Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution
Proceedings IAU Symposium No. 363, 2023
E. Troja & M. G. Baring, eds.
doi:10.1017/S1743921322000515

Kilonovae and short GRBs observations in the multi-messenger era

Paolo D'Avanzo

INAF - Osservatorio Astronomico di Brera
email: `paolo.davanzo@inaf.it`

Abstract. The spectacular detection of the first electromagnetic counterpart of a gravitational wave event detected by the LIGO/Virgo interferometers and originated by the coalescence of a double neutron star (NS) system (GW 170817) marked the dawn of a new era for astronomy. The short GRB 170817A associated to the gravitational wave event provided the long-sought evidence that at least a fraction of short GRBs are originated by NS-NS merging and suggested the intriguing possibility that relativistic jets can be launched in the process of a NS-NS merger. The wealth of data collected provided the first compelling observational evidence for the existence of kilonovae, i.e. the emission due to radioactive decay of heavy nuclei produced through rapid neutron capture. Besides the remarkable event associated to GW 170817, kilonova signatures have been identified in a few short GRBs light curves, supporting a scenario where kilonovae are ubiquitous and can probe neutron star mergers well beyond the horizon of the gravitational wave detectors. In this paper I will review the situation and perspectives of our understanding of short GRBs progenitors and kilonovae in the multi-messenger era.

Keywords. gravitational waves, gamma rays: bursts

1. Introduction

Two classes of GRBs (at least), short and long, have been identified. Short GRBs are those with burst duration less than about two seconds and with harder high-energy spectra with respect to long bursts (Kouveliotou et al. 1993). While it has been firmly established that long GRBs originate in core-collapse supernova (SN) explosions (Hjorth & Bloom 2012), according to the most popular model short GRBs are produced by the merger of compact objects (neutron stars, NSs, and black holes, BHs). The knowledge of the class of short GRBs experienced an impressive boost in the past two decades. The discovery of short GRB afterglows in 2005 by the *Neil Gehrels Swift Observatory* (*Swift*) and the *HETE-II* satellites represented a watershed moment in the study of these sources, providing the key to unravel their distance, energy scale, environments and host galaxies (Gehrels et al. 2005; Fox et al. 2005; Villasenor et al. 2005; Hjorth et al. 2005a; Barthelmy et al. 2005; Berger et al. 2005; Covino et al. 2006). To date, more than 150 short GRBs have been found by *Swift* (~ 10/yr). A sizeable fraction of them have X-ray and optical afterglows detections, a few have been detected also in radio (Fong et al. 2015). Short GRB afterglows are fainter on average than those of long GRBs and the great majority of short GRB redshifts are obtained through optical spectroscopy of their associated host galaxies. To this end, the precise localisation with *Swift* is a crucial asset to achieve a firm short GRB-host galaxy association (D'Avanzo et al. 2014). Properties like the absence of associated SNe, the afterglow faintness, the occurrence in early type galaxies, the offset and redshift distribution definitely point towards a compact star origin, at variance with what observed for long GRBs (Berger 2014; D'Avanzo et al. 2015). All these findings are in agreement with the compact object binary progenitor model (Eichler *et al.* 1989; Narayan et al. 1992; Nakar 2007). These progenitors are also expected to be sources of high-frequency gravitational waves (GWs). Another key signature of a NS-NS/NS-BH binary merger is the production of a so-called kilonova, whose electromagnetic emission is powered by the decay of heavy radioactive species produced by rapid neutron capture (r-process) and ejected during the merger process (Li & Paczyinski 1998; Rosswog 2005; Metzger et al. 2010). The compact object binary progenitor model for short GRBs has been spectacularly confirmed on Aug 17 2017, when the first GW event ever originated by a NS-NS merger was detected by LIGO/Virgo (GW 170817) and associated to the weak short GRB 170817A and to the bright kilonova AT2017gfo (Abbott et al. 2017). The emergence, days after the GW/GRB event, of a X-ray and radio counterpart suggested for the possibility of off-axis GRB afterglow emission (Hallinan *et al.* 2017; Troja et al. 2017). Besides providing the long-sought "smoking gun" of short GRB progenitors, the case of GW 170817 / GRB 170817A demonstrated that the GRB emission geometry differs from a simple uniform jet (Mooley et al. 2018; Ghirlanda et al. 2019).

