Einstein Telescope: Science Case, Design Study and Feasibility Report

August 2020

Executive Summary

The Einstein Telescope (ET) is a planned European 3rd Generation Gravitational Wave (GW) Observatory, a new research infrastructure designed to observe the entire Universe using gravitational waves. ET will be a multi-interferometer observatory covering the whole gravitational wave spectrum observable from Earth. This document provides a summary of the science case for ET, the design and feasibility of the required infrastructure, and the design study of the ET detectors. For a more extensive treatment of the same topics please see the ET Design Report Update 2020, available at: `https://apps.et-gw.eu/tds/?content=3&r=16984`.

The LIGO and Virgo detectors have reported confirmed detections of 10 black hole binaries (BBH), and one binary neutron star system (BNS) seen in coincidence with a Gamma ray burst (GRB), observed in the first two joint observation runs O1 and O2. Further GW candidates have been detected at an average rate of approximately one per week during the latest observing run O3. Recent publications based on O3 data have already confirmed another BNS observation, and reported interesting physical effects associated with two other BBH events. Additional important O3 detections are still to be announced. For the next decade, the scientific program of the network of the LIGO, Virgo and KAGRA detectors foresees two more data taking periods (O4 in [2022/2023] and O5 in [2025/2026]), alternating with periods of detector upgrades, until $\sim$ 2026 - 2027. During this period, the detector sensitivity will increase by up to a factor $\sim 3-5$ for Virgo and ~ 3 for LIGO, i.e. about a factor of two beyond their design sensitivities. The Japanese detector KAGRA joined the network in April 2020 and LIGO India will be operational around 2025. Concrete plans for the period after 2027 have not yet been made. However, it is likely that the three LIGO detectors together with Virgo and KAGRA will be operating until the end of the next decade.

The current infrastructures will then have reached physical limitations, both in terms of durability and performance, and hence will not allow further significant sensitivity improvements. A new, third generation of Earth-based detectors will be needed. The Virgo and LIGO infrastructures initially carried the first generation (1G) of GW detectors, and now host the upgraded second-generation (2G) detectors Advanced Virgo and Advanced LIGO. The Einstein Telescope will be a new infrastructure, which will host a third generation (3G) observatory. A similar effort is being pursued in the US (Cosmic Explorer). After a design and preparatory phase, the Einstein Telescope can be constructed between 2026 and 2035 and then remain in operation for a period of 50 years.

The instrument

ET will improve the sensitivity by an order of magnitude with respect to the design sensitivity of Advanced Virgo and Advanced LIGO and extend the observation band towards lower frequencies, i.e. down to about 3 Hz compared to $\sim$ 10 Hz for Virgo. ET will be based on the same basic concept demonstrated in the framework of LIGO and Virgo: a modified Michelson interferometer, with Fabry-Perot cavities in the arms and the techniques of power recycling and signal recycling. However, ET's ambitious sensitivity target, in particular at low frequencies, is based on several technology innovations. Specific ET design concepts are:

Triangle ET will be composed of three nested detectors in a configuration of an equilateral triangle, pair-wise sharing a 10 km long tunnel. With a minimum of tunnelling, this configuration will enable ET to resolve the GW polarization, provide a null stream and allow for continuous operation during maintenance.

10 km The ET detectors will have 10 km long arms, to increase the signal produced by the GWs. This change will provide a factor of about three improvement compared to Virgo (with 3 km long arms) with respect to virtually all of the sensitivity-limiting noises.

Xylophone Each of the three ET detectors will be composed of a pair of complementary interferometers, one with a peak sensitivity at low frequencies and the other with a sensitivity optimised for higher frequencies. The reason is to separate the challenges related to the use of high power stored in the arms (needed to reduce the photon shot noise) such as thermal and radiation pressure effects, from those related to achieving the targeted low-frequency sensitivity (limited by Brownian noise, quantum back-action noise and radiation pressure driven control noise). The low-power detector (ET-LF), operating at a temperature of 10-20 K, will be optimised for low frequency gravitational wave sources and the high-power detector (ET-HF), operating at room temperature, will work at high frequencies.

