Scientific objectives of Einstein Telescope

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Abstract
The advanced interferometer network will herald a new era in observational astronomy. There is a very strong science case to go beyond the advanced detector network and build detectors that operate in a frequency range from 1 Hz to 10 kHz, with sensitivity a factor 10 better in amplitude. Such detectors will be able to probe a range of topics in nuclear physics, astronomy, cosmology and fundamental physics, providing insights into many unsolved problems in these areas.

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(Some figures may appear in colour only in the online journal)

1. Introduction

Einstein Gravitational-Wave Telescope (ET) is conceived to be a third-generation detector whose conceptual design study was funded by the European Framework Programme FP7. The study completed in July 2011 helped produce a straw-man design of the detector and a summary of the science (both instrumental and astrophysical) that it promises to deliver [1]. The accompanying article by Stefan Hild will discuss the technological challenges and the infrastructure needed for building the ET. In this paper, we will discuss the rationale for going beyond advanced detectors and the huge spectrum of science and sources that the ET has the potential to uncover.

The discussion presented here is the result of a specific study carried out in the context of ET. However, much of it is relevant to an extension of either the advanced detectors or designs alternative to the ET that target a sensitivity window from 1 Hz to 10 kHz, with the best strain sensitivity of $\sim$few $\times\ 10^{-25}\ \mathrm{Hz}^{-1/2}$ in the frequency range of 20–200 Hz. What will the ET observe in this frequency window? Why do we need detectors that are even more sensitive than the advanced detectors? What astrophysical problems can be addressed with the ET? These are the primary questions addressed in this paper.

The ET, for that matter any gravitational-wave (GW) detector, is sensitive to compact objects with time-varying quadrupole moment. Black holes (BHs) and neutron stars (NSs) being the most compact objects, close interactions between them, involving ultra-strong gravitational fields, will produce the most luminous gravitational radiation. ET's frequency range essentially determines the masses of compact objects that it could observe. The largest angular frequency that a BH of mass M produces is roughly[60] $\omega^2 \sim M/R^3$, where R is its size. Taking $R = 2M$, the frequency works out to be $f \sim 1.14$ kHz $(M/10\,M_\odot)^{-1}$. For comparison, the most dominant quasi-normal mode frequency of a $10\,M_\odot$ Schwarzschild BH is 1.19 kHz and that of a Kerr BH (with dimensionless spin of 0.9) is 2.15 kHz. Thus, the frequency range of 1–10^4 Hz gives a mass range of 1–$10^4\,M_\odot$.

It might at first appear that the low-frequency window of 10–20 Hz, where the noise floor could be an order of magnitude or two larger than at 20–200 Hz, has no particular advantage for enhancing the visibility of signals. This is possibly true in the case of sources that sweep past the best part of the detector sensitivity. However, good low-frequency sensitivity does two things. First, opens up a window for observing intermediate mass black holes (IMBHs) [2, 3] with masses in the range 10^3–$10^4\,M_\odot$. There is as yet no conclusive evidence for the existence of IMBH, let alone their binaries. However, there are strong indications that certain ultra-luminous x-ray sources (e.g. HLX-1 in ESO 243–49 [4]) are host to IMBH. If a population of such objects exists and they grow by merger, then, depending on their masses, the ET will be able to explore their dynamics out to $z \sim 6$–15 and study their mass function, redshift distribution and evolution. Second, lower frequencies help improve measurement accuracies of source parameters. Binary systems spend very long periods at lower frequencies, with the time to coalescence from a frequency f rising as $f^{-8/3}$. The long duration over which the sources slowly chirp-up in frequency helps in measuring the parameters of the source very accurately. For instance, in the case of advanced LIGO, the signal-to-noise ratio (SNR) for a binary neutron star (BNS) signal integrated from 10 Hz to 20 Hz is less than 1% of the SNR that accumulates above 20 Hz until merger. Yet, the measurement accuracy of the system's masses is a factor of 2 better if the signal is integrated from 10 Hz instead of 20 Hz. This effect will be even stronger in the case of ET as its lower frequency cutoff could be a factor 10 smaller compared to advanced detectors.

The population of sources in the frequency window from 100 Hz to 10 kHz is also known to be very rich and there are many challenges and opportunities in this frequency region, both in instrument design and astrophysical potential. Quakes in NSs (believed to be the root cause of glitches in radio pulsar observations), giant explosions that occur in magnetars, gravitational collapse and supernovae (SNe), dynamics of accreting NSs, relativistic instabilities in young and accreting NSs are all the potential sources where observations could reveal a wealth of information that is complementary to radio, x-ray or gamma-ray observations.

We will begin the discussion with a brief recap of what we can expect from a network of advanced detectors over the next decade. We will then go on to describe the topology and sensitivity of ET and why the ET has additional advantages over equivalent L-shaped detectors. This is followed by a list of sources that the ET can observe and how that benefits in furthering our knowledge of fundamental physics, cosmology and astrophysics.

