Multimessenger astronomy with the Einstein Telescope

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Abstract Gravitational waves (GWs) are expected to play a crucial rôle in the development of multimessenger astrophysics. The combination of GW observations with other astrophysical triggers, such as from gamma-ray and X-ray satellites, optical/radio telescopes, and neutrino detectors allows us to decipher science that would otherwise be inaccessible. In this paper, we provide a broad review from the multimessenger perspective of the science reach offered by the third generation interferometric GW detectors and by the Einstein Telescope (ET) in particular. We focus on cosmic transients, and base our estimates on the results obtained by ET’s predecessors GEO, LIGO, and Virgo.

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1 Introduction

Coalescing binaries, core-collapse supernovae, and magnetars are not only interesting candidates for gravitational wave (GW) searches, but are also observed by other means, such as gamma-rays, X-rays, visible light, radio waves, and neutrinos. Therefore GW science in particular and astrophysics in general can profit from joint observations of astrophysical events detected by multiple observatories. Even simple correlation in time and direction between different messengers that correspond to the same astrophysical event can greatly increase the confidence in a detection of GWs, and search strategies can be optimized in this respect. Furthermore, several long-term goals of GW astrophysics require detection of astrophysical events in other channels beyond GWs. For example, an association between short hard GRBs and inspiralling neutron star binaries may be confirmed in this manner. The joint detection of GWs and neutrinos together with the observation of the optical light curve from a nearby supernova would greatly enhance our understanding of supernova explosions. Thanks to their ten-fold improvement in sensitivity, the third generation of interferometric GW detectors and the Einstein Telescope (ET) in particular will allow valuable astrophysical statements to be made through multimessenger observations. In this paper, we present an overview of the science reach that can be attained this way, focusing on astrophysical transient topics. Our goal is not to be complete in our coverage, but instead to highlight a sample of the science topics that will benefit from a multimessenger approach – emphasising both the wide range and the potential impact of these topics.

Before beginning an examination of particular astrophysical systems, it is worthwhile to consider how the nascent field of GW astronomy has interacted with traditional electromagnetic (EM) astronomy to date. There has not yet been a direct detection of GWs; expected GW signal strengths are weak compared to the background noise levels of current detectors, and searches are hampered by the non-stationary (“glitchy”) nature of that background noise. With this in mind, it is perhaps not surprising that the application of other messengers (mainly EM observations) in GW astronomy has been primarily with an eye to making a first detection. Information obtained from EM observations is used to improve the sensitivity of GW searches, and to increase the confidence of a putative GW candidate. For example, knowing the time of an astrophysical event permits a focused GW search on a short period of data for an associated gravitational-wave signal, reducing the false alarm probability of the GW search. Knowledge of the sky position (or sometimes other parameters such as frequency, e.g. from the measurement of quasi periodic oscillations) allows the rejection of background events inconsistent with those constraints. An estimated distance to the source (as may be available for SGRs and GRBs) allows the selection of particularly promising systems for analysis. In this light, the natural mode for multimessenger cooperation is that EM observation of an astrophysical transient triggers a GW search – this approach has been adopted in many searches by LIGO, Virgo and other GW detectors, particularly searches triggered by observations from gamma-ray and X-ray satellites, e.g. [126,127,128,129,130,131,133,134,135,60].

This EM-triggered mode of collaboration is also natural when one considers the qualitatively different nature of EM and GW observatories. GW detector networks are all-sky monitors, with a typical angular resolution of several degrees. The data are in the form of digitized times-series collected at rather low rates typically of $\sim O(10^4)$ samples/s). The low data rate allows all data to be archived; since pointing is achieved by aperture synthesis,
triggered searches can be conducted well after the data are collected. EM observatories, by contrast, are generally highly directional, typically with a field of view (FOV) that is arcminutes in scale. Current and planned future radio arrays such as LOFAR and the Square Kilometre Array have a much larger FOV, and point via aperture synthesis, but their large data rate prevents all data from being archived, so in general decisions about pointing must still be made at the time of observation.

Nascent efforts already exist to conduct multimessenger searches which go the other way: EM observations being conducted as follow-up to GW triggers. This approach recognises the potential value of having multimessenger observations of a candidate GW detection: these can provide independent confirmation of the signal and assist with its interpretation. Large FOV optical and infrared telescopes which are already in existence, or which will see first light in the near future, provide very exciting prospects for such joint observations. However, these opportunities come with significant challenges. Perhaps foremost among these is the task of imaging areas of O(10 deg²), and from all of the objects in that FOV identifying the single EM transient associated with the GW event. Looking ahead to the advanced LIGO / Virgo era, and further to the ET era, we expect GW detections to be a regular occurrence. In those circumstances multimessenger observations will be essential to maximize the scientific benefit from opening the new GW spectrum.

Of course we should also mention here neutrino observatories. These provide an interesting case for joint GW observations because, as we shall see, the FOV, angular resolution and distance sensitivity are similar to those of GW detectors.
To complete our introductory remarks it is helpful to define a rule of thumb to approximate the distance sensitivity of a generic gravitational wave detector. Most of the sources considered here do not have well-modelled gravitational waveforms. However, if we consider narrowband emission (i.e., bandwidths much smaller than the central frequency of the emission, and smaller than the typical frequency range over which the detector noise spectrum changes), we can estimate the distance to which a detector is sensitive as a function of frequency. Assuming emission of energy $E_{GW}$ in gravitational waves at source frequency $f_e$, the typical sensitive range $D_L$ (luminosity distance) is approximately [123]

$$D_L \simeq \sqrt{\frac{G (1 + z) E_{GW}}{2\pi^2 c^3 S(f)}} \frac{1}{\rho_{det} f} \simeq 2 \text{ Gpc} (1 + z)^{1/2} \frac{100 \text{ Hz}}{f} \left( \frac{E_{GW}}{10^{-2} M_\odot c^2} \right)^{1/2} \frac{2.5 \times 10^{-25} \text{Hz}^{-1/2}}{S(f)^{1/2}}. \quad (1)$$

Here $\rho_{det}$ is the signal-to-noise ratio in a single detector required for a detection, $f = f_e/(1 + z)$ is the observed frequency, and $S(f)$ is the detector noise power spectrum. Design noise spectra for LIGO, Virgo, Advanced LIGO, and ET are shown in Figure 1.

The remainder of this paper is organized as follows. In Section 2 we discuss possible common sources of gravitational waves and high-energy electromagnetic radiation (gamma- and X-rays). In Section 3 we highlight the possible scientific impact of joint observations with infrared, optical and ultraviolet astronomy. In Section 4 we outline the benefits of coordinated science with radio astronomy. Section 5 provides insight on the promise of multimessenger observations with cosmic neutrinos. Finally, in Section 6 we consider some additional paths and benefits of cross-disciplinary studies involving gravitational waves.

2 High-energy photons

We begin with an overview of systems that are potentially sources of both gravitational waves and gamma- or X-ray photons: gamma-ray bursts (GRBs), soft gamma repeaters (SGRs), ultra-luminous X-ray sources (ULXs), and micro-quasar flares. Most of these systems are also likely candidates for strong neutrino emission; as such we will revisit them in Section 5. As well as addressing key physical questions about their origin and specific emission mechanisms, multimessenger observations of these systems may allow us to harness their potential as probes of stellar astrophysics, galaxy formation, and cosmology.