2. Clues for progenitors

Short GRB progenitors can originate from the evolution of massive stars in a primordial binary (i.e. a system born as binary) or by dynamical interactions and capture in globular clusters during their core collapse. In primordial systems, the delay between binary formation and merging is driven by the gravitational wave inspiral time, which is strongly dependent on the initial system separation. Some systems are thus expected to drift away from the star–forming regions in which they formed, before merging takes place, also because they experience a natal kick at the time of the formation of the compact object. Simulations (Belczynski, Bulik & Kalogera 2002; Belczynski et al. 2006) show that a large fraction of the merging events should take place in the outskirts or even outside the galaxies, in low density environments. A low density circumburst environment is expected also for short GRBs of dynamical origin occurring in globular clusters. For these events, the resulting time delay between star-formation and merging would be dominated by the cluster core-collapse time and thus be comparable to the Hubble time (Hopman et al. 2006). A much faster evolutionary channel has been proposed (Belczynski & Kalogera 2001; Perna & Belczynski 2002; Belczynski et al. 2006), leading to merging in only $\sim 10^6 - 10^7$ yr, when most systems are still immersed in their star-forming regions. According to the above scenario, with the exception of the events originated by the "fast" primordial channel, short GRBs are generally expected to occur in regions where the density of the diffuse medium is low, giving rise to fainter afterglows, setting in at later times than those of long GRBs (e.g. Vietri 2000; Panaitescu, Kumar & Narayan 2001; Salvaterra et al. 2010).

Key issues that could help in discriminating between the different theoretical scenarios summarized above and, more in general, in confirming the validity of the current short GRB progenitor model are the study of the afterglows and host galaxies properties, accurate measurements of the spatial offsets between afterglows and host galaxy centers, reliable redshift determinations, the absence of associated supernovae, evidences for r-process kilonova emission and the emission of associated gravitational waves over a sufficiently large sample of events.

2.1. *Host galaxies*

Although indirect, a key observational evidence that long and short GRBs are originated by two distinct classes of progenitors comes from the study of their host galaxies. As expected for young massive star progenitors, long GRBs are found to occur in star-forming galaxies (Bloom, Kulkarni & Djorgovski 2002; Fruchter et al. 2006; Wainwright, Berger & Penprase 2007; Savaglio, Glazebrook & Le Borgne 2009). On the other hand, the occurrence of short GRBs in both star-forming and early-type galaxies indicates that their progenitors can be associated to both young and old stellar population (Berger et al. 2005; Fox et al. 2005; Bloom et al. 2006; Fong, Berger & Fox 2010; Fong et al. 2013). Considering the short GRB-elliptical host galaxies associations proposed on chance probability arguments and those whose optical afterglow was found to lie within the host galaxy light with a sub-arcsecond precision, Fong et al. (2013) estimates that about 20% of short GRBs are associated with early-type host galaxies. In these cases, the study of the galaxies' optical spectra and optical/NIR spectral energy distributions provided evidence for low star-formation activity ($< 0.1 M_\odot$ yr^{-1}) and old stellar population (≥ 1 Gyr), leading to a secure identifications for these hosts as early-type galaxies (e.g. Barthelmy et al. 2005; Berger 2009; Malesani et al. 2007; Fong et al. 2011).

In terms of properties like mass, stellar population age, specific star formation rate and metallicity, the host galaxies of short GRBs are found to be significantly different with respect to galaxies hosting long GRBs. As inferred from the modeling of their optical/NIR spectral energy distributions, the short GRB host galaxies have a median stellar mass $< M_* >\sim 10^{10.0}\, M_\odot$ (Leibler & Berger 2010), an higher value with respect to the median stellar mass found for long GRB hosts ($10^{9.2}\, M_\odot$; Savaglio, Glazebrook & Le Borgne 2009; Leibler & Berger 2010). As reported above, short GRBs are associated to a mixed population of early and late-type host galaxies. This is indicative of a wide range of stellar population ages, that can be expected to be on average older with respect to the one associated to long GRB, occuring in star-forming galaxies only. Indeed, as reported in Leibler & Berger 2010, the median stellar population age is of $< \tau_* >\sim 0.25$ Gyr and $< \tau_* >\sim 60$ Myr for the host galaxies of short and long GRBs, respectively. The median specific star formation rate (star formation rate as a function of luminosity) for long GRB host galaxies is $10\, M_\odot$ yr^{-1} L_*^{-1} (Christensen et al. 2004), about an order of magnitude higher than that of short GRB hosts (Berger 2009, 2014). Also in terms of metallicity, the short GRB hosts span a wide range of values, with $12 + \log(\mathrm{O/H}) \sim 8.5 - 9.2$, with a median value of $<12 + \log(\mathrm{O/H})>\sim 8.8 \sim 1 Z_\odot$ (Berger 2009; D'Avanzo et al. 2009). More in general, when compared to survey field star-forming galaxies in similar ranges of redshift and luminosity, short GRBs host galaxies (at variance with long GRB hosts) reveal a very good agreement in terms of specific SFRs and metallicity (Berger 2009).