2. Advanced GW detectors

Advanced interferometric GW detectors (advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) [5, 6] in the US, advanced Virgo [7] in Italy and Kamioka Gravitational Radiation Antenna (KAGRA) [8] in Japan) will be built and become operational over the next 3–5 years. As discussed by Alan Weinstein in this issue, the global network of advanced

[60] We use a system of units in which the speed of light and gravitational constant are both equal to unity: $c = G = 1$. In this system, the mass, length and time all have the same dimensions, taken, for convenience, to be seconds.

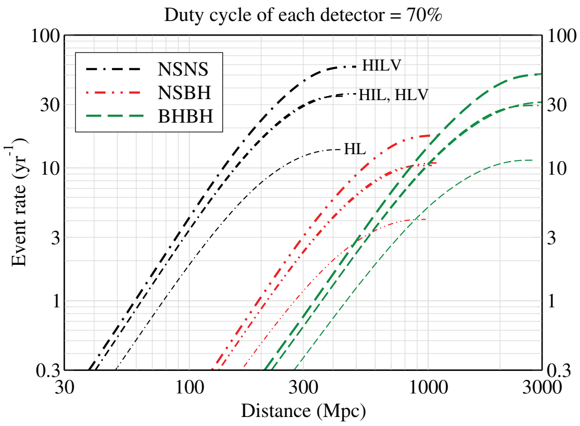

Figure 1. The plot shows the cumulative number of compact binary events expected to be detected by a network within a given distance, for three archetypal compact binaries and four different advanced detector networks. The curves flatten (and stay constant) upon reaching the *horizon distance* of the network, the distance beyond which a network cannot detect signals with the desired SNRs. See the text for further details.

detectors is expected to open the gravitational window for observational astronomy. BNS mergers are the prime candidate sources for advanced detectors. Extrapolation of the galactic BNS population to extragalactic Universe suggests that we may nominally observe one merger event every week [9]. Figure 1 plots the expected number of compact binary mergers detectable within a given volume by the advanced detector network of LIGO and Virgo, for three archetypal compact binaries and four different detector networks.

The various networks considered are: (1) a two-detector network consisting of LIGO Hanford and LIGO Livingston (HL) detectors, (2) two three-detector networks, consisting of HL and either Virgo (HLV) or LIGO India[61] (HIL) and (3) the full four-detector network of three LIGO detectors and Virgo (HILV). NSs are assumed to be 1.4 $M_\odot$ and BH 10 $M_\odot$.

A signal is said to be detectable by a detector network if it produces an SNR of 5 or more in at least two detectors and a network SNR $\geqslant 12$. Note that the criterion used in computing the detection rate here is somewhat different from that used in [9]. In computing the detection rate, we have taken the local merger rate of BNS, neutron star–black hole (NS-BH) and binary black hole (BBH) sources, in a volume of 10^6 Mpc^3, to be 1, 0.03 and 5×10^{-3} year^{-1}, respectively [9], and included a factor of $(1 + z)^{-1}$ to account for the reduction in the rate due to cosmological expansion. The expected detection rate (per year) also takes into account the varying efficiency of the detector as a function of distance, the lifetime of the different networks (assuming a duty cycle of 70% for each detector in a network) and 'redshift' effect of binary masses, by which observed masses are larger by a factor $(1 + z)$ relative to intrinsic masses. The redshift of masses has a significant effect on the reach of the network for BBHs, leading to a 30% increase in the reach and a factor of 2 in the event rate compared to numbers quoted in [9]. The detection rate increases by a factor of 3 as we go from two to three detectors and by little less than a factor of 2 as we go from three to four detectors.

The point at which the various curves level off is the *horizon* of the network—the maximum distance up to which events can be detected in that network. For instance, the reach for BNS sources is about ∼500 Mpc for all networks considered and the expected event rate per year within this volume is 13, 33 and 60 in HL, HIL/HLV and HILV networks, respectively. The

[61] LIGO is currently considering moving one of the Hanford detectors to India. However, the event rates shown here do not depend on whether the third LIGO detector is relocated to India or remains at Hanford.

uncertainty in the expected rate of BNS mergers is so large that the detected number of events could be several per day to once every 2 years. At any rate, the advanced detector network will make the first direct detection of gravitational waves (GWs) in this decade.

The immediate consequence of the first observations (of BNS systems) is to pin down the merger rate to within an order of magnitude. If the actual rate is close to the mode of the distribution of predicted rates, then there will be occasional events with large enough SNR to measure the mass and radius of NSs and constrain their equation of state [10, 11]. The observed population will also give us the mass function of NSs in binary systems, which is important for testing models of compact binary formation and evolution.

Advanced detectors might also verify if compact binaries, in which at least one of the component objects is a NS, and the other either a NS or a BH, are progenitors of short-hard gamma-ray bursts (shGRBs) [12]. The observed rate of shGRBs suggests that their rate could be once per year within $z \sim 0.5$ [13]. The reach of the network can be significantly larger for a search that is focussed around an event like a GRB than it is for a 'blind' search in the entire data set. This is largely because the duration over which the search needs to be carried out will be seconds, instead of years, and so it is possible to detect events with a network SNR of about 6, instead of 12 [14]. In the case of GRBs, the reach for BNS is about 1 Gpc and for NH-BS is $z \simeq 0.4$. Thus, within 5 years of operation, an advanced detector network should confirm whether BNS or NS-BH mergers are progenitors of shGRBs. However, it is unlikely that the advanced network will be able to carry out a detailed study of different types of GRBs and the relationship between their duration, spectra and demographics.