It is difficult to predict today which instruments will be observing the electromagnetic spectrum at high energies during the ET era, and in particular whether an all-sky burst survey (primarily needed to monitor the sources described in this section) will be on-going. The currently active space missions Swift, INTEGRAL and Fermi are expected to cease operation before then. A number of future X- and gamma-ray satellites – including ASTROSAT (India), MAXI (Japan) and SVOM (China/France) – are close to the launch pad but it is unclear yet whether any of them will still be in operation by 2020. Three of the promising missions on the drawing board are the Energetic X-ray Imaging Survey Telescope (EXIST) [42], the International X-ray Observatory (IXO) [93] and the Xenia/EDGE mission [1]. The EXIST mission concept is specifically optimized for study of high-z GRBs. EXIST [79]

2 The details of the assumed polarization content and emission pattern affect the result by a factor of $O(1)$ [123], which we can ignore for an order-of-magnitude estimate.

3 This detector has been installed on the International Space Station during the summer 2009.
promises the detection of \( \sim 600 \) GRBs/yr and it intends to carry out a rich program targeting transient-source science \[12,43\].

In order to fully exploit the scientific benefits offered by joint observations with ET, it will be essential to have high-energy satellites operating during the ET era.

2.1 Gamma-Ray Bursts

Gamma-ray bursts are extraordinarily luminous flashes of gamma rays which occur approximately once per day and are isotropically distributed over the sky; see e.g. \[85\] and references therein. Some GRBs show variability on time scales as short as a millisecond, indicating that the sources are very compact. Host galaxies have been identified and their redshifts measured for more than 100 bursts, demonstrating that GRBs are of extra-galactic origin.

GRBs are grouped into two broad classes by their characteristic duration and spectral hardness \[40,67\]. The progenitors of most short hard bursts (SHBs, with duration \( \lesssim 2 \) s and hard spectra) are widely thought to be mergers of neutron star binaries or neutron star-black hole binaries \[92\]. Long GRBs (\( \gtrsim 2 \) s, with soft spectra) are definitively associated with core-collapse supernovae, particularly type Ic supernovae \[152\]. Both scenarios are thought to result in the formation of a solar-mass black hole with a massive \( (\sim 0.1 - 1 M_{\odot}) \) accretion disk. The gamma rays are thought to be produced by internal shocks in a jet fed by the accretion disk and powered by its gravitational potential energy or by the spin of the black hole.

The LIGO and Virgo detectors have placed upper limits on the strength of GWs associated with many individual GRBs \[126,129,131,135,136\]. The most recent LIGO-Virgo search \[135\] placed lower limits of 5–20 Mpc on the distance to the GRBs studied, assuming isotropic emission of 0.01 \( M_{\odot} c^2 \) at the network’s most sensitive frequency, 150 Hz. An analysis of GRB070201, a SHB with sky position error box overlapping M31, ruled out the hypothesis that this burst was due to a binary progenitor in M31 at >99% confidence \[129\].

The binary coalescence leading to a SHB will produce copious amounts of gravitational radiation that will be easily detectable by ET to \( z \sim 2 - 4 \). See the article by van den Broeck \textit{et al.} in this issue for a discussion of how joint GW and gamma-ray observations of these systems can be used to measure cosmological parameters. Specific multimessenger issues relevant to these cosmological applications of short GRBs are discussed in Section 3.2 below.

For the remainder of this section we focus on long GRBs. The rate density of observed long GRBs is estimated at 0.5 Gpc\(^{-3}\) yr\(^{-1}\) \[119,108,71\], so the typical distance to the closest GRB observed in a year is \( \sim 1 \) Gpc. Their progenitors are thought to be Wolf-Rayet stars – very massive stars (\( > 25 M_{\odot} \), with helium cores \( > 10 M_{\odot} \)) that have lost their hydrogen mantle. In the collapsar scenario \[81,151\], the core collapses to form a \( \sim 3M_{\odot} \) black hole with a \( \gtrsim 1M_{\odot} \) accretion disk. It is not yet known which of various proposed mechanisms is responsible for converting the disk binding energy or black hole rotational energy into the jets: neutrino annihilation; magnetic instabilities in the disk; or magnetohydrodynamic extraction of the rotational energy. Other details of the collapsar scenario are also uncertain; for example, it is possible that the collapsar leads to a black hole only after fall-back accretion (in which case the energy source must be magnetohydrodynamic as the neutrino annihilation is too inefficient at the low accretion rates in this scenario). In another variant, the supernova model \[143\], the core collapse produces a hypermassive neutron star supported by rotation, which later collapses to a black hole after spinning down due to dipole radiation. Other
groups have put forward models in which the GRB marks the birth of a magnetar rather than complete collapse to a black hole \cite{148,79,32,80}. Since the gamma-ray emission and afterglow are produced at large distances (\(\gtrsim 10^{13}\) cm) from the central engine, they provide only indirect evidence for the nature of that engine. By contrast, gravitational waves should be produced in the immediate vicinity of the central engine, offering a direct probe of its physics.

The collapsar scenario requires a rapidly rotating stellar core, so that the disk is centrifugally supported and able to supply the jet. This rapid rotation may lead to non-axisymmetric instabilities, such as the fragmentation of the collapsing core or the development of clumps in the accretion disk.

For example, Davies et al. \cite{29} suggest that fragmentation is generic, with a minimum lump size of \(\sim 0.2M_\odot\). In this case we may see inspiral-like GW signals for which the combined component masses are \(\sim 1.4M_\odot\); such signals will be observable with ET to luminosity distances of order 1 Gpc. Piro and Pfahl \cite{103} argue that gravitational instability coupled with cooling by helium photodisintegration will produce \(\sim 0.1 - 1M_\odot\) neutron star fragments with a lifetime of \(\sim 1\) s. For a source at 100 Mpc they estimate the SNR for the advanced LIGO detectors to lie in the range \(1 - 10\), depending on the unknown viscous timescale in the disk which determines the frequency of transition between viscosity-dominated evolution and gravitational-radiation dominated evolution. Scaling to ET sensitivity gives a detection rate of a few times \(10^{-3}\) yr\(^{-1}\) to \(\sim 2\) yr\(^{-1}\) for large viscous timescales, which are expected for thin disks when neutrino cooling is efficient. In this case the viscous timescale would be measurable from the peak of the GW spectrum.

Alternatively, the suspended accretion model of van Putten et al. \cite{141}, in which the torus is supported by the residual magnetic field of the star, predicts the development of strong non-axisymmetries and copious GW emission in a relatively narrow band, \(E_{\text{GW}} \approx \) \(0.2M_\odot\) at a typical frequency of 500 Hz. From \cite{1} such emission would be detectable by ET to a distance of approximately 0.5 Gpc.

Long GRBs appear to include a sub-class known as “low-luminosity GRBs,” which are associated with particularly energetic core-collapse supernovae. Examples of these objects include GRB980425 / SN1998bw \cite{39,69}, GRB031203 / SN2003lw \cite{83,116}, and GRB060218 / SN2006aj \cite{22,26,101,117}. As these events are less luminous than typical long GRBs, they are often discovered at smaller distances, for example: SN1998bw at redshift \(z = 0.0085\), less than 40 Mpc from Earth; SN2003lw at \(z = 0.105\); SN2006aj at \(z = 0.033\). Recent studies \cite{76,117,24} indicate the local rate density of under-luminous long GRBs may be as much as \(10^3\) times that of the high-luminosity population – with the closest such GRB observed, in one year of operation, lying at a typical distance of only 100 Mpc. This is an encouraging prospect for their detection in GWs, particularly given the consensus that these events are the extreme end of a continuum of events with the same underlying physical model, rather than physically distinct progenitors \cite{152}. In the same way, X-ray flashes (XRFs) and X-ray rich (XRR) GRBs \cite{47} are observationally similar to ordinary long GRBs, and could also be produced by the same underlying progenitors. Again, ET observations may confirm or refute this conjecture.

2.2 Soft gamma-ray repeaters

Soft gamma-ray repeaters are systems that emit brief bursts of soft gamma rays and X-rays at irregular intervals \cite{85,150}. These bursts have typical durations of \(\sim 0.1\) s and luminosities up to \(10^{42}\) erg s\(^{-1}\). Three of the five known SGRs have also been observed to emit rare
According to the magnetar model, SGRs are galactic neutron stars with magnetic fields of $\sim 10^{15}$ G. Flares occur when the solid crust cracks due to deformations induced by the magnetic field [139,110,53]. This cracking may excite the star’s nonradial modes, particularly $f$ modes [51,56], producing GWs [54,96]. The most optimistic estimates for the energy reservoir available in a giant flare is $10^{49}$ erg [56]; a more recent analysis [27] indicates that a more realistic limit is between $10^{45}$ erg (about the same as the total EM emission) and $10^{47}$ erg. However, the efficiency of conversion of this energy to GWs is unknown.

LIGO has placed upper limits [128,130,133] on GW emission by SGRs in the range $10^{45} - 10^{51}$ erg, depending on frequency, and assuming a nominal source distance of 10 kpc. Typical LIGO limits in the 1-3 kHz range, expected for $f$ modes, are $10^{49} - 10^{50}$ erg.

Figure 2 shows the sensitivity of ET to an SGR source at a distance of 10 kpc (a typical galactic distance) and 0.8 kpc (the estimated distance to SGR 0501+4516 [13,38,72]). At $f$-mode frequencies ET will be sensitive to GW emissions as low as $10^{42} - 10^{44}$ erg at 0.8 kpc, or about 0.01% to 1% of the energy content in the EM emission in a giant flare. In the region of 20 – 100 Hz, ET will be able to probe emissions as low as $10^{39}$ erg, i.e. as little as $10^{-7}$ of the total energy budget.

2.3 Ultra Luminous X-ray binaries (ULXs)

Stellar-mass black holes ($M < 20M_{\odot}$) have an Eddington luminosity of $10^{39}$ erg/s. This fixes an upper limit on the luminosity for “normal” X-ray binaries. However, several objects (the nearest being in M33) have observed luminosities (i.e. inferred from their measured fluxes and assuming isotropic emission) in the range $10^{39}$ to $10^{41}$ erg/s. Three scenarios have been proposed to explain this apparent anomaly:
– ULXs contain a stellar-mass black hole but the X-ray emission from the surrounding accretion disk is beamed, implying a significantly lower (sub-Eddington) luminosity;
– ULXs contain a stellar-mass black hole and the X-ray emission from the accretion disk is isotropic, thus implying a super-Eddington luminosity;
– ULXs contain an intermediate-mass black hole (IMBH), with \( M > 100M_\odot \), for which the Eddington luminosity is compatible with the luminosities observed for these systems.

While the third scenario offers an intriguing explanation of the ULX phenomenon, the existence of IMBHs is not well established. These objects have been proposed as light ‘seeds’ of the massive black holes found in the centres of galaxies; they are thought to form at high redshift as the end product of the first generation of stars. Should these IMBHs exist, the GW signatures of their mergers will likely fall between the sensitivity bands of 2nd generation ground-based detectors and LISA. However, these merger events would be bright GW sources for ET, visible to \( z \sim 10 \). Recently Sesana et al. [112] computed the number of IMBH merger events, for a variety of black hole ‘seed’ formation models, that would be detected in three years of operation by a single ET with 10 km arms. They found that for almost all models ET could expect to observe a few, to a few tens of mergers per year – with the black hole masses measurable from analysis of the waveform during the inspiral phase. While not resulting strictly speaking from a multimessenger approach, observations with ET may, therefore, help to discriminate between the proposed ULX scenarios since they should confirm or refute the existence of IMBHs.

2.4 Microquasar flares

Microquasars [87] are radio-emitting X-ray binaries. Their name is motivated by their observational similarities to quasars, particularly their strong, variable radio emission and the presence of radio jets. The jets are powered by accretion from a normal companion star onto a central object which may be a neutron star or a solar-mass black hole. The accretion disk is very luminous in the optical and X-ray regimes.

Microquasars exhibit X-ray and radio/IR flares which may be explained by ejection of “blobs” of accreting matter. The X-rays originate from the inner accretion disk, while the radio/IR emission is due to the ejection of ultra-relativistic blobs of plasma (ballistic motion). In this “cannonball model” one can expect the emission of a GW burst with memory from the microquasar, with typical strain amplitude [111,104]

\[
h \sim 10^{-22} \frac{\Gamma}{10} \frac{m}{10^{-7}M_\odot} \frac{1\text{kpc}}{D}.
\]

Here \( D \) is the distance to the microquasar, \( m \) is the mass of the blob, and \( \Gamma \) is the Lorentz factor; the nominal value of \( m \) is of order of the mass of the Moon. The corresponding energy in GWs is of order

\[
E_{\text{GW}} \sim \frac{c^3 h^2 D^2}{8G T}.
\]

where \( T \) is the duration of the burst.

The acceleration time of the blob determines the duration of the burst and hence its typical frequency. This may range from \( T \sim 10^{-5} \) s (the free-fall time for a solar-mass

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4 In [122], the authors claim to have observed one associated with the ULX NGC 5408 X-1.
compact object) up to minutes. An acceleration timescale of $\sim 1$ ms would place most of the radiated energy $E_{GW} \sim 10^{-15} M_\odot = 2 \times 10^{39}$ erg at frequencies around 100 Hz. From equation (1), this would yield a typical signal-to-noise ratio of $\rho \sim 6$ at 1 kpc; such a GW burst might be marginally detectable by ET. The observation of such a GW pulse coincident in time and direction with a microquasar flare would confirm that the jet is relativistic and would possibly provide an independent measurement of the mass of the ejecta.

3 Medium-energy photons

As discussed in Sections 1 and 2, the well-established history of multimessenger astronomy involving GWs has focussed mainly on high-energy EM (i.e., gamma- and X-ray) observations being used to trigger searches in GW data for signals associated with GRBs and SGRs. By contrast efforts are only now beginning on joint observations between GWs and the medium and low-energy EM spectrum (optical, radio, etc.), and in this context we can also envision an alternative procedure, where EM observations are triggered by GW detections.

While the range of possibilities is great when considering the science enabled by joint optical and gravitational wave observation, here we will only discuss two of the best surveyed and understood topics: optically detected core-collapse supernovae and short GRBs. Both of these are potentially interesting as GW sources.

For optically detected extragalactic supernovae, the GW arrival time must be predicted from data derived from an early optical detection. This results in a large uncertainty (of order several hours) on the predicted arrival time, which makes the GW data analysis task challenging. However, information on the direction – and to a lesser extent the distance – of an optically detected supernova is usually rather precise, which at least permits the use of directional GW search analysis methods. The large number of extragalactic supernova discoveries expected in the future, from e.g. ground-based optical telescopes such as PanSTARRS and LSST (see below), makes this line of analysis potentially very fruitful – even though its theoretical motivation is still evolving.

Targetted observations in the optical and infrared of short GRBs shall help us measure the redshift of these coalescing compact binary systems. The coincident gravitational wave amplitude, frequency and frequency derivative during inspiral and coalescence phases can yield a precise estimate of their luminosity distance. The combination of the two could in turn provide a completely independent way to calibrate the cosmological distance scale and constrain cosmological models.

3.1 Optically Detected Core-Collapse Supernovae

Core-collapse supernovae have long been considered as one of the most interesting targets for gravitational-wave observations. Many different physical phenomena during and after the collapse have been studied in the context of GW emission; unfortunately, most studies indicate that even the second-generation LIGO detectors will only be able to detect GWs from supernovae in our Galaxy. Since the galactic supernova rate is approximately $0.02$ yr$^{-1}$, the GW observation of a SN will have to rely on luck – until ET.

The solid line on the upper panel of Figure 3 shows the GW energy that a supernova core collapse is required to radiate, in order to be detectable by the Einstein Telescope. Also shown as horizontal bands are the predicted ranges of GW energy for several theoretical
The upper plot displays the minimum GW energy that a supernova core collapse is required to radiate in order to be detectable by the Einstein telescope. We give two estimates obtained from Eq. (1) assuming a GW signature with a low frequency content $f = 100$ Hz and high frequency content $f = 1$ kHz. This quantity is given as a function of the source distance. We also indicate the expected range of radiated GW energy for several processes [95]. The lower plot shows an estimate of the cumulative event rate (with error bars) obtained from the star formation rate computed over a catalog of nearby galaxies [6].

SN mechanisms. The lower panel of Figure 3 shows the expected cumulative event rate as a function of distance. While the upper plot indicates that a significant fraction of the modelled waveforms should be visible to ET from the distance of M31 (∼770 kpc), the lower plot shows that the event rate at that distance is still low – likely requiring decade(s) of observation to secure a single supernova detection. Nevertheless, we note from the upper plot that some mechanisms are predicted to be sufficiently energetic to be detectable by ET at a distance of up to 10 Mpc, where the SN event rate reaches a value of order unity. Therefore, extended observations by ET should be able to detect or place strong constraints on the role of the more energetic theoretical processes shown in Figure 3.

Ott [95] provides an in-depth and comprehensive review of the state-of-the-art understanding of the GW signatures of core-collapse supernovae. Section 5 of this paper discusses supernovae in more detail and outlines the possible benefits of observing them jointly in low-energy neutrinos and gravitational waves.

3.2 Gravitational wave standard sirens

Perhaps the clearest role for multimessenger observations in the optical and infrared lies in the exploitation of very deep imaging and spectroscopic data to identify the host galaxy, and
thence measure the redshift of coalescing compact binary systems – so-called “gravitational wave standard sirens”.

In the past few years there has been growing interest in the potential future use of these systems as high-precision cosmological distance indicators, since measurement of their gravitational wave amplitude, frequency and frequency derivative during inspiral and coalescence can yield a precise estimate of their luminosity distance. While much attention has been focussed on binary supermassive black hole mergers that will be a major observational target of the LISA satellite, recently Nissanke et al. have investigated the prospects for detecting binary neutron star mergers with a network of advanced ground-based detectors. They showed that the source’s luminosity distance could be determined to an accuracy of better than 30%, out to a distance of 600 Mpc. Thus, gravitational wave standard sirens could provide a completely independent way to calibrate the cosmological distance scale and constrain cosmological models via their luminosity distance redshift relation – in a manner complementary to other, electromagnetic, cosmological probes.

Crucial to their usefulness for cosmology, however, is the inference of each source’s redshift, which is not possible from the gravitational wave data alone. This may not require explicit association of the source with a single, host galaxy: MacLeod and Hogan have developed a interesting method for obtaining unbiased estimates of standard siren redshifts by exploiting information about the clustering of galaxies in each source’s 3-D error box. However definitive identification of the source’s electromagnetic counterpart, and thus measurement of an accurate sky location, is in any case highly desirable since it will also significantly improve the determination of the source’s intrinsic parameters – including its luminosity distance – by breaking parameter degeneracies and avoiding the need to marginalise over sky position.

Recently Sathyaprakash et al. have considered the prospects for using the Einstein Telescope as a precision tool for cosmology. The annual rate of coalescence for binary neutron star and neutron star-black hole systems within the volume observable by ET is expected to be several $\times 10^5$. As discussed in the previous section, these systems are believed to be the progenitors of short-hard gamma ray bursts. Sathyaprakash et al. assumed that over a three-year period of ET operation the electromagnetic counterparts of about 1,000 standard sirens, distributed with constant comoving number density over the redshift range $0 \leq z \leq 2$, would be detected optically, and their redshifts and sky positions measured. The authors showed that, with these observations, the dark energy equation of state parameter $w$ could be measured to a precision of 15% (1 − $\sigma$ error) – assuming also that the effects of weak lensing could be corrected (see below and for further discussion). In fact if $w$ were the only parameter to be fitted (e.g. if the dimensionless density parameter were assumed known, from other cosmological observations, and the Universe were assumed to be flat) then $w$ could be measured to a precision of about 1% (1 − $\sigma$ error).

Is identifying the optical counterpart and host galaxy of GW sirens observed by ET out to $z = 2$ a realistic prospect? As pointed out in Bloom et al., short-hard GRBs are now known to produce faint optical and infrared afterglows, detectable for a few days with current and planned future instrumentation. Perley et al. compare light curve models for a $^{56}$Ni-powered “mini-SN” with optical observations of the transient associated with the short-hard GRB 080503; these data may represent the first electromagnetic signature of a binary neutron star inspiral. The optical observations of the afterglow were extremely faint, however – never exceeding 25th magnitude – and no coincident host galaxy brighter than 28.5 mag. was found with HST.
On the other hand Berger et al. \cite{15} presented optical observations of nine short-hard GRBs, obtained with Gemini, Magellan, and the Hubble Space Telescope. They identified candidate host galaxies from optical and X-ray afterglow observations, and measured spectroscopic redshifts in the approximate range $0.4 \leq z \leq 1.1$ for four of them. For eight of the nine GRBs in this sample the most probable host galaxy had an $R$-band magnitude in the range $R \sim 23 - 26.5$ mag. This is certainly faint by the standards of current instrumentation and, together with the lack of an HST-detected host galaxy for GRB 080503, underlines the current observational challenge of determining the redshift of more distant sirens.