To date, an associated host galaxy candidate has been found for about half of the *Swift* short GRBs. In particular, almost all well localized short GRBs ($< 5''$ error radius) have a candidate host galaxy inside their position error circle, but only for those events with an observed optical (ora radio) afterglow could a firm GRB-galaxy association be established (Berger 2014). Among the bursts with a sub-arcsec localization, about 20% currently lack a secure host identification in spite of the careful observing campaigns carried out down to deep magnitude limits ($R \sim 25 - 28$ mag; see, e.g, Stratta et al. 2007; Perley et al. 2009; Fong, Berger & Fox 2010; Berger 2010). As discussed in Berger 2010, the "host-less" nature of these short GRBs may be caused by a progenitor having been kicked out from its host (or that is sited in an outlying globular cluster) or by high-redshift ($z > 1$) events, whose host galaxies are too faint to be detected by the current observational campaigns. A statistical study carried out by Tunnicliffe et al. (2014) pointed out that the proximity of these events to nearby galaxies is higher than is seen for random positions on the sky, in contrast with the high-redshift scenario.

2.1.1. *The host galaxy of GW 170817 / GRB 170817A*

So far, GRB 170817A is the only short GRB unambiguosly associated with a NS-NS GW event and with a kilonova (Abbott et al. 2017). Its host galaxy has been identified as NGC 4993, an early-type S0 galaxy at 41 Mpc (Hjorth et al. 2017; Cantiello et al. 2018), hosting a weak active nucleus observed in the X-rays with Chandra and XMM-Newton (Troja et al. 2017; D'Avanzo et al. 2018). Detailed optical imaging reveals large, face-on shell-like structures and dust lanes suggesting that NGC 4993 experienced a relatively recent galaxy merger (Levan et al. 2017; Im et al. 2017; Palmese et al. 2017). The galaxy properties, including the observed offset of the counterpart location with respect to the galaxy centre, are typically consistent with those of the population of short GRB host galaxies. Optical spectroscopy carried out at the transient location provides no evidence for narrow interstellar medium features, implying low extinction, and that the binary system may be located in front of the host galaxy. Inspection of the location of the counterpart carried out with *HST* revealed that no globular cluster can be detected, with a limit of a few thousand solar masses (Levan et al. 2017).

2.2. *Offsets*

In the context of double compact object progenitors, the offset distribution of the short GRB afterglows with respect to their host galaxies contains information on the merging times and thus on the evolutionary channels regulating binary systems evolution (Salvaterra et al. 2010). Preliminary studies of short GRB offsets (Berger et al. 2005; Fox et al. 2005; Bloom et al. 2006; Soderberg et al. 2006; Troja et al. 2008; D'Avanzo et al. 2009) reveal a somewhat larger projected physical offsets than for long GRBs, although no conclusive evidence was found for afterglows lying outside the light of their hosts and/or presenting evidence for low local absorption in their X-ray spectra (D'Avanzo et al. 2009). Evidences for local X-ray absorption, with no correlation with the short GRBs offset has been reported also by Kopac et al. (2012). A first, systematic study performed by Fong, Berger & Fox (2010) shows that the observed distribution of projected physical offsets for short GRBs is about five times larger than that for long GRBs and in good agreement with the predicted offset distributions for (NS-NS) binary mergers. On the other hand, the distinction between the two offset distributions is significantly reduced when considering host-normalized offsets, due to the larger size of short GRB hosts. However, even when taking into account the host galaxy size, the short GRB normalized offsets are still on average about 1.5 times larger than the values found for long GRBs (Fong & Berger 2013). Furthermore, these authors report that the spatial distribution of short GRBs inside their host galaxies do not track the hosts' rest-frame UV or optical light, an indication that these systems migrate from their birth sites to their eventual explosion sites.

In the scenario of compact binary progenitors, these results suggest that most short GRBs are likely originated by the merging of "primordial" binary compact object systems. However this conclusion can be valid only for those short GRBs with a secure host galaxy association.