Underground operation In order to reduce the impact of seismic noise and gravity gradient noise induced by seismic waves and compression waves of the surrounding air, ET will be built underground. The underground operation will allow to extend the frequency band of the observatory down to a few Hz. The three 10 km long tunnels, each having an inner diameter of 6.5 m and containing 4 vacuum pipes, and the caverns containing the large vacuum tanks, will be excavated using well-established tunneling and underground excavation techniques. Besides the main caverns at the vertices of the triangle, several auxiliary caverns will host further interferometer components.

The site

One of the consequences of the extension of the observation band towards lower frequencies is that environmental disturbances and therefore the quality of the observatory location play an increasingly important role. A strong reduction of environmental noise is achieved by placing the detectors in an underground location, provided that a suitable site is chosen. The key evaluation criteria for the site selection for the Einstein Telescope include: impact on infrastructure lifetime, observatory sensitivity, observatory operation and duty cycle, site-quality preservation, construction cost, and socio-economic impact of the observatory. Two candidate sites have been identified for a detailed site-characterization: one in the north of Lula in Sardinia, and one in the Meuse-Rhine Euroregion.

The technologies

The ET design is based on well proven and experimentally tested concepts. However, to achieve the ambitious sensitivity goal of the Einstein Telescope it will be necessary to exploit many state-of-the-art technologies and drive them to their physical limits. The Einstein Telescope will incorporate the technologies from the Advanced LIGO and Virgo detectors (ultra-sensitive optical interferometry, complex active and passive seismic isolation systems and injection of non-classical 'squeezed' light) as well as from upgrades envisaged for the Advanced Detectors (cryogenic mirrors and frequency-dependent squeezing). The infrastructure is designed to accommodate several technology upgrades during the 50 years of operation.

Cryogenic optics will be tested in specific testbenches and integrated prototypes within the ET consortium. In addition, important experience will be gained from the operation of the Japanese project KAGRA, which already uses cryotechnology. Frequency-dependent squeezing will be tested in upgraded versions of Virgo and LIGO. Specific technologies implemented in ET are the following:

Seismic isolation and Suspensions Seismic isolation and suspension systems are needed to isolate the mirrors from the seismic motion of the ground. ET is aiming at a lower cut-off frequency than the 2nd detector generation. The baseline for ET consists of using a longer Virgo-style Superattenuator. An increased length (17 m) allows to reduce the normal mode frequencies and to push the ‘seismic wall’ down to ~ 2 Hz. A possible alternative to be investigated via a dedicated research and development program could be coupling a Superattenuator to an inertial platform actively controlled in six degrees of freedom.

Materials for mirrors and suspensions Monolithic suspensions, i.e. from the same material as the mirrors, will be used in the cryogenic and in the room-temperature interferometers of ET for managing suspension thermal noise. The HF interferometer will use special-grade fused silica mirrors and suspensions, as used in GEO 600, Advanced Virgo and Advanced LIGO. The ET-LF interferometer will use ultra-pure crystalline silicon. The KAGRA detector currently uses Sapphire as a cryogenic material, providing a valuable in-situ test of an alternative material.

Vacuum To keep the residual refractive index fluctuations low enough, the 10 km optical path between the mirror test masses must be evacuated. The residual gas composition will be dominated by hydrogen, followd by water and other gases; we will keep the total residual pressure below 10^{-10} mbar, which corresponds to a strain noise level below $10^{-25}\,\mathrm{Hz}^{-1/2}$. The hydrocarbon partial pressure (>100 *amu*) will be kept below a level of 10^{-14} mbar.