However it is expected that by 2020 the available ground-based optical and infrared facilities will include the proposed European Extremely Large Telescope (ELT) \cite{35} and the Thirty Meter Telescope \cite{138} – both of which could begin operations as early as 2018. These instruments will target observations of ‘First Light’ galaxies at high redshift, and should be capable of obtaining high quality spectra, even at $z \sim 6$ with modest $\sim 1$ hour integration times, from galaxies significantly fainter than $L^*$, which is a parameter (representing the luminosity of a typical galaxy) of the Schechter function widely used to model the distribution of galaxy luminosities. The task of determining standard siren redshifts out to $z \sim 2$ from imaging and spectroscopy of their host galaxies should, therefore, be straightforward \footnote{Indeed this task should also be possible in the radio, assuming that the SKA begins operation on a similar timescale to ET. See also Section 4.}

Of course the above remarks make an important assumption: that an electromagnetic counterpart of the short-hard GRB is identified, in X-rays, UV or optical, from a wide-spectrum monitoring satellite such as SWIFT. Five of the short-hard GRBs considered in Berger et al., for example, had no observed optical afterglow but had X-ray positions measured to within a radius of 6 arcseconds – sufficient to identify the probable host galaxy with good confidence. In the absence of this precise directional information the task of determining the siren redshift is rendered significantly more difficult: in addition to the source parameter degeneracies discussed above the issue of source confusion becomes very serious, as we now briefly consider.

The angular size of the source position error box derived from GW observations alone will be large. Recent analyses (see e.g. \cite{23, 17, 36}) suggest that a network of second generation detectors will locate NS binaries to within a field of about 10 square degrees, and a similar angular precision could be expected from a network of ETs. A realistic future observational strategy for second and third generation detectors may, therefore, require using deep and wide optical/infrared survey data to search for siren host galaxies. Crucial for this purpose will be facilities such as the Large Synoptic Survey Telescope (LSST, \cite{58}): this is an optical imaging survey instrument with a $\sim 10$ square degree field of view, which will map 20,000 square degrees in 6 photometric bands to a depth of $0.3\mu Jy$. LSST will potentially be a very powerful tool for multimessenger astronomy with ET – both via a ‘rapid response’ mode that would slew to the putative GW source location to search for transient optical signatures, and via the use of archival ‘survey mode’ data to identify candidate host galaxies within the GW source error box.

The potential number of such candidate hosts can be gauged by considering, for example the Hubble Ultra Deep Field which contained more than 8000 galaxy detections within an area of 12 square arcmin. Scaling this number density to an area of 10 square degrees would yield 24 million galaxies! Of course one is searching amongst those galaxies for a specific optical transient signature, but with so many galaxies in the error box several such transients may be observed. This underlines the importance of developing a much better theoretical understanding of the electromagnetic signatures of short-hard GRBs in the decade
or so before ET begins operation. Without a clear pre- and/or post-merger electromagnetic signature to narrow the search, identifying the siren’s host galaxy becomes like searching for a small needle in a very large haystack. Efforts to better understand the electromagnetic signatures of supermassive black hole mergers for LISA are already well underway (see, for example, [64,65,45]) and a similar effort for short-hard GRBs should be undertaken. Of course one advantage for ET, unlike LISA, is that we can confidently expect the detection of a number of binary inspirals with second generation detectors. Thus there should be several years’ worth of intensive multimessenger observations of standard sirens to draw upon before ET begins operation. These observations should hopefully provide a powerful incentive to drive forward our theoretical understanding of these systems, and the electromagnetic signatures that will reveal their presence in the skies probed by ET.

Finally, we should mention another important multimessenger role for deep and wide optical/infrared survey data in the context of gravitational wave standard sirens. For several years it has been recognised that the performance of sirens as cosmological probes will be significantly undermined at high redshift by the impact of weak gravitational lensing from intervening large-scale structure [52,23,107]. One possible method to mitigate this problem is to construct high-resolution maps of the cosmic shear and convergence along the line of sight to a siren, in order to identify – and attempt to correct for – the amount of weak lensing (de-)magnification. Recently Shapiro et al. [113] have investigated this approach in detail for putative LISA supermassive black hole binaries, although the methodology would be equally applicable to standard sirens observed with ET. The authors demonstrate that the weak lensing scatter can indeed be partially corrected so as to reduce the distance error dispersion by up to 50% for a source at $z = 2$. However this result assumes the availability of weak lensing magnification maps constructed from a 2-D ELT mosaic image and a wide-field image from a space survey telescope such as JDEM or EUCLID. Thus the requirement for a multimessenger approach is also very strong in this context.

4 Low-energy photons

4.1 Radio Astronomy

The existence of theoretical models in which various mechanisms give rise to a prompt pulse of radio emission from some putative gravitational wave sources, particularly coalescing compact binaries, motivates joint GW searches with radio telescopes. Moreover, the use of GW detectors as a trigger for follow-up radio searches could provide a method of detecting faint radio transients that might otherwise be missed.

Future ground-based radio telescopes, such as LOFAR [78] and the Square Kilometre Array [121], will employ aperture synthesis to allow the observations to combine a field of view that is a large fraction of the sky with an angular resolution that is a fraction of an arc second. Such telescopes could therefore use digital signal processing to match the telescope field of view with the error circle of a gravitational wave trigger supplied by a network of ETs. The bandwidth of LOFAR is limited to the UHF (40-240 MHz) by the useable bandwidth of the antennae. For other conventional steerable dish telescopes, with a much smaller field of view, the task of identifying the radio counterpart of a GW source is more challenging, although these telescopes do at least have the advantage of covering a wide range of radio frequencies across a frequency band for which the radio counterpart signature is better understood. Hence steerable dish telescopes could be employed for dedicated follow up observations, once the source location had been determined precisely using LOFAR or
the SKA. Moreover the use of gravitational waves as the search trigger would at least make optimal use of the wide field of view of GW interferometers to maximize the probability of transient detection in GWs. Furthermore

What would multimessenger astronomers ‘see’ with their radio telescopes? Models for prompt radio emission from compact binaries generally require that one of the compact objects is a magnetar. In the simplest of these model classes [77,46], the orbital motion of the binary generates time dependent magnetic fields and consequently induced electric and magnetic fields. These fields then lead to the emission of radiation, which is predicted to be in the radio band.

A second, larger class of models similarly require a high magnetic field from one member of the binary; in these models the field either confines or otherwise interacts with a plasma. For example, the unmagnetized companion object can develop surface charge that can then be ejected from the surface of the star and subsequently undergo acceleration as it follows the magnetic field lines of the magnetar. Alternatively, gravitational waves emitted during the inspiral and merger of a binary neutron star system may excite magnetohydrodynamic waves in the plasma (see [88,33] for details), which then interact with charged particles in the plasma, inducing coherent radio emission.

There are a series of proposed models for radio afterglows for SHBs that may be observed seconds to minutes after the burst. One of the models put forward by Usov and Katz [140] predicts that immediately after merger the rotational energy of the binary system is transferred to a highly magnetized, highly relativistic particle wind that interacts with the ambient warm gas and as a result EM radiation is emitted. The main bulk of the radiation is below 1 MHz but its tail can reach 1–30 MHz. A key prediction of their model is that there should be an incoherent radio pulse in the frequency range 1 – 30 MHz, with a duration of 1 – 100 seconds and a fluence of a few percent of the total gamma-ray fluence from the source. The expected time delay for the pulse would be around $10^4$ s for a source placed at 3.2 Gpc. Published results on radio afterglows for SHBs show only weak signals hours or days after the burst.

The detection of such a radio pulse might well require observations at lower frequencies than are usual for ground-based radio astronomy. Even the LOFAR low frequency radio array [78] is not sensitive below about 30 MHz, and the proposed Phase 2 design specification for the Square Kilometre Array radio telescope [121] extends only to 70 MHz. Thus, as acknowledged by Usov and Katz, radio observations from space may be required to detect the afterglow signatures predicted in their model: these observations would be free from the effects of ionospheric refraction, although interstellar scintillation would still be very strong.

On the other hand, higher frequency radio afterglow signatures – while harder to predict theoretically at present – might be accessible from the ground. In that regard (as was similarly noted in Section 3.2 in the context of optical signatures) before the ET era begins we can confidently expect the detection of a number of SHBs with second generation GW detectors. These should present important opportunities to carry out radio follow-up searches, using e.g. LOFAR, the various SKA precursors and indeed possibly the SKA itself. These crucial first GW discovery events will, therefore, hopefully equip us with a much better understanding of their radio afterglows in the frequency range that will be accessible to ground-based radio telescopes during the ET era.

In fact prospects for detecting the radio precursor of an SHB appear to be better. Hansen and Lyutikov [46] have modelled the electromagnetic signature expected from the magnetospheric interactions of a neutron star binary prior to merger. In view of the lack of a complete theory of pulsar radio emission, they adopted a simple parameterisation based on what is known about pulsars; nevertheless they found that detectable signals were possible
in both radio and X-rays, estimating the radio flux density at 400 MHz to be

\[ F_\nu \sim 2.1 \text{mJy} \epsilon \left( \frac{D}{100 \text{Mpc}} \right)^{-2} B_{15}^{2/3} a_7^{-5/2}, \]

where \( \epsilon \) is a dimensionless efficiency factor, \( D \) is the distance to the binary, \( B_{15} \) is the magnetic field in units of \( 10^{15} \text{G} \), and \( a_7 \) is the orbital semi-major axis of the binary in units of \( 10^7 \text{cm} \). As noted by Hansen and Lyutikov, for an SHB within a few hundred Mpc this emission would already in principle be detectable by the larger radio telescopes operating today – although it would lie somewhat below the sensitivities of current radio transient searches. If the model predictions of these authors are reasonable, therefore, pre-merger radio emission from neutron star–neutron star binaries should be a straightforward observational target for LOFAR and the SKA out to cosmological distances – at least provided the problem of source confusion is overcome and the radio and GW emission are both associated with the correct source.

To summarise, all of the above suggests interesting future possibilities for joint radio and GW observations of SHBs. For binary mergers ET will provide a very precise time of coalescence (to within milliseconds). It will also provide the redshifted masses and spins of the binary components, a rough sky position (to within about \( \sim 10 \text{ deg}^2 \)), and an approximate luminosity distance (perhaps to a factor of 2). These data could then be used to trigger detailed follow-up radio observations, to identify the radio transient associated with the GW signal. While the task of identifying this radio counterpart is clearly challenging, sharing many of the source confusion issues discussed in Section 3.2, note that we can determine the dispersion measure for any candidate counterpart. This will provide an independent measure of the distance, allowing us to better predict when the GW emission should have arrived at our detectors – and thus hopefully narrowing the search for the ‘true’ radio counterpart.

Most importantly, a robust and reliable identification of the radio transient associated with a binary merger event could open the door to using the full binary population (of order \( 10^6 \) systems) observed by ET for cosmological measurements, rather than just the small fraction of binaries which are also detected as GRBs. Moreover, determining the redshift of the host galaxy could also be carried out in the radio – thus avoiding the need to identify the host galaxy optically and so providing an alternative route to mapping out the luminosity distance redshift relation for GW sirens.

5 Neutrinos

Many of the astrophysical systems observable by ET are also expected to be strong emitters of neutrinos. Two energy ranges of the neutrino spectrum are of observational interest: low energies, \( E_\nu \lesssim 10 \text{ MeV} \); and high energies, \( E_\nu \gtrsim 100 \text{ GeV} \). (The intermediate range around 100 MeV is currently inaccessible to earth-based detectors because it is overwhelmed by atmospheric neutrinos from air showers). Cosmic neutrinos in these different energy ranges originate from different astrophysical processes. Consequently in this section we treat low and high energies separately when compiling a list of potential joint sources of gravitational waves and neutrinos.

Neutrino observatories have quantitatively similar characteristics – in terms of FOV, angular resolution and distance sensitivity – to GW observatories. Hence, for many astrophysical sources joint neutrino and GW observations would represent a “marriage of equals” – although a notable exception would be the case of a galactic core-collapse supernova, which
for current GW and neutrino detector sensitivities would be a much higher SNR source of low energy neutrinos than of gravitational waves.

For the low-energy range, detectors are composed of a vessel filled with pure water or a liquid scintillator. The sensitivity of the neutrino detectors scales linearly with the mass of liquid. The main detectors currently are Super-Kamiokande (Japan) with 50 kilotons of pure water, and LVD (Italy), KamLAND (US/Japan) and the upcoming SNO+ (Canada), with 1 kiloton of liquid scintillator. This list can be extended to smaller detectors (less than 1 kiloton) such as Borexino (Italy) and Baksan (Russia). The ASPERA roadmap, which projects the future of astroparticle physics in Europe, includes a megaton neutrino detector that should be operational simultaneously with ET. (Large-scale prototypes such as MEMPHYS, LENA and GLACIER will serve as pathfinders.) Elsewhere in the world similar projects are under development, such as the DUSEL LBNE detector, or have entered early design phase, such as Hyper-Kamiokande in Japan. There are also more advanced proposals for multi-megaton detectors such as Deep-TITAND.

A similar process is exploited for the neutrinos in the high-energy range: A charged particle results from the interaction of the neutrino and the detector environment. The flash of Cherenkov light generated by the muon (preferred because it travels straight through the detector, thus leaving a distinct trace) is detected and provides evidence of the impinging neutrinos. Given the low expected fluxes at those energies and the small cross sections, immense instruments (km$^3$ in size) are required to detect them in sufficient numbers. Currently, the leading experiments are IceCube, a cubic kilometer-scale detector under construction in the ice at the geographic South Pole, and ANTARES, which employs about $10^{-2}$ km$^3$ of seawater at 2500 m depth in the Mediterranean sea near Marseilles (France). Looking ahead, the KM3NeT European network recently started a design study for a km$^3$ detector in the Mediterranean sea, which is part of the ASPERA roadmap. The high-energy neutrino detectors also have some sensitivity to neutrinos in the low-energy range; this is the case with IceCube and a possibility under study with ANTARES. Experiments which rely upon radio-based detection of the highest energy neutrinos through the Askaryan effect, enhancing IceCube’s sensitivity, might operate together with ET – presenting potentially interesting possibilities for multimessenger science at the GZK frontier.

5.1 Low-energy neutrinos

As discussed previously, core-collapse supernovae are potential sources of gravitational waves. They also have a well-established low-energy neutrino signature, and so are the flagship candidate for coincident GW-neutrino detection. The time delay between the neutrino pulse and the gravitational-wave emission is very small, usually assumed to be sub-second. The almost simultaneous gravitational wave and low-energy neutrino signal is followed by the optical signal that starts to rise after a several-hour delay. Therefore, both gravitational-wave and neutrino signals can be used as an early warning for electromagnetic observers.

The core collapse of a massive star produces an O(0.1 s) long pulse of low-energy neutrinos and antineutrinos, amounting to a total energy release of up to $10^{53}$ ergs. The neutrinos produced are of all flavours, and have energies in the few tens of MeV range. SN1987A, a supernova that occurred at 51.4 kpc from Earth, provides us with an observational example from which we can extrapolate our expected neutrino signal:

$$N \simeq 4.6 \left( \frac{50 \text{kpc}}{D} \right)^2 \left( \frac{50 \text{kt}}{M} \right),$$  \hspace{1cm} (5)
where $N$ is the approximate number of neutrino interactions expected, $D$ is the distance to the supernova and $M$ is the fiducial mass of the low-energy neutrino detector.

A total of 24 neutrinos from SN1987A were observed by the Kamiokande-II (Japan) [49], IMB (US) [16], and Baksan (USSR) [3] detectors. Present and future neutrino detectors are much more sensitive. For example, Super-Kamiokande (SK) would observe $\sim 230$ neutrino interactions from the same event and a megaton detector, several thousand.

Currently, the distance reach of the global network of neutrino detectors (including SK, LVD and SNO+) is of order $O(100 \, \text{kpc})$. Equation (5) indicates that for a 50 kt detector like Super-Kamiokande the $N \geq 1$ reach is about the distance to M31, $\sim 770 \, \text{kpc}$. Super-Kamiokande requires at least 2 neutrino interactions in coincidence to reject background; consequently the chance of it detecting a SN in M31 on its own is estimated at around $\sim 8\%$.

This reach will gain a factor of $\sim 5$ to $O(1 \, \text{Mpc})$ with the advent of megaton class detectors [30,90,59,11] by the ET era, thus allowing the observation of neutrinos from M31 and M33 [62,7]. A future neutrino detector fiducial mass increase reaching $\sim 5 \, \text{MegaTons}$, the size of the proposed Deep-TITAND, would permit observations at a significantly larger distance, where the $N \geq 1$ reach is about $\sim 8 \, \text{Mpc}$. At this distance the supernova rate estimate can be as large as $1 \, \text{yr}^{-1}$ (see [62] and Fig. 3). It is thus reasonable to expect at least one such event during the lifetime of ET.

Significant uncertainties exist in the modelling of supernovae (see also Section 3.1) and their gravitational wave signature. The sophisticated simulations of the core collapse of massive stars do not robustly lead to the supernova explosion [21]. This indicates that important physics may be lacking from the models; moreover it seems that the electromagnetic observations alone cannot reveal the missing part of the puzzle. Gravitational waves and neutrinos carry important information from the innermost part of the exploding star, on the physical parameters that govern the dynamics (e.g., degree of non-axisymmetry, rotation, magnetic field). Those parameters might be extracted from multimessenger observations. The exact impact of those observations is directly connected to the availability of a comprehensive model and a complete simulation of the core collapse process. A pathfinder effort [74] is currently conducted based on SNEWS (SuperNova Early Warning System) alerts [8] for a nearby supernova. Due to the relatively low event rate and limited reach of both low-energy neutrino and GW detectors for observing core-collapse supernovae, the boost in sensitivity and detection confidence that comes from a multimessenger approach will be a significant positive development of the ET era.

5.2 High-energy neutrinos

The processes leading to the production of high-energy neutrinos are tightly connected with those of high-energy photons. Indeed, three of the sources discussed in Sec. 2 – gamma-ray bursts, soft gamma-ray repeaters, and microquasar flares – have also been identified as potential sources of high-energy neutrinos [57,104]. In this section we will focus our attention on GRBs, complementing the discussion of Sec. 2.4 by considering their neutrino emission.

GRBs are thought to be strong neutrino emitters. The gamma-ray and afterglow radiation are likely to be emitted from relativistic electrons accelerated in shock waves; the same shocks should also accelerate protons. The protons then collide with gamma-ray photons to

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6 Since 1999, 20 core-collapse supernovae have been observed within 10 Mpc.
produce charged pions that decay into neutrinos \( \left( 10^5 - 10^{10} \text{ GeV} \right) \)\(^{146,142,145}\). This scenario was first investigated for the internal shock model \(^{146,102}\), and it has been pointed out that a km-scale neutrino detector would observe at least several tens of events per year \(^{145}\) correlated with GRBs. Many subsequent studies (e.g., \(^{106,4,147}\)) have resulted in a range of different models and predictions that will be tested against the observational data during the coming years.\(^7\)

We consider now in turn the two main classes of GRBs, long and short, starting with the former. As discussed in Sec. 2 observed long GRBs are located at cosmological distances. In the collapsar model (e.g., \(^{81,151}\)), they are associated with the collapse of a massive, rapidly rotating star to a black hole. The instabilities that develop during the collapse may generate gravitational waves \(^{63,66,95}\). Several models, along with estimates of their associated GW strength, were described in Sec. 2.1. Although the GW signature is model-dependent, we can expect a distance reach to order of 1 Gpc with ET under some scenarios.

The extensively studied GRB 080319B provides us with a case study on searching for neutrino emission from long GRBs. GRB 080319B, which had a duration of 66 s, occurred at \( z = 0.937 \) (i.e., at a luminosity distance \( \sim 6 \) Gpc \(^{20,51}\)). It was exceptionally bright, with \( L_{\gamma}^{iso} = 10^{54} \text{ erg} \), compared to \( 10^{53} \text{ erg} \) for typical GRBs. It is expected \( ^{21} \) that such an event would be associated with O(1) neutrino interaction in IceCube in its complete \( \text{km}^3 \) configuration. Scaling down to a typical long GRB at 1 Gpc, we expect a few neutrino events since the decrease in the distance compensates for the lower energy.

High-energy neutrinos could also be emitted from short-hard GRBs \(^{92,18,73,34}\). We recall that the short GRBs are thought to be associated with neutron star—neutron star or neutron star—black hole mergers. The GW signature emitted by such binaries is detectable to typical distances of \( z \sim 2 - 4 \) by ET. There is no widely accepted prediction concerning the flux of high-energy neutrinos.