2.3. *Environment*

When compared in the same redshift bin ($z \leq 1$), the distribution of the intrinsic X-ray absorbing column densities obtained from X-ray afterglow spectroscopy of long and short GRBs are fully consistent (Kopac et al. 2012; Margutti et al. 2013; D'Avanzo et al. 2014). Although this result can be intepreted as the evidence of a common environment for long and short GRBs, we caution that the intrinsc X-ray N_H might be a good proxy of the GRB host galaxy global properties but not for the specific properties of the circumburst medium. Furthermore, the possibility that gas along the line of sight in the diffuse intergalactic medium or intervening absorbing systems can contribute to the absorption observed in the X-ray emission of GRBs has to be taken into account (Behar et al. 2011; Campana et al. 2012; Starling et al. 2013). However, such effect is expected to dominate at $z \geq 3$, while at lower redshifts, comparable to the values found for short GRBs, the absorption within the GRB host galaxy is expected to dominate (Starling et al. 2013). For long GRBs, the massive star progenitor is expected to significantly enrich the surrounding environment with metals (whose X-ray N_H is a proxy) before the collapse with its stellar wind. Alternatively, it has been recently proposed that the Helium in the H II regions where the burst may occur is responsible for the observed X-ray absorption in long GRBs (Watson et al. 2013). Under these hypothesis, a high intrinsic X-ray N_H, can be interpreted as the evidence of a dense circumburst medium. Something similar can happen for short GRBs, under the condition that a short time (of the order of Myrs) separates the supernova explosions which gave origin to the compact objects in the primordial binary system progenitor and its coalescence, with the result that the burst would occur inside its host galaxy and near its star forming birthplace (Perna & Belczynski 2002). Such formation channel of "fast merging" primordial binaries is in agreement with the observed short GRB redshift distribution (D'Avanzo et al. 2014).

Short GRBs originated by double compact object systems which experienced a large natal kick or which are dynamically formed in globular clusters are expected to be associated with a low-density environments. By taking into account the fraction of host-less short GRBs, together with those events having tight upper limits on the intrinsic X-ray N_H, D'Avanzo et al. (2014) propose that about $10\% - 25\%$ of short GRBs might have occurred in low-density environments because formed via the dynamical channel (or having experienced a large natal kick).

2.4. *Lack of supernova associations*

Several attempts of search for associated supernovae (SNe) to sufficiently nearby short GRB have been carried out so far. However, at variance with the findings obtained for long GRBs, no signature of underlying SN in the light curves of eight short GRB optical afterglows have been found to date (namely, GRB 050509B, GRB 050709, GRB 050724, GRB 051221A, GRB 070724A, GRB 071227, GRB 080905A, GRB 130603B; Hjorth et al. 2005a,b; Fox et al. 2005; Covino et al. 2006; Soderberg et al. 2006; D'Avanzo et al. 2009; Rowlinson et al. 2010; Kocevski et al. 2010; Kann et al. 2011; Berger, Fong & Chornock 2013), in spite of the predominance of star-forming host galaxies for these events. In all cases, the search have been carried out down to very stringent magnitude limits (significantly fainter than the prototypical long GRB/SN 1998bw). At least for those short GRBs with deep SN limits, a massive-star origin can be safely excluded.

2.5. *Kilonova emission*

Predictions based on the opacities connected to r-process matter indicated that the bulk of kilonova emission is expected to peak in the UV/optical band in a couple of days ("blue kilonova", arising from lanthanide-free components of the polar ejecta) and in the near-Infrared band on a timescale of a week ("red kilonova", characterised by lanthanide-rich equatorial ejecta; Kasen, Badnell & Barnes 2013; Grossman et al. 2013; Tanaka & Hotokezaka 2013; Metzger & Fernandez 2014). The great interest in these sources is linked to two fundamental factors: 1) the efficient r-process nucleosynthesis makes them the most important sites for heavy element production in the Universe, and 2) their isotropy makes them easily detectable, and thus the most promising electromagnetic counterparts of gravitational wave (GW) events. Such a scenario has been confirmed on Aug 17 2017, towards the end of the second science run of the GW observatories LIGO/Virgo (O2), when the first GW event ever originated by a NS-NS merger was detected by LIGO/Virgo (GW 170817) and associated to the weak short GRB 170817A and to the bright kilonova AT2017gfo (Abbott et al. 2017). The proximity of the event (~ 40 Mpc) and the relative accuracy of the localization (~ 33 deg^2, thanks to the joint LIGO and Virgo operations) led to a rapid ($\Delta t < 11$h) identification of a relatively bright ($i \sim 17.3$ mag) optical counterpart, AT2017gfo (Coulter *et al.* 2017). Following the detection of this source, a huge, worldwide imaging, spectroscopic and polarimetric follow-up campaign at optical and NIR wavelengths begun. The obtained dataset shows that the combined spectral properties and evolution of AT2017gfo are unlike those of any known supernova types. The analysis and modelling of the spectral characteristics of this source, together with their evolution with time, result instead in a good match with the expectations for kilonovae, providing the first compelling observational evidence for the existence of such elusive transient sources (Pian et al. 2017; Smartt et al. 2017; Tanvir et al. 2017; Covino et al. 2017; Evans et al. 2017). The comprehensive spectral series covering the ultraviolet through the NIR show that the kilonova can be characterized by rapidly expanding ejecta with spectroscopic features similar to those predicted in current models (Kasen et al. 2015; Tanaka et al. 2017). The ejecta are optically thick early on after merger and move with ~0.2c, reaching a radius of ~ 50 AU in only 1.5 days. As the ejecta expand, atomic species imprint broad absorption-like lines on the spectral continuum, the products of nucleosynthesis occurring in a post-merger fast-moving (0.2c) dynamical ejecta and two slower (0.05c) wind regions (Pian et al. 2017). Comparison with spectral models suggests the merger ejected 0.03–0.05 solar masses, including high-opacity lanthanides. Besides the remarkable event associated to GW 170817, kilonova signatures have been tentatively identified in a few short GRBs light curves (Tanvir et al. 2013; Berger et al. 2013; Yang et al. 2015; Jin et al. 2015, 2016; Gao et al. 2017; Troja et al. 2018b, 2019; Lamb et al. 2019; Jin et al. 2020; Rossi et al. 2020; Gompertz et al. 2020; Fong et al. 2021; Rastinejad et al. 2021).

The study of kilonovae has a scientific impact that goes beyond the study of compact binary mergers. The single (by now) case of GW 170817/AT2017gfo, besides representing a historical result, demonstrates that the general predictions of the kilonova model are correct, but much has still to be done. Basic kilonova models are successful in explaining the major characteristics of the invaluable dataset obtained, but fits are far from being viable. Lanthanides built up during the merger and single element opacities are barely known (Watson et al. 2019). In the case of a NS-NS merger, a further complication is given by the fact that the ejecta properties depend sensitively on the fate of the massive NS remnant which is created by the coalescence event. Indeed, additional energy input from a long-lived magnetar remnant could substantially boost the kilonova emission, possibly leading to a light curve with an increased peak luminosity, more rapid evolution and bluer colors (Metzger 2017). GW 170817/AT2017gfo confirmed the general predictions for kilonovae and, at the same time, opened the path for a deeper understanding of this phenomenon. While the available dataset will provide a benchmark for any further model development, new events will clearly provide a stress test for these updated models in different conditions, allowing to disentangle micro-physics from viewing effects (geometry) and energetics (masses of the NSs).

3. Jets

The possibility that the GRB emission is collimated was proposed as a possible explanation for their otherwise huge isotropic equivalent energy (Waxman et al. 1998;

Fruchter et al. 1999). The observational evidence supporting this scenario is determined from temporal steepenings in the afterglow light curves, termed “jet breaks”, which are expected to be achromatic (Sari et al. 1999; Rhoads 1999; Panaitescu 2005). Jet breaks have been observed in a few tens of long GRB afterglow light curves (e.g. Ghirlanda et al. 2004). For short GRBs, the search for jet breaks has been more challenging, primarily due to the intrinsic faintness of their afterglows. The direct measure of the opening angle of short GRBs allows to properly estimate the true energy scale: the collimation-corrected energy is $E = (1 - cos\theta_j)E_{\gamma,iso}$. Furthermore, given that we detect more easily those bursts whose jet is pointing at the Earth, the opening angle is also crucial to envisage the event rate: the true event rate is higher compared to the observed rate by a factor $(1 - cos\,\theta_j)^{-1}$. Based on the current available measures and limits of θ_j, Fong et al. (2015) estimate a median $<\theta_j>= 16 \pm 10$ deg, which implies a beaming factor $f_b = (1 - cos\theta_j)^{-1} \sim 10 - 200$ for short GRBs. This translates into a median beaming-corrected energy $<E>\sim 10^{50}$ erg and a true event rate of $\sim 8^{+47}_{-5}$ yr^{-1} within the Universe volume of 200 Mpc covered by Advanced LIGO/Virgo. However, these estimates are based on the results obtained with the study of a handful of bursts, which represents a small fraction (∼10%) of the whole sample of the short GRBs detected by *Swift*. Furthermore, the GRB emission geometry can be more complicated than a simple “top-hat” homogeneous jet. Indeed, the most compelling evidence for the presence of a structured jet (i.e. the energy and Lorentz factor scale with the angular distance from the jet axis) in GRB outflows was provided by the impressive monitoring of the evolution of the afterglow of the short GRB 170817A associated to the GW 170817 event (Alexander et al. 2017, 2018; Haggard et al. 2017; Hallinan *et al.* 2017; Margutti et al. 2017, 2018; Kim et al. 2017; Troja et al. 2017, 2018a, 2019, 2020; Dobie et al. 2018; Lyman et al. 2018; D’Avanzo et al. 2018; Mooley et al. 2018; Resmi et al. 2018; Ruan et al. 2018; Ghirlanda et al. 2019; Fong et al. 2019; Hajela et al. 2019; Piro et al. 2019). These studies demonstrated that the best explanation for GRB 170817A is a jet endowed with an angular velocity and energy profile, featuring a narrow ($\theta_j \sim 3.4^o$) and energetic ($E \sim 2.5 \times 10^{52}$ erg) core seen under a viewing angle of $\sim 15^o$, surrounded by a slower, less energetic layer/sheath/cocoon (Ghirlanda et al. 2019; for a recent review see Margutti & Chornock 2021). After more than 1000 days, the GRB 170817A afterglow emission is still detected (Hajela et al. 2021; Troja et al. 2022), displaying a possible late-time rebrightening in the X-rays, which can be due to the kilonova afterglow originated by synchrotron emission from a mildly relativistic shock generated by the expanding merger ejecta (Hajela et al. 2019).

4. Conclusions and future perspectives

We are now at the dawn of a new, exciting era for short GRB studies. Almost two decades of systematic short GRB observations of their prompt emission, afterglows, host galaxies and associated kilonovae provided an impressive advance in the knowledge of these sources. After the recent major breakthroughs, we now have direct evidence for: the NS-NS / short GRB association, short GRB outflows shaped as structured jets, off-axis afterglow emission, the existence of r-process kilonovae and their association with short GRBs. The multi-frequency and multi-messenger approach to the study of short GRBs provided and will provide substantial advancements in several fields of physics and astrophysics (relativistic shocks, jets, radiation processes, chemical enrichment of the Universe, binary star evolution) with strong impact beyond each specific field.

The high-energy satellites (*Swift, Fermi, INTEGRAL, Agile* and, from 2023, *SVOM*) are expected be active for the next years and will routinely detect new short GRBs. *Swift* so far detected more than 150 short GRBs (∼10/yr), with an afterglow detected with a few arcsec (sub-arcsec) precision in the $\sim$ 80% (35%) of the cases. The SVOM rates are expected to be ∼20% lower than *Swift* (with similar positional accuracies), compensated by a dedicated ground-segment for optical follow-up and by a wider high-energy range that will led to a better characterisation of the short GRB prompt emission (Wei et al. 2016).

In a near future, the Cherenkov Telescope Array, the Vera Rubin Observatory and the James Webb Telescope will start operations. This will translate in the possibility to study short GRBs in the TeV domain (Bernardini et al. 2019), in a significant step forward for the detection of orphan afterglows and kilonovae (Ghirlanda et al. 2015; Andreoni et al. 2022) and in detailed studies of kilonovae and host galaxies.

Concerning the association of short GRBs with gravitational waves, during the third LIGO/Virgo science run (O3) a few merger events possibly involving at least one NS (i.e. a compact object with $M < 3\,M_\odot$) have been detected (Abbott et al. 2021a,b). Unfortunately, for none of them an electromagnetic counterpart was found, despite extensive searches. This can be due to a combination of still large error regions (hundreds of deg^2), distant events (i.e. dimmer counterparts) and possibly unfavorable conditions for the tidal disruption of the NS during the merger (as in the case of GW 190814; Ackley et al. 2020). The O3 run ended in March 2020 due to the COVID-19 pandemic. The next GW run (O4) will take place in late 2022. This run should extend the reach of the GW detectors to ~ 250 Mpc, with a median distance of ~ 150 Mpc (Abbott et al. 2020, LRR, 23, 3). This is a factor of 3-4 further than GW 170817, and may imply EM counterparts a factor 10 - 15 times fainter. However the increase in sensitivity over O3 will approximately double the survey volume. Based on the latest astrophysical rate of BNS mergers, $R_{NS-NS} = 320^{+490}_{-240}$ Gpc^{-3} yr^{-1} (Abbott et al. 2020), 5^{+7}_{-4} yr^{-1} NS-NS mergers are expected at the sensitivity of O4.

References

Abbott, B. P., et al., 2017, ApJ, 848, L12
Abbott B. P. et al. 2020, LRR, 23, 3
Abbott B. P. et al. 2021a, Phys. Rev. X 11, 021053
Abbott B. P. et al. 2021b, arXiv:2111.03606
Alexander et al., 2017, ApJL, 848, L21
Alexander et al., 2018, ApJL, 863, L18
Ackley, K. et al., A&A, 634, 113
Andreoni, I. et al. 2022, ApJS, 258, 5
Barthelmy, S. D., et al. 2005, Nature, 438, 994
Belczynski, K. & Kalogera, V., 2001, ApJ, 550, L183
Belczynski, K., Bulik, T. & Kalogera, V., 2002, ApJ, 571, L147
Belczynski, K., Perna, R., Bulik, T. et al. 2006, ApJ, 648, 1110
Behar, E. et al., 2011, ApJ, 734, 26
Berger, E. et al. 2005, Nature, 438, 988
Berger, E., 2009, ApJ, 690, 231
Berger, E., 2010, ApJ, 722, 1946
Berger, E., Fong, W. & Chornock, R., 2013, ApJ, 774, L23
Berger et al. 2013, ApJ, 774, L23
Berger, E. 2014, ARA&A, 52, 43
Bernardini, M. G. et al. 2019, ICRC, 36, 598
Bloom, J. S., Kulkarni, S. R., Djorgovski, S. G., 2002, AJ, 123, 1111
Bloom, J. S. et al., 2006, ApJ, 638, 354
Campana, S. et al. 2012, MNRAS, 421, 1697
Cantiello, M., et al., 2018, ApJ, 854, L31
Christensen, L. et al. 2004, A&A, 425, 913
Coulter, D. A. et al. 2017, Science, 358, 1556

Covino, S. et al. 2006, A&A, 447, L5
Covino, S. et al. 2017, Nature Astronomy, 1, 791
D'Avanzo, P. et al. 2009, A&A, 498, 711
D'Avanzo, P. et al. 2014, MNRAS, 442, 2342
D'Avanzo, P. et al., 2015, JHEAp, 7, 73
D'Avanzo, P. et al., 2018, A&A, 613, L1
Dobie, D. et al., 2018, ApJL, 858, L15
Eichler, D. et al., 1989, Nature, 340, 126
Evans, P. A. et al., 2017, Science, 358, 1565
Fong, W. F., Berger, E. & Fox, D.B, 2010, ApJ, 708, 9
Fong, W. F. et al. 2011, ApJ, 730, 26
Fong, W. F. et al. 2013, ApJ, 769, 56
Fong, W. F. & Berger, E., 2013, ApJ, 776, 18
Fong, W. et al., 2015, ApJ, 815, 102
Fong, W. et al., 2019, ApJL, 883, L1
Fong et al. 2021, ApJ, 906, 127
Fox, D. B. et al. 2005, Nature, 437, 845
Fruchter et al. 1999, ApJ, 519, L13
Fruchter, A.S. et al., 2006, Nature, 441, 463
Gao et al., 2017, ApJ, 837, 50
Gehrels, N. et al., 2005, Nature, 437, 851
Ghirlanda et al. 2004, ApJ, 616, 331
Ghirlanda et al. 2015, A&A, 578, A71
Ghirlanda, G. et al., 2019, Science, 363, 968
Gompertz et al. 2020, ApJ, 895, 58
Grossman et al. 2013, MNRAS, 439, 757
Haggard et al., 2017, ApJL, 848, L25
Hajela, A. et al. 2019, ApJ, 886, L17
Hajela, A. et al. 2021, arXiv:2104.02070
Hallinan, G. et al. 2017, Science, 358, 6370, 1579
Hjorth, J. et al., 2005a, Nature, 437, 859
Hjorth, J. et al., 2005b, ApJL, 630, L117
Hjorth, J., Bloom, J. S., 2012, Gamma-Ray Bursts, Cambridge Astrophysics Series 51, pp. 169–190
Hjorth, J. et al., 2017, ApJ, 848, L31
Hopman, C. et al., 2006, ApJ, 643, L91
Im, M. et al., 2017, ApJ, 849, L16
Jin et al. 2015, ApJ, 811, L22
Jin et al. 2016, Nature Communications 7, 12898
Jin et al., 2020, Nature Astronomy, 4, 77
Kann, D. A., et al. 2011, ApJ, 734, 96
Kasen, D., Badnell, N. R. & Barnes, J., 2013, ApJ, 413, L101
Kasen, D. et al., 2015, MNRAS, 450, 1770
Kim, S. et al., 2017, ApJL, 850, L21
Kocevski, D. et al., 2010, MNRAS, 404, 963
Kopac, D. et al., 2012, MNRAS, 424, 2392
Kouveliotou, C. et al., 1993, ApJ, 413, L101
Lamb et al., 2019, 883, 48
Leibler, C. N. & Berger, E. 2010, ApJ, 725, 1202
Levan, A. J. et al., 2017, ApJ, 848, L28
Li, L., Paczynski, B., 1998, ApJ, 507, L59
Lyman J. D. et al., 2018, Nature Astronomy, 2, 751
Malesani, D. et al. 2007, A&A, 473, 77
Margutti, R. et al., 2013, MNRAS, 428, 729