Cryogenics The ET-LF test masses will be cooled to a temperature of 10-20 K in order to reduce thermal noise of the interferometers. The last stage of the suspension is composed by the test mass, suspended from a penultimate mass (the so called "marionette"), a mechanical system able to steer the test mass in several degrees of freedom. The silicon mirror, i.e. the main test mass, is suspended from this penultimate mass by silicon fibres. The total mass of this stage (including recoil masses) will be about one ton. It will be cooled in a dedicated cryostat, which will include two radiation shields at 8 K and 80 K. Heat from absorbed laser light or ambient thermal radiation is extracted by thermal conduction through the suspension fibers.

Computing The data collected by ET must be analyzed in real time to generate timely alerts for multi-messenger observations together with other observatories, such as optical telescopes. The deep analyses of individual GW observations requires an enormous amount of computing power due to the sheer number of events, the lower cut-off frequency of ET compared to the current detector generation, and the expected better signal quality and therefore a larger number of necessary templates. Since this computing capacity must be available 24/7, dedicated data centers will be required. However, a mere increase in computing capacity will not be sufficient. New, more efficient algorithms will also have to be developed to meet the increased demand.

The science

GW detection has literally opened a new window on the Universe. With new third-generation observatories such as ET we will begin to look far out through this window. As with any scientific enterprise of this scale, there will be certain questions for which, based on our current understanding, we can say that ET is guaranteed to provide the answers, but ET will also be a discovery machine. It will venture into unexplored territories where further surprises are expected. The following is a summary of the key science capabilities:

(1) ET will **detect BBH coalescences up to cosmological distances**. For a total mass of the system between a few tens and a few hundreds solar masses, as typical of the population of black hole (BH) binaries revealed by 2G detectors, ET will be able to detect their coalescence up to redshift $z \sim 20$ and beyond, see Fig. 1.1 on page 6. The corresponding rates will be in the order of $10^5 - 10^6$ events per year. This will provide a census of the population of BHs across the whole epoch of star formation and beyond, answering crucial questions on the progenitors, formation, binary evolution and demographics of stellar BHs. The astrophysical potential in this direction is guaranteed. An observatory network of two or more 3rd-generation observatories would of course be beneficial, in particular for source localization, but even

ET as a single observatory is adequate to uncover much of this compelling science.

(2) ET will **extend the region of BH masses** compared to that explored by 2G detectors, including sources of several hundreds of solar masses, that could be detected up to redshifts of order 10 or more, see Fig. 1.1, and sources of several thousands solar masses, that could be detected up to $z \sim 1-5$. This opens the possibility of detecting these intermediate mass BHs, providing the first clear evidence for their existence and studying the possibility that they are the seeds of the supermassive BHs in the center of galaxies. On the low-mass side, ET would detect, up to $z \sim 0.5-1$, the coalescence of hypothetical binary BHs with a total mass of order one solar mass; any BH with such a mass would necessarily be of primordial, rather than stellar, origin.

(3) ET will **detect the coalescence of BNS up to $\mathbf{z \simeq 2-3}$**, with a rate of about 6×10^4 events per year. This range reaches the peak of the star formation rate and therefore covers the vast majority of neutron star (NS) binaries coalescing throughout the Universe. This will allow us to investigate their formation mechanisms, evolution, and demographics. The sensitivity of ET in the high-frequency regime will allow us to access the GW signal of the merger phase that is inaccessible to 2G detectors and carries detailed information on the internal structure of neutron stars and on their equation of state. This will have important implications also for fundamental physics, allowing us to study QCD at ultra-high density and the possibility of phase transitions in the NS core, such as a transition to deconfined quarks or the formation of exotic states of matter. These detections, and a rich science output coming from them, are guaranteed. Again, these goals can be obtained even by ET as a single observatory. A network of three 3G observatories would bring, on top of this, the possibility of accurate localization of the source, allowing to give information to electromagnetic telescopes necessary to identify an electromagnetic counterpart and perform multi-messenger studies.