However, an estimate of the neutrino flux associated with internal shocks (i.e., interactions of \( 10^{16} \) eV cosmic rays with the prompt gamma-rays) can be obtained \(^{92}\) assuming that the efficiency of this process is similar to that of long GRBs. Following the Waxman and Bahcall model \(^{146}\) (which estimates that in optimal conditions about 10% of the burst energy is emitted in the form of \( 10^{14} \) eV neutrinos) and considering standard values for the jet characteristics \(^{92}\) (with burst energy \( \sim 10^{50} \) erg, typical duration 1 s and Lorentz factor \( \sim 30 \)), a source at a distance of 200 Mpc would produce \( \sim 4 \) km\(^-2\) upward muons.

In conclusion, we should expect to see coincident detections of high-energy neutrinos and GWs associated with both long and short GRBs during ET’s lifetime if a km\(^3\) neutrino detector operates concomitantly. Such observations would improve our understanding of the details of astrophysical processes connecting the gravitational collapse/merger of compact objects to black-hole formation as well as to the formation of fireballs.

This conclusion also applies to the low-luminosity GRBs, a subclass of long GRBs with gamma-ray luminosities a few orders of magnitude smaller than those of conventional GRBs (already presented in Sec. 2.1). Low-luminosity GRBs are associated with the lower end of the continuum of sources of long GRBs. Significant emission of high-energy neutrinos is expected for those sources \(^{89,44,144}\).

In addition to the high- and low-luminosity GRB populations, neutrino detectors will provide access to another subclass of GRBs that are largely inaccessible to EM observations. “Failed” gamma-ray bursts are thought to be associated with baryon-rich jets. In the presence of baryons (heavy particles), the jet cannot reach ultra-relativistic velocities. In such

\(^7\) Some of the models have been already excluding thanks to the observations made by AMANDA \(^{125}\).
cases, the relativistic space-time dilation which decreases the density of $\gamma$ photons in the jet does not occur. Over a critical density, photons are annihilated through gamma-gamma interaction. The jet is optically thick: no gamma-ray photons can escape. For this reason, this class of bursts might be more challenging to observe through conventional astronomical telescopes. GWs and high energy neutrinos can be significant sources of information to reveal the properties of these elusive objects.

The observation of late-time radio emission by some type Ic supernovae suggests the existence of such mildly relativistic ($\Gamma \lesssim 5$) jets. The fraction of all core-collapse supernovae with jets could perhaps be as large as $\sim 1$–10%, and the occurrence rate of failed GRBs is estimated to be $\sim 1$–10 yr$^{-1}$ within 30 Mpc. Ando and Beacom find that, for an object at a distance of 30 Mpc producing a jet with kinetic energy of $3 \times 10^{51}$ erg and Lorentz factor of 3, one would expect $\sim 3$ neutrino events for a km$^3$ detector. To our knowledge, there is no specific study providing an estimate of the GW emission by such an object. However, since the progenitor is similar in nature to that of long GRBs, we may expect them to be sources of GWs accessible to ET, hence providing another candidate for multimessenger studies with high-energy neutrinos.

6 Discussion

Interesting results from multimessenger searches using interferometric GW data have already been published. The LIGO and VIRGO detectors have made specific scientific statements for some nearby events; for example, constraining the source type or location of GRB070201 – a short-hard GRB event observed to come from a direction overlapping M31. These detectors are currently taking data near or beyond their initial design sensitivities, with planned upgrades to “advanced” configurations in the next few years. One result is growing interest from the external astrophysics community in multimessenger observations with gravitational waves. The anticipated further improvement in their sensitivity gives us confidence that associations between GWs and their electromagnetic counterparts will be confirmed during the lifetime of the advanced gravitational detectors. Undoubtedly these exciting – albeit somewhat opportunistic – discoveries will have to be followed up via systematic studies with better statistics. This is the clear and fundamental promise of the ET era: the Einstein Telescope has the potential to turn rare discoveries into routine observations, enabling precise measurements we could not carry out before and facilitating population studies of GW sources. In order to fully exploit the scientific benefits offered by multimessenger observations, however, it will be essential that ET operates alongside partner satellites, observatories and telescopes across the entire electromagnetic spectrum – from radio waves to gamma-rays – and neutrino detectors sensitive from low to ultra-high energies.

To conclude, we briefly summarise some of the key astrophysical questions which multimessenger observations in the ET era may address.

- Some models predict that ET’s reach for long GRBs could be as large as $\sim$O(1 Gpc). The gamma-ray emission and afterglow of long GRBs only provide an indirect indication of the nature of the GRB engine. By contrast gravitational waves produced in the immediate vicinity of the central engine, and detected by ET, will for the first time offer a direct probe of its physics. Furthermore ET should be able to decisively test the validity of predictions that a substantial population of under-luminous long GRBs are
found within $\sim O(100 \text{ Mpc})$. ET may also provide insight on the nature of XRFs and their relationship to long GRBs.

– ET should be able to detect of order $O(10^3)$ gravitational wave sirens – coalescing binary neutron star systems – in the redshift range 2 – 4, providing precise estimates of their masses and luminosity distances. Multimessenger observations of a subset of these systems, identified as short duration GRBs, should allow measurement of their redshifts. These data can provide a completely independent way to calibrate the cosmological distance scale and constrain cosmological models – in a manner complementary to other, electromagnetic, cosmological probes.

– During ET’s lifetime we should expect to see coincident detections of high-energy neutrinos and GWs associated with both long and short GRBs, if a km$^3$ neutrino detector operates concurrently. Such observations would improve our understanding of the details of astrophysical processes connecting the gravitational collapse/merger of compact objects to black-hole formation as well as to the formation of fireballs. “Failed” gamma-ray bursts are difficult to observe with conventional astronomical telescopes. GWs and high energy neutrinos can be significant sources of information to reveal the properties of these elusive objects.

– At frequencies of 1-3 kHz ET will be sensitive to GW emissions from giant SGR flares, at a level as low as 0.01% to 1% of the energy content in their EM emission. In the region of 20 – 100 Hz, ET will be able to probe SGR gravitational wave emissions as low as $10^{-7}$ of the total energy budget.

– ET may be able to confirm or refute the existence of the putative high redshift population of IMBHs predicted in some ‘seed’ black hole formation models. These observations may, therefore, help to discriminate between the various scenarios proposed to explain the origin of Ultra-Luminous X-ray binaries.

– More generally ET will provide precise timing and acceptable sky localisation to prompt searches for the associated optical and radio signatures of GW sources, enabling early observations that are traditionally opportunistic and regularly missed today.

– Multi-megaton low-energy neutrino detectors such as Deep-TITAN would permit observation of low energy neutrinos from a supernova at $\sim 8 \text{ Mpc}$. Within this distance the supernova rate could be as large as 1 yr$^{-1}$. It is thus reasonable to expect at least one such event during the lifetime of ET. Multimessenger observations could reveal crucial information from the innermost part of the exploding star, such as the role of rotation and magnetic fields.

While the anticipated benefits of multimessenger observations with ET-class sensitivity are greatly encouraging in themselves, one should not forget about the unexpected. Humanity has never aimed a new kind of telescope at the sky without it revealing surprises, in the form of completely new types of astrophysical objects not imagined before. Multimessenger observations were often the key to disentangling the nature of these surprise discoveries, and we can confidently expect that ET will play a similar role in exploring the new astrophysical frontiers of the next decade.

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