Margutti, R. et al., 2017, ApJL, 848, L20
Margutti, R. et al., 2018, ApJL, 856, L18
Margutti, R. & Chornock 2021, ARA&A, 59, 155
Metzger, B. D. et al., 2010, MNRAS, 406, 2650
Metzger, B. D. & Fernandez 2014, MNRAS, 441, 3444
Metzger, B. D., 2017, LRR, 23 1
Mooley, K. P. et al., 2018, Nature, 561, 355
Nakar, E., 2007, Phys. Rev., 442, 166
Narayan, R., Paczynski, B., Piran, T., 1992, ApJ, 395, L83
Palmese, A. et al., 2017, ApJ, 849, L34
Panaitescu, A., Kumar, P., & Narayan, R. 2001, ApJL, 561, L171
Panaitescu 2005, MNRAS, 362, 921
Perley, D.A. et al., 2009, ApJ, 696, 1871
Perna, R. & Belczynski, K., 2002, ApJ, 570, 252
Pian, E., et al. 2017, Nature, 551, 67
Piro, L. et al., 2019, MNRAS, 483, 1912
Rastinejad et al. 2021, ApJ, 916, 89
Resmi, L. et al., 2018, ApJ, 867, 57
Rhoads 1999, ApJ, 525, 737
Rowlinson, A. et al., 2010, MNRAS, 408, 383
Rossi et al., 2020, MNRAS, 493, 3379
Rosswog, S., 2005, ApJ, 634, 1202
Ruan, J. J. et al., 2018, ApJL, 853, L4
Salvaterra, R. et al., 2010, MNRAS, 406, 1248
Sari et al. 1999, ApJ, 524, L43
Savaglio, S., Glazebrook, K., Le Borgne, D., 2009, ApJ, 691, 182
Smartt, S. J et al., 2017, Nature, 551, 75
Soderberg, A. M. et al., 2006, ApJ, 650, 261
Starling, R. L. C. et al., 2013, MNRAS, 431, 3159
Stratta, G. et al. 2007, A&A, 474, 827
Tanaka, M. & Hotokezaka, K. 2013, ApJ, 775, 113
Tanaka, M. et al., 2017, PASJ, 69, 102
Tanaka, M. et al. 2018, ApJ, 852, 109
Tanvir et al. 2013, Nature, 500, 547
Tanvir et al. 2017, ApJ, 848, L27
Troja, E. et al., 2008, MNRAS, 385, L10
Troja, E., et al. 2017, Nature, 551, 71
Troja, E. et al., 2018a, MNRAS, 478, L18
Troja, E. et al., 2018b, Nature Communications, 9, 4089
Troja, E. et al., 2019, MNRAS, 489, 1919
Troja, E. et al., 2020, MNRAS, 498, 5643
Troja, E. et al., 2022, MNRAS, 510, 1902
Troja et al., 2019 MNRAS 489, 2104
Tunnicliffe, R.L. et al., 2014, MNRAS, 437, 1495
Vietri, M. 2000, Astroparticle Physics, 14, 211
Villasenor, J. S. et al., 2005, Nature, 437, 855
Yang et al. 2015, Nature Communications, 6, 7323
Wainwright, C., Berger, E., Penprase, B. E., 2007, ApJ, 657, 367
Watson, D. et al., 2013, ApJ, 768, 23
Watson, D. et al., 2019, Nature, 574, 497
Waxman et al. 1998, ApJ, 497, 288
Wei, J. et al., 2016, arXiv:1610.06892