(4) ET could **detect several new astrophysical sources of GWs**, such as signals emitted during core collapse supernovae, continuous signals from isolated rotating NSs, and possibly burst signals from NSs. While not guaranteed, these signals would bring rich information. Detecting the GWs from supernovae would elucidate the mechanisms of supernova explosions and its post-collapse phase. The detection of continuous GWs from NSs would allow us to explore the condition of formation and evolution of isolated NS, providing information on their spin, thermal evolution and magnetic field. ET will be able to detect 'mountains' on the surface of a NS as small as 10^{-3} mm, which in turn would again give us information on the inner structure of NS and on the corresponding aspects of nuclear and particle physics, such as the existence of exotic matter in the NS core.

(5) The waveform from the loudest BH-BH and NS-NS coalescences will be **observed by ET with exquisite precision**. This will allow accurate tests of General Relativity (GR), both in the inspiral phase, where one can test the validity of the post-Newtonian expansion of GR to sub-permille accuracy, and in the merger and post-merger phase. The latter is particularly interesting since it would allow us to test the nature of BHs and the dynamics of space-time close to the horizon of the final BH, through the observation of the frequencies and lifetimes of its longer-lived quasi-normal modes. This would allow us to perform new accurate quantitative tests of the predictions of GR in this extreme domain. The possibility of performing such accurate tests is guaranteed, and can also be performed by ET as a single observatory, also thanks to the triangle configuration that will allow the measurement of the individual polarization amplitudes and more stringent tests on the existence of extra, non-GR, polarizations. These tests could also in principle lead to surprises, such as revealing the existence of exotic compact objects, and could even carry observable imprints of quantum gravity effects. While the latter goals are more speculative, their impact would be revolutionary.

(6) ET will **test several dark matter candidates**, such as primordial black holes, ultralight scalars or vector fields, or dark matter particles accreting on compact objects. ET will be able to explore these possibilities even as a single observatory.

(7) ET will **explore the nature of dark energy** and the possibility of modifications of GR at cosmological

distances. The crucial point here is again the ability to detect compact binary coalescences up to cosmological distances, providing an absolute measurement of their distance. The relation between luminosity distance and redshift, in the range of redshifts explored by ET, carries very distinctive signature of the dark energy sector of a modified gravity theory, through the dark energy equation of state and, especially, through an observable related to modified GW propagation. The latter is a particularly powerful probe of dark energy, which is accessible only by GW observations. From the point of view of cosmology, ET is guaranteed to obtain important results (alternative precision measurements of H_0, significant limits on the equation of state of dark energy), complementing measurements obtained with electromagnetic probes. The possibility of detecting modifications of General Relativity at cosmological scales and understanding the origin of dark energy is not guaranteed, but would be revolutionary.

(8) ET will **search for stochastic backgrounds of GWs**, which are relics of the earliest cosmological epochs. Such a background, if detected, would carry information of the earliest moment of the Universe (much earlier than from the cosmic microwave background observations), and on physics at the corresponding high-energy scales, that is inaccessible by electromagnetic (or neutrino) observations or with particle accelerators. Stochastic backgrounds of cosmological origin in the ET frequency window and sensitivity depend on physics beyond the Standard Model. Thus, the predictions are unavoidably uncertain, and the gain from a successful detection would be correspondingly high, allowing us to explore the earliest moments after the Big Bang.

1 Science Case

The first direct detection of GWs from a binary BH (BBH) coalescence, in September 2015, was a historic moment, and the culmination of decades of efforts from a large community. Another historic moment was the first detection of a binary neutron star (BNS) coalescence, together with the simultaneous detection of the associated gamma-ray burst, and the subsequent observation of the electromagnetic counterpart in all bands of the electromagnetic spectrum. A number of additional detections have taken place since, to the extent that, at the current level of sensitivity of 2G experiments, BBH detections are taking place on a weekly basis. Many remarkable results in astrophysics and in fundamental physics have already been obtained thanks to these first detections. To mention only a few highlights, the observation of the BNS coalescence GW170817 solved the long-standing problem of the origin of (at least some) short gamma ray bursts; the multi-band observations of the associated kilonova revealed that BNS mergers are a site for the formation of some of the heaviest elements through r-process nucleosynthesis; the observation of tens of BBