However, it is possible that there could be a counterpart if material accretes onto the remnant black hole.

Such a counterpart has potentially been found for GW190521, a gravitational-wave signal originating from the merger of two heavy stellar-mass black holes (Abbott *et al*. 2020i). The claimed counterpart was found by the Zwicky Transient Facility (ZTF; Graham *et al*. 2020). They targeted AGN to look for counterparts: the bright cores of galaxies where the central supermassive black hole is feeding upon a surrounding disc. These discs have been posited as a good environment for the formation of the stellar-mass black-hole binaries already observed by LIGO and Virgo (Stone *et al*. 2017, Secunda *et al*. 2019, Gröbner *et al*. 2020). An artist's impression of a binary black hole system within a disc of gas orbiting a supermassive black hole is shown in figure 5. In the case of GW190521, the ZTF team found an AGN consistent with the source localization inferred by LIGO and Virgo which underwent a flare, peaking around 50 days after the merger.

When two black holes merge, gravitational waves are not emitted equally in all directions, and hence there can be a recoil kick. This kick could have sent the remnant black hole into the disc of the supermassive black hole. As the black hole travels through the disc, material can begin accreting onto it, causing emission of light. The ZTF team estimated the probability for such a flare to occur randomly at the right place and time to coincide with GW190521 by chance is small, suggesting that the two are connected. However, AGNs are difficult to model, and we do not yet understand their variability, meaning that the association is not definite (Ashton *et al*. 2020, Palmese *et al*. 2021). More observations of similar phenomena are likely needed before we can be certain that we have found a counterpart to merging black holes. The observations by the ZTF team should motivate further searches for counterparts from binary black holes, and potentially more unexpected discoveries.

The future

Since 2015, the global gravitational-wave detector network has completed three observing runs (Abbott *et al*. 2020c). Between these runs, improvements to detector sensitivity have been made. The next observing run, O4, will be the first with the four-detector network of the two US-based LIGO detectors, Virgo and KAGRA, that is due to start in the summer of 2022, although the exact timeline is still to be finalized (being somewhat complicated by the ongoing pandemic). A five-detector network including LIGO India (Iyer *et al*. 2011) is further off: work is starting on the site and it may be up and running around 2025. The development of the global detector network will present both benefits and challenges for counterpart searches.

Having more detectors improves the localization of sources (Abbott *et al.* 2020c). With a single detector, transient signals could be anywhere in the sky. With two detectors, it is possible to narrow down to a band on the sky. Adding in a third detector means that you can localize the source to a single blob or two. Going to four (or five) will increase the overall signal-to-noise ratio for the detection, shrinking the uncertainties. While observing a signal with more than three detectors provides only modest improvement to localization, having a four- or five-detector network does make a huge difference to the localization performance. The detectors do not operate continuously, so having a larger network increases the probability that at any given moment at least three detectors will be online. With a five-detector network, we will be able to have three-detector localizations for the majority of all detections (Pankow *et al.* 2020).

The increase in detector sensitivity means that a source at a given distance will be observed with higher signal-to-noise ratio. This will improve the measurement precision of both the sky position and the distance. This significantly improves the prospects of finding a counterpart. One of the common strategies for hunting for counterparts is to cross-reference localizations with galaxy catalogues (e.g. Gehrels *et al.* 2016), so having a smaller volume to search is a big advantage.

While the increase in sensitivity will be a blessing for nearby sources, it will also mean that we can detect sources further away. Sources at further distances are more difficult to follow up with telescopes for a few reasons. First, any counterparts will be fainter and so harder to spot (Chase *et al.* 2021). Second, the volume localizations will be much larger (Del Pozzo *et al.* 2018). A source with a 30% distance uncertainty at 200 Mpc will have a volume uncertainty eight times larger than a source with a 30% distance uncertainty at 100 Mpc and the same uncertainty in sky position. Finally, galaxy catalogues become less complete as distance increases (e.g. Dálya *et al.* 2018), making it harder to identify potential hosts. Searching for counterparts at larger distances is like looking for smaller needles in larger haystacks while also not knowing where all the haystacks are.

The increase in sensitivity over the coming years will mean that the best localized sources will be much better localized than in the past. Potentially, a single pointing of a wide-field telescope like the Vera Rubin Observatory (Ivezić *et al.* 2019) or the Gravitational-wave Optical Transient Observer (Dyer *et al.* 2020) will be all that is needed for these. However, the typical (three-dimensional) localizations will be much more difficult to follow up. As detections become more frequent, we may therefore see a change in observing patterns, with only the most promising events receiving detailed follow up.

Boosting our detectors' sensitivities also increases the prospects of detecting new types of signals. With the current generation of gravitational-wave detectors, we would only be able to observe a supernova within our galactic neighbourhood. This is well within range of both EM (which may struggle to observe due to the emission being so bright) and neutrino observatories. Hence, if we were lucky enough for such an event to occur, we can expect to get the combination of all three messengers. Even more speculative is a new, unexpected source: if there is something new out there waiting to be discovered with gravitational waves, will there be a counterpart to find too?

In the coming years, gravitational-wave detection will become an everyday occurrence. This is an amazing achievement. The hunt for multimessenger counterparts, however, will remain a challenge. Multimessenger detections will remain extraordinary. ●

> *"A larger network increases the probability that at any given moment at least three detectors will be online"*

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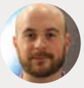

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REFERENCES

Aasi J ***et al.*** 2015 *Class. Quantum Grav.* **32** 074001

Abbott BP ***et al.*** 2016a *Phys. Rev. Lett.* **116** 061102

Abbott BP ***et al.*** 2016b *Phys. Rev. D* **93** 122008

Abbott BP ***et al.*** 2016c *Phys. Rev. Lett.* **116** 241102

Abbott BP ***et al.*** 2016d *Class. Quantum Grav.* **33** 134001

Abbott BP ***et al.*** 2017a *Astrophys. J. Lett.* **851** L16

Abbott BP ***et al.*** 2017b *Phys. Rev. Lett.* **119** 161101

Abbott BP ***et al.*** 2017c *Astrophys. J. Lett.* **848** L13

Abbott BP ***et al.*** 2017d *Astrophys. J. Lett.* **848** L12

Abbott BP ***et al.*** 2017e *Nature* **551** 85

Abbott BP ***et al.*** 2019a *Phys. Rev. X* **9** 031040

Abbott BP ***et al.*** 2019b *Astrophys. J.* **875** 160

Abbott BP ***et al.*** 2019c *Astrophys. J.* **875** 161

Abbott BP ***et al.*** 2020a *Astrophys. J. Lett.* **892** L3

Abbott BP ***et al.*** 2020b *Phys Rev. D* **101** 084002

Abbott BP ***et al.*** 2020c *Living Rev. Relat.* **23** 3

Abbott BP ***et al.*** 2020d *Class. Quantum Grav.* **37** 055002

Abbott BP ***et al.*** 2021 *Astrophys. J.* **909** 218

Abbott R ***et al.*** 2020e *Phys. Rev. X* **11** 021053

Abbott R ***et al.*** 2020f *Astrophys. J. Lett.* **913** L7

Abbott R ***et al.*** 2020g *Phys. Rev. D* **103** 122002

Abbott R ***et al.*** 2020h *Astrophys. J. Lett.* **896** L44

Abbott R ***et al.*** 2020i *Phys. Rev. Lett.* **125** 101102

Acernese F ***et al.*** 2015 *Class. Quantum Grav.* **32** 024001

Akutsu T ***et al.*** 2019 *Nature Astron.* **3** 35

Andersen BC ***et al.*** 2020 *Nature* **587** 54

Ashton G ***et al.*** 2020 *Mon. Not. R. Astron. Soc.* submitted arXiv:2009.12346

Arnett WD ***et al.*** 1989 *Ann. Rev. Astron. & Astrophys.* **27** 629

Aubin F ***et al.*** 2021 *Class. Quantum Grav.* **38** 095004

Balasubramanian A ***et al.*** 2021 *Astrophys. J. Lett.* **914** L20

Barnes J & Kasen D 2013 *Astrophys. J.* **775** 18

Berger E ***et al.*** 2013 *Astrophys. J. Lett.* **774** L23

Berry CPL ***et al.*** 2015 *Astrophys. J.* **804** 114

Bochenek CD 2020 *Nature* **587** 59

Burns E 2020 *Living Rev. Relat.* **23** 4

Cannon K ***et al.*** 2021 *SoftwareX* **14** 100680

Chase EA ***et al.*** 2021 *Astrophys. J.* submitted arXiv:2105.12268

Chatterjee S 2021 *Astron. & Geophys.* **62** 1.29

Chen H-Y ***et al.*** 2018 *Nature* **562** 545

Chu Q ***et al.*** 2020 *Astrophys. J.* submitted arXiv:2011.06787

Cordes JM & Chatterjee S 2019 *Ann. Rev. Astron. & Astrophys.* **57** 417

Coulter DA ***et al.*** 2017 *Science* **358** 1556

Côté B ***et al.*** 2018 *Astrophys. J.* **855** 99

Dal Canton T ***et al.*** 2020 arXiv:2008.07494

Davis D ***et al.*** 2021 *Class. Quantum Grav.* **38** 135014

Dálya G ***et al.*** 2018 *Mon. Not. R. Astron. Soc.* **479** 2374

Del Pozzo W ***et al.*** 2018 *Mon. Not. R. Astron. Soc.* **479** 601

Di Valentino E ***et al.*** 2021 *Class. Quantum Grav.* in press arXiv:2103.01183

Dietrich T ***et al.*** 2017 *Phys. Rev. D* **95** 024029

Dobie D ***et al.*** 2018 *Astrophys. J. Lett.* **858** L15

Drago M ***et al.*** 2021 *SoftwareX* **14** 100678

Dyer MJ ***et al.*** 2020 *Proc. SPIE Int. Soc. Opt. Eng.* **11445** 114457G

Fairhurst S 2011 *Class. Quantum Grav.* **28** 105021

Fernández R & Metzger BD 2016 *Ann. Rev. Nucl. Part. Sci.* **66** 23

Fernández R ***et al.*** 2020 *Mon. Not. R. Astron. Soc.* **497** 3221

Fong W ***et al.*** 2015 *Astrophys. J.* **815** 102

Fong W ***et al.*** 2019 *Astrophys. J. Lett.* **883** L1

Foucart F ***et al.*** 2018 *Phys. Rev. D* **98** 081501

Gehrels N ***et al.*** 2016 *Astrophys. J.* **820** 136

Goldstein A ***et al.*** 2017 *Astrophys. J. Lett.* **848** L14

Graham MJ ***et al.*** 2020 *Phys. Rev. Lett.* **124** 251102

Gray R ***et al.*** 2020 *Phys. Rev. D* **101** 122001

Gröbner M ***et al.*** 2020 *Astron. & Astrophys.* **638** A119

Hallinan G ***et al.*** 2017 *Science* **358** 1579

Hajela A ***et al.*** 2021 arXiv:2104.02070

Hotokezaka K ***et al.*** 2018 *Int. J. Mod. Phys. D* **27** 1842005

Kirsten F ***et al.*** 2021 arXiv:2105.11445

Ivezić Z ***et al.*** 2019 *Astrophys. J.* **873** 111

Iyer B ***et al.*** 2011 LIGO Document M1100296-v2 dcc.ligo.org/LIGO-M1100296/public

Kajino T ***et al.*** 2019 *Prog. Part. Nucl. Phys.* **107** 109

Krüger CJ & Foucart F 2020 *Phys. Rev. D* **101** 103002

Lamb GP ***et al.*** 2019 *Astrophys. J. Lett.* **870** L15

Lyman JD ***et al.*** 2018 *Nature Astron.* **2** 751

Magee R ***et al.*** 2021 *Astrophys. J. Lett.* **910** L21

Makhathini S ***et al.*** 2020 *Astrophys. J.* submitted arXiv:2006.02382

Margutti R ***et al.*** 2017 *Astrophys. J. Lett.* **848** L20

Margutti R ***et al.*** 2018 *Astrophys. J. Lett.* **856** L18

Metzger BD ***et al.*** 2010 *Mon. Not. R. Astron. Soc.* **406** 2650

Metzger BD 2019 *Living Rev. Relat.* **23** 1

Meyer R ***et al.*** 2020 *WIREs Comput. Stat.* **2020** e1532

Mortlock DJ ***et al.*** 2019 *Phys. Rev. D* **100** 103523

Nakar E 2020 *Phys. Rept.* **886** 1

Nuttall LK 2018 *Phil. Trans. R. Soc. A* **376** 201702862

Palmese A ***et al.*** 2021 *Astrophys. J.* submitted arXiv:2103.16069

Pankow C ***et al.*** 2018 *Phys. Rev. D* **98** 084016

Pankow C ***et al.*** 2020 *Astrophys. J.* **902** 71

Petroff E ***et al.*** 2019r *Astron. Astrophys. Rev.* **27** 4

Schutz BF 1986 *Nature* **323** 310

Secunda A ***et al.*** 2019 *Astrophys. J.* **878** 85

Shibata M & Hotokezaka K 2019 *Ann. Rev. Nucl. Part. Sci.* **69** 41

Singer LP ***et al.*** 2014 *Astrophys. J.* **795** 105

Singer LP & Price LR 2016 *Phys. Rev. D* **93** 024013

Stone NC ***et al.*** 2017 *Mon. Not. R. Astron. Soc.* **464** 946

Svinkin D ***et al.*** 2021 *Nature* **589** 211

Tanvir NR ***et al.*** 2013 *Nature* **500** 547

Troja E ***et al.*** 2010 *Astrophys. J.* **723** 1711

Troja E ***et al.*** 2017 *Nature* **551** 71

Troja E ***et al.*** 2021 *Mon. Not. R. Astron. Soc.* submitted arXiv:2104.13378

Turolla R ***et al.*** 2015 *Rep. Prog. Phys.* **78** 116901

Wen L & Chen Y 2010 *Phys. Rev. D* **81** 082001

Wu M-R ***et al.*** 2019 *Astrophys. J.* **880** 23

Zevin M ***et al.*** 2021 *Astrophys. J.* **910** 152