The advanced network has a great discovery potential. For instance, they could observe, for the first time, populations of NS-BH binaries and BBHs. Although it is largely expected that radio, x-ray and gamma-ray observations could soon discover a NS-BH system, the observation of a stellar-mass BBH is most likely to come from GW observations. If the rate of BBH mergers in the Universe is $\sim 5 \times 10^{-9}$ year^{-1} Mpc^{-3}, then we might see as many as $\sim$60 events per year (see figure 1). At the lower end of the merger rate (10^{-10} year^{-1} Mpc^{-3}), the observed number of signals could still be $\sim$1 year^{-1}. Some authors predict far higher rates [15], in which case the advanced detector network will routinely observe many bright BH mergers. Whatever the rate, the advanced GW network is expected to detect first BBHs and constrain astrophysical models of their formation and evolution, as also indirectly constraining the metallicity of gas as a function of redshift [16].

Advanced detectors could also observe weak galactic sources, such as NSs with mountains that have an effective ellipticity of [1] $\epsilon \sim 10^{-9}$–10^{-7} (with spin frequencies in the range 0.1–1 kHz), an occasional supernova and other galactic sources, if they occur in sufficient strength and numbers. Advanced detectors could provide a handful of sources with moderately high SNR ($\gtrsim$50) events, but they are unlikely to yield a great number of sources, nor sources with a very large SNR—essential requisites for precision astronomy. To do so would necessitate a detector that has improved low-frequency sensitivity and greater amplitude sensitivity, i.e. a factor of 10 in both.

3. Beyond the advanced detector network

The rich variety of sources (rich, both in terms of the types of sources and their spectra) that a GW detector promises to observe opens the possibility of using the GW window for furthering our understanding of fundamental physics, cosmology and astrophysics. Detailed study of individual sources, e.g., NS cores, BH quasi-normal modes, is only possible if the SNR is in excess of $\sim$50. The same is true for strong-field tests of gravity, which would benefit from loud events with an SNR $\gg 50$.

However, loud events are not the only reason why we need to go beyond the advanced network. Let us look at an example why this is so. Compact binaries are standard sirens that could be used to precisely measure the luminosity distance to a source without the aid of any cosmic distance ladder. Additionally, if one can also identify their host galaxies and measure their redshifts, then one could infer the cosmological parameters. For accurate measurement of cosmological parameters, it is not sufficient to have a few loud sources. This is because gravitational weak lensing of cosmological sources could bias the luminosity distance of a source, the systematic error being as large as 5% at a redshift of $z = 1$. It is not possible to correct for such errors [17], but it is possible to mitigate the effect of weak lensing if the number of sources is ∼400. Since gravitational lensing can cause the distance to be under- or overestimated, the availability of a large number of sources helps in statistically nullifying the bias.

A network of detectors with ten times better amplitude sensitivity and a factor 10 reduction in the low-frequency seismic floor compared to advanced detectors can help explore stellar-mass BHs when the Universe was still assembling its first galaxies, discover binaries consisting of IMBHs out to a redshift of $z \simeq 6$ [2, 3], detect every shGRB within a redshift of $z \simeq 4$ assuming that BNS or NS-BH are their progenitors and observe a variety of weaker galactic sources, such as NSs with ellipticity larger than few $\times 10^{-8}$–few $\times 10^{-10}$, glitching pulsars in the Milky Way that deposit more than $10^{-12} M_\odot$ of rotational energy in GW [11], magnetars within Andromeda that emit $\sim 10^{-8} M_\odot$ in GW [18] and core-collapse SNe that occur within 2–4 Mpc. Such a detector is equivalent to going from a 1 m class optical telescope to a 100 m class telescope but also extending the observation to infrared frequencies. The massive scientific potential makes a very compelling case to go beyond the advanced detector network.

While a single-site third-generation detector might achieve some of the scientific goals discussed in this review, any problem that necessitates a knowledge of the position of the source on the sky and its distance from the Earth will require a network of detectors. For example, while strong-field tests of general relativity (GR) could be performed with events detected in a single-site ET, measurement of cosmological parameters would require a network of detectors. Likewise, testing the propagation speed of GWs relative to electromagnetic waves from a supernova would not require a network of detectors; optical identification of the supernova and coincident detection of GWs in a single ET could confirm if gravitons are massive. One should also be mindful of the covariance between various parameters of a source before deciding if it is safe to draw scientific conclusions based on observations in a single-site ET.

The rest of this section is organized as follows. We will first take a look at the topology of ET and its advantages over the conventional L-shape configuration. We will then review ET's sensitivity and its ability to detect compact binaries and other sources. We will conclude with the data-analysis challenges posed by the ET and effort to tackle signal discrimination and measurement problems.

3.1. Topology

The ET design study team concluded that a triangular topology is the optimal strategy to achieve the sensitivity goal of a third-generation detector [19, 20]. The arms of the triangle are each used twice to form three Michelson interferometers as shown in figure 2. Each V-shaped detector in the array has $L = 10$ km arms, with an opening angle of $\alpha = 60^\circ$ and the detectors are rotated relative to each other by an angle of 120°. One way to characterize the topology is to look at the antenna pattern of the network. The pattern functions F_+ and $F_\times$ of each detector in the ET array are identical to that of an L-shaped detector with an arm length

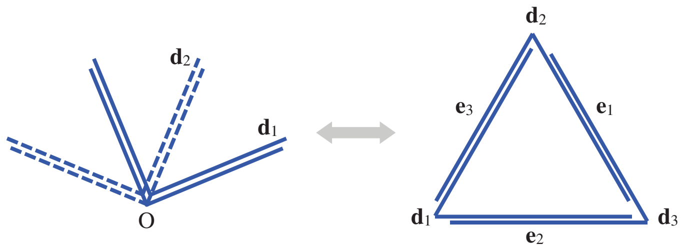

Figure 2. Triangular topology of ET, in which each arm of length L is used twice to form three detectors with a 60° opening angle, is equivalent to that of two L-shaped detectors of length $3L/4$, whose arms house two detectors each [19]. (Arms are drawn to scale.)

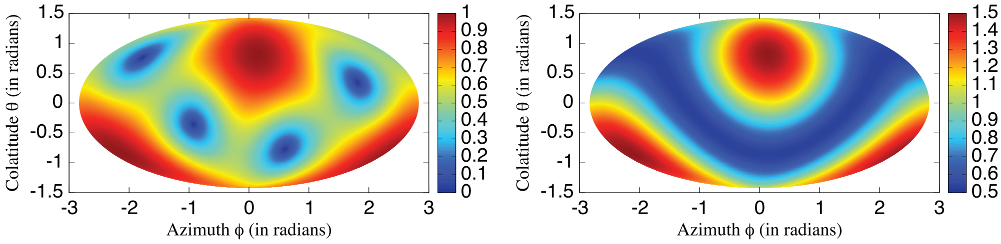

Figure 3. Antenna pattern of the Virgo interferometer (left) compared to that of the ET (right) located at the same site.

$L\sin^2\alpha = 7.5$ km. Figure 3 compares the quadrature sum $(F_+^2 + F_\times^2)^{1/2}$ of Virgo (which is an L-shaped interferometer) to the *joint* antenna pattern of the three ET interferometers located at the same site as Virgo. ET has essentially no blind spots on the sky [1, 21]. In a coordinate system in which the three arms of ET lie in the xy plane, the array is insensitive to the source's azimuth angle.

The three detectors of the ET array are equivalent, in terms of the antenna pattern and sensitivity, to two L-shaped detectors whose arms are three-quarters in length and rotated relative to each other by an angle of 45° [19]. The ET will have fewer end stations than the design with two L-shapes. ET's three interferometers allow the construction of a *null* data stream [22] that is completely devoid of GWs [19, 21], as do a pair of L-shaped detectors sharing the two arms. Finally, each pair of ET interferometers can solve for the plus and cross polarizations.

3.2. Null data stream and polarization of gravitational radiation

For a triangular detector (for that matter for any closed topology), the sum of the responses contains only the sum of the background noise from the different interferometers and no GW signal [19]. Let us denote by $h^A(t)$, $A = 1, 2, 3$, the response functions of the three interferometers in the ET array. By definition

$$h^A(t) = F_+^A h_+ + F_\times^A h_\times,$$

where h_+ and $h_\times$ are the plus and cross polarizations of the incident signal and F_+^A and $F_\times^A$ are the plus and cross antenna pattern functions. The plus and cross pattern functions are the inner products of the detector tensors d_A^{ij} and the polarization tensors e_{ij}^+ and $e_{ij}^\times$, respectively:

$$F_+^A = d_A^{ij} e_{ij}^+, \quad F_\times^A = d_A^{ij} e_{ij}^\times.$$

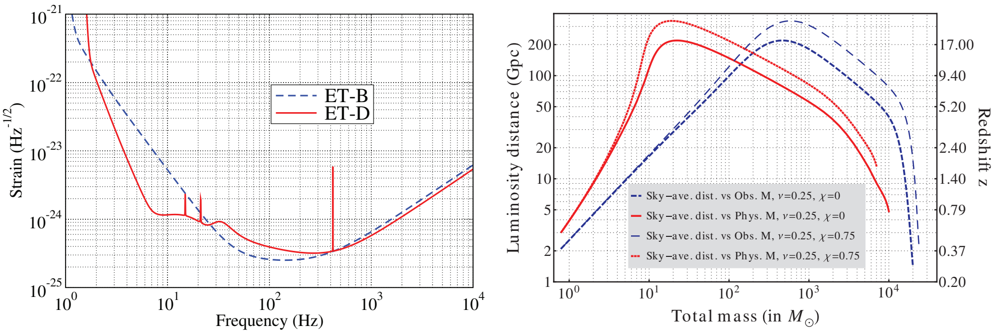

Figure 4. (Left) ET's strain sensitivity for two optical configurations: ET-B [24] and ET-D [25]. (Right) ET-B's distance reach for compact binary mergers as a function of the observed total mass (blue dashed curves) and intrinsic total mass (red solid curves) for non-spinning binaries (lower curves) and binaries with dimensionless spins of 0.75 (upper curves).

Since the detector tensors are given by

$$d_1^{ij} = \tfrac{1}{2}\left(\mathbf{e}_2^i\mathbf{e}_3^j - \mathbf{e}_3^i\mathbf{e}_2^j\right), \quad d_2^{ij} = \tfrac{1}{2}\left(\mathbf{e}_3^i\mathbf{e}_1^j - \mathbf{e}_1^i\mathbf{e}_3^j\right), \quad d_3^{ij} = \tfrac{1}{2}\left(\mathbf{e}_1^i\mathbf{e}_2^j - \mathbf{e}_2^i\mathbf{e}_1^j\right),$$

where $\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$ are the unit vectors along the arms of the detectors as in figure 2. It is easy to see that $\sum_A h^A = 0$, irrespective of the direction in which the radiation is incident or its polarization. Thus, the sum of the detector outputs $\sum_A x^A(t) = \sum_A [n^A(t) + h^A(t)] = \sum_A n^A(t)$ contains only the sum of the three noise backgrounds. This is the *null data stream,* which is completely devoid of any GWs. It is like the dark-current of an optical telescope. It can be used to veto spurious events [22], to estimate the noise spectral density of the detectors (which is critical for a signal-dominated instrument such as the ET) and to detect a stochastic GW background that may be buried in the data streams [21].

The ET has also the ability to resolve the wave's two polarization states. It is straightforward to invert ET's response functions $h^A = F_+^A h_+ + F_\times^A h_\times$, $A = 1, 2, 3$, to solve for the signal's two polarizations. We would not have direct access to h^A but only to detector outputs $x^A = h^A + n^A$ whose linear combinations could be used to get estimates of the two polarizations.

For a pair of misaligned L-shaped detectors (i.e. detectors that are not rotated relative to each other by multiples of $\pi/2$ rad), there is no linear combination of their responses that gives a null data stream. Nevertheless, as noted before, two interferometers sharing common arms (as in the LIGO Hanford setup) can be used to construct a sky-independent null stream. Even so, a triangular topology can provide the same information and yet incur lower infrastructure costs. If one is going to build two pairs of L-shaped detectors, then it makes sense to build them at geographically widely separated sites, as that would help in obtaining at least partial information about source position, which would obviously increase the science reach over a single-site ET.

3.3. ET's sensitivity

Figure 4(left) shows the sensitivity of each V-shaped detector in the ET, for two different optical configurations. The red solid curve, labeled ET-D, shows the sensitivity of a xylophone configuration [23] in which two interferometers are installed in each V of the triangle: one that has good high-frequency sensitivity and the other with good low-frequency sensitivity. The blue dashed curve, labeled ET-B, shows the best possible sensitivity for a single detector in each

V of the triangle. Compared to a single Michelson interferometer, the xylophone configuration improves the sensitivity by a factor of 2–10 in the frequency range 6–10 Hz. This improved low-frequency sensitivity makes ET-D a lot more attractive as it greatly enhances the lifetime of stellar-mass binaries in band and also makes it possible to observe IMBH binaries in the mass range 100–$10^3\,M_\odot$, at redshifts up to $z \sim 20$, depending on their total mass, compared to ET-B's reach of $z \sim 5$–10.

In figure 4(right), we plot the distance reach of ET-B for compact binary signals as a function of the source's total mass [1]. More precisely, what is plotted is the distance at which a source with random orientation, polarization and location on the sky would, on average, produce an SNR of 8. Blue dashed curves give the reach as a function of the *observed mass* of the source. The reach is shown for two archetypal systems: the long-dashed curve corresponds to systems with large spins, while the short-dashed curve is the reach for non-spinning systems. Red solid curves correspond to the reach as a function of the *intrinsic mass* of the source. They are obtained by shifting each point on the blue curve to the left by a factor $(1 + z)$ to account for the 'redshift' of the system's total mass.

3.4. ET mock data challenges

Extrapolating the local rate of expected compact binary coalescences to the distant Universe, a third-generation detector like the ET should detect millions of merging events per year [26]. At any time, hundreds of overlapping signals could be present in the sensitive band of the detector. The number and variety of sources detected depends a lot on the nature of data-analysis algorithms used in discriminating one signal from the other. The ET poses real challenges in signal discrimination and accurate measurement of the source parameters; the latter is critical if the ET were to be used for precision cosmography and novel tests of GR. The problem has begun to be addressed via ET mock data challenges.

The first challenge, concluded recently [21], tackled a limited set of questions of how effective are the pipelines currently used in GW data analysis in discriminating overlapping signals in the ET and whether the population of sources causes a confusion background degrading the detector sensitivity at lower frequencies. We found that the population of overlapping sources in ET's sensitive band do not form a confusion background obscuring foreground sources. However, the presence of the population, its spectrum and gross properties of the underlying sources can be inferred by cross-correlating the three ET data streams. The `iHOPE` pipeline [27], currently used by the LIGO-Virgo collaboration to detect compact binary coalescences, is already very effective in discriminating overlapping sources. Indeed, we found that `iHOPE`'s detection efficiency, at a given redshift, was about ~20% smaller than that of an ideal coherent search pipeline. Equivalently, the redshift reach of `iHOPE` at 50% efficiency is 10% smaller than an ideal search pipeline. This is expected as `iHOPE` is designed for coincidence analysis and does not take the full advantage of the signal coherence in a detector network. Most interestingly, we found that the null stream is a very powerful tool to identify stochastic GW backgrounds [21]. The residual formed by subtracting the power spectral densities of each detector from that of the null stream clearly showed the presence of the background compact binary population.

3.5. Measuring the intrinsic masses of a binary

It is well known that GW interferometers can measure the total mass and mass ratio of binaries to phenomenal accuracies [28]. For sources at cosmological distances, the expansion of the Universe causes the observed frequencies to be redshifted and so our detectors measure 'redshifted' masses, not the intrinsic masses. The observed mass is larger than the intrinsic mass by $(1 + z) : M_{\rm obs} = M_{\rm int}(1 + z)$. To infer the intrinsic mass, it is necessary to know the source's cosmological redshift. It might not always be possible to identify the host galaxy and directly measure its redshift, either because the source is not well localized on the sky or because the host galaxy is too far away. Hence, one is faced with the problem of having to infer the source's redshift from the luminosity distance.

Compact binary signals are standard sirens and our detectors can directly measure the source's luminosity distance $D_{\rm L}$, which, together with a cosmological model $D_{\rm L}(z;\ \Omega_\Lambda,\ \Omega_{\rm M},\ w,\ \ldots)$, can, in principle, give the source's redshift. However, the luminosity distance is not measured very accurately due to its strong correlation with the source's orientation and polarization. For sources with an SNR of 10, the ET can measure the distance to within 30%. This means that the source's inferred redshift will be uncertain by a similar factor. Therefore, the error in the determination of the intrinsic masses of a binary will be dominated by the uncertainty in the measurement of the luminosity distance. Even so, the ET should be able to measure the masses of most binaries to within a factor of 2—an important factor in some of the scientific objectives of ET[62].

4. ET's science objectives

The goal of advanced detectors is to make the first detection of GWs and establish the field of gravitational astronomy. Third-generation detectors will be sensitive to a greater variety of sources, sources at cosmological distances, signals with large SNRs and so on. Consequently, the ET has a very impressive science potential and it will not be possible to cover every topic in great detail. We will, therefore, highlight an example each from cosmology, fundamental physics, nuclear physics and astrophysics and refer the reader to the ET design study document for further details [1].

4.1. Cosmology: exploring BH seeds

The origin and evolution of BHs that seem to populate galactic cores is one of the unsolved problems in modern cosmology. Seeds of supermassive BHs might have been initially very small (hundreds to thousands of $M_\odot$) and grew by accretion of gas and merger with other BHs or perhaps they were already massive when they formed and have undergone few mergers. Current observations are insufficient to pin down even the basic questions: when did the first BHs form, what was the spectrum of their masses, how did they grow, and so on. The ET should be able to provide answers to some of these questions and constrain models of BH formation and growth in the early history of the Universe [2, 3]. An IMBH binary of intrinsic total mass of $500\,M_\odot$ at $z = 2$ will appear in the ET as a $1.5 \times 10^3\,M_\odot$ binary, lasting for about 14 s from 1 Hz until merger. It will have an SNR of 120 and 490 in ET-B and ET-D, respectively. The same system will appear twice as massive at $z = 5$ and produces an SNR of 28 and 190 in ET-B and ET-D, respectively.

The ET has its best reach for stellar-mass BBHs. Systems with their total mass in the range 10–200 $M_\odot$ can be observed in both ET-B and ET-D at the redshift range of 9.5–17 (cf, Figure 4(right)). IMBH binaries of mass 100–10^3 $M_\odot$ can be observed in the redshift range $z \sim$ 5–10 in ET-B and up to redshift of 20 in ET-D.

[62] Note that ET's test of GR, which requires accurate measurement of the system's masses and spins, will not suffer from the redshift-induced errors as they test the orbital evolution of the source and are agnostic to whether the masses are intrinsic or redshifted.

Moreover, the ET should be able to measure their total mass to an accuracy of at least 50%, even after accounting for the error introduced by the conversion of the luminosity distance to redshift that is needed to infer the intrinsic mass from the observed mass. Therefore, the ET could confirm or rule out hierarchical models [29], according to which seed BHs are IMBHs, which grow by accreting gas and merging with other BHs. The ET will carry out a census of the BH population in the mass range $[10,\ 10^3]\,M_\odot$ throughout the Universe and study their evolution as a function of redshift. If IMBHs form a significant population of seeds, the ET is arguably the best instrument to study them [2].

4.2. Fundamental physics: testing gravity with BHs

Nearly a hundred years after its formulation, GR continues to be the preferred theory of gravity. However, the theory is yet to be tested in strong gravitational fields that occur in the vicinity of BH horizons. Gravitational wave observations of compact binaries could facilitate many such tests [30–35]. A new Bayesian approach [36] to testing the post-Newtonian formula for the phasing of GWs, which is known to seven orders in perturbation theory [37–39] beyond the quadrupole formula, has shown that such tests should already be possible with advanced detectors. A 10% deviation in the 'tail effect' [40, 41], an effect that accounts for scattering of GWs off the curved geometry in the vicinity of the binary, from GR would be easily discernible with a catalog of just 15 BNSs observed with advanced detectors. The ET will be able to push this limit by several orders of magnitude with the millions of systems that it could observe.

In addition to the inspiral phase, it should also be possible to use the merger phase of BBHs to test strong-field predictions of GR. The coalescence of a pair of BHs in a binary results in a single BH that is initially highly deformed. Deformed BHs emit gravitational radiation that consists of a superposition of, in principle, an infinitely large number of exponentially damped sinusoidal waves, called *quasi-normal modes* [42]. The no-hair theorem implies that the mode frequencies and time constants of an astronomical BH should all be determined by just two parameters: BH's mass and its spin magnitude. Observation of quasi-normal modes consistent with this prediction would provide a smoking gun evidence of the presence of BHs, as no other body will have such a unique spectrum of modes [43]. Furthermore, by resolving two or more quasi-normal modes, it might be possible to test strong-field predictions of GR [43]. For instance, it is possible, in principle, to measure the system's total mass before and after merger and test if the mass lost to gravitational radiation is as predicted by GR.

Until now such tests have largely remained speculative as no one knew the spectrum of modes that would be excited in a newly formed BH. Recent work [44–46] used numerical simulations of non-spinning BH binaries for an in-depth investigation of which modes are excited and what their amplitudes are. The study showed that the amplitude of the different modes excited in the process of merger depend on the mass ratio of the progenitor binary and that it will be possible to infer the masses of the component stars that merged to form a BH [45]. It will be interesting to see if a progenitor binary's component spins can also be measured from a knowledge of the amplitude of various modes. To test GR using quasi-normal modes, a Bayesian model selection approach has now been developed [47]. A preliminary study carried out using this approach shows that the ET will be able to detect 6% or more departure from GR of the frequency of the dominant quasi-normal mode excited during the merger of a pair of IMBHs at $z = 1$. Future work covering the full spectrum of the normal modes and using a population of detected events, instead of just one event, is necessary to judge how good such tests are.

4.3. Cosmography: measuring the Universe with standard sirens

One of the most spectacular aspects of compact binary signals is that their amplitude is completely determined by GR, without the need for any complicated astrophysical modeling of their environments. Moreover, imprinted in the evolution of their phase is the absolute luminosity of the source. Our detectors can, therefore, measure both the apparent luminosity and the absolute luminosity of a source as they are related to the signal's amplitude and the rate at which the signal's frequency changes, respectively. This means that compact binaries are *standard sirens*[63] and it would be possible to measure the luminosity distance to their host galaxies without any additional calibrators of distance [48].

The availability of a standard siren immediately raises the possibility of their application in cosmography [49, 50]. However, two hurdles have to be overcome for a successful use of these sirens. First, it is necessary to measure the redshift of host galaxies, and second, it is imperative to control the bias in the luminosity distance arising from weak gravitational lensing of cosmological sources. Both of these have been addressed in the context of ET and it has been shown that coincident observation of shGRBs and GWs could be used to simultaneously measure the redshift and luminosity distance. With about 500 shGRBs, which the ET could observe over 5 years, it would be possible to infer the dark-energy equation of the state parameter w to within a percent or two [26]. Moreover, the tidal effects in NSs could facilitate a direct measurement of the intrinsic masses and hence decipher the source's redshift [51]. This is currently being explored and could greatly enhance ET's capability to measure cosmological parameters, as one can use the entire BNS population instead of a subset observed in coincidence with shGRBs.

Del Pozzo has recently studied [52] a statistical approach, proposed originally by Schutz [48], to measure the luminosity distance–redshift relation using a population of BBHs. He has shown that such a population observed with advanced detectors could determine the Hubble constant to within a few percent. This is a very encouraging result as the ET would observe millions of BBHs and such a large population can be used to measure not just the Hubble constant but other cosmological parameters. A detailed study is needed to assess ET's ability to measure cosmological parameters with BBHs.

4.4. Nuclear physics: probing NS cores

NS cores are laboratories of extreme conditions of density, gravity and magnetic fields (for reviews on NSs and their dynamics see [53, 54, 11]). The structure and composition of NS cores have largely remained unresolved even half-century after pulsars were first discovered. Their cores could be host to unknown physics and might be composed of quark–gluon plasma, hyperons or other exotica [53, 54]. Understanding the equation of state of NSs and the structure and composition of their cores could provide deeper insights into the fundamental nuclear physics, complimentary to heavy-ion-collision experiments [55].

The crust–core interaction in NSs involve vast amount of energy that could generate transient bursts of GW. Such bursts would be observed in the ET if the energy involved is $\gtrsim 10^{-12}\,M_\odot$ and the source is within the Milky Way, or if the energy is $\gtrsim 10^{-8}\,M_\odot$ and the source is not farther than the Andromeda galaxy. Transient phenomena observed with radio, x-ray and gamma-ray telescopes require that NSs are frequently converting such vast amount of energy into electromagnetic waves. For example, sudden decrease in the rotation periods of NSs, the so-called glitches [56], in radio pulsars are believed to be caused by the exchange of energy between the differentially rotating core and crust. Glitches in the Vela pulsar

[63] GW signals are referred to as *sirens,* as opposed to *candles,* due to their close analogy with audio.

are quite frequent, occurring once every few years. The largest of the glitches could involve $10^{-12} M_\odot$. Similarly, giant explosions in highly magnetized NSs, the so-called magnetars [57] with magnetic fields of $\sim 10^{15}$ G, require that isotropic emissions of $\sim 10^{46}$ erg could be involved.

Such star quakes might lead to normal mode oscillations of NS cores, resulting in characteristic oscillation modes. A wide range of different modes are possible, their frequencies and damping times depending on the mass and radius of the star [58]. The nature of the modes depends on the restoring force in play and these could be fundamental- or f-modes, g-modes, p-modes and so on [58]. By observing a particular mode, it should be possible to solve for the star's mass and radius. In turn, the relationship between the mass and the radius of a star depends almost uniquely on the equation of state of the star, with little degeneracy amongst different equations of state. Thus, detection and identification of NS normal modes could provide invaluable insight into NSs.

More recently, several groups have pointed out that the inspiral phase in the coalescence of BNS systems could also be used to measure the equation of state of NSs [59, 60, 10, 11, 61]. It might actually be possible to do this in two different ways. The finite size of NSs induces a post-Newtonian correction to the phasing of GWs, called tidal terms, which first occur at the order $(v/c)^{10}$ beyond the quadrupole approximation [59]. Currently, the first two tidal terms are known and should be adequate for deciphering the equation of state. In addition to the secular post-Newtonian tidal effect, the merger of NSs results in an unstable bar-like structure that spins at a frequency of 1.5 kHz and could last for tens of milliseconds [11]. The precise nature of the bar-mode instability and the spectrum of emitted radiation depends on the equation of state of NSs, which the ET could decipher from events that occur within 100 Mpc.

4.5. Astrophysics: catching SNe in their act

First, GW detectors, resonant bar antennas, were built solely to detect GWs from SNe. They are still sought after by current GW detectors due to the immense insight they could provide about the phenomenon [62]. It is expected that the gravitational collapse and the ensuing explosion can be fully understood only by studying the deep interiors of the proto-NS that was formed in the process, which is inaccessible to electromagnetic observations. Modeling SNe involves inputs from almost all branches of physics and current simulations of the process are far from complete [63]. Most of these models predict that the collapse could be quite non-axisymmetric and SNe could convert $\sim 10^{-7}$–$10^{-8} M_\odot$ into a burst of gravitational radiation in the frequency range of 200–1000 Hz that lasts for tens of milliseconds [63].

Imprint in the gravitational radiation emitted during a SN is the dynamics of the SN engine of a dying massive star. The emitted radiation could place strong constraints on the SN mechanism. Advanced interferometers should be able to observe an event occurring in the Milky Way or the Magellanic Clouds. However, even the most optimistic estimates predict no more than a few events per century. Thanks to a number of starburst galaxies, the rate increases to a few per decade within a distance of about 5 Mpc [64, 65], while ET's distance reach to SNe is about 2–4 Mpc. Therefore, the ET may observe some SNe during its lifetime and would have the ability to provide strong hints for a particular SN mechanism or evidence against another—crucial astrophysics information that is unlikely to be attainable in other ways.

SNe are conceivably the most interesting multi-messenger sources that could be observed using optical, radio, x-ray and gamma-ray telescopes, neutrino detectors and GW interferometers. Transient astronomy, currently under vigorous development, will enable frequent all-sky surveys of transient phenomena and will regularly detect SNe in the nearby universe. On a timescale similar to the ET, megaton-class water Čerenkov neutrino detectors could be in operation with a distance reach of ∼5 Mpc [66]. Coincident observation of SNe in neutrino, optical and GW windows will provide astrophysical information that is critical to understanding a range of phenomena associated with SNe: stellar collapse, core-collapse SNe, formation of BHs and NSs by gravitational collapse, gamma-ray bursts, etc. However, the astrophysics and physics information provided by GWs observed from a core-collapse SNe with the ET goes beyond this as the emitted radiation carries information on the high-density nuclear equation of state, explosion asymmetries and NS kicks, and can help uncover rare events, such as the accretion-induced collapse of a white dwarf to a NS, or silent SNe that have very weak electromagnetic signatures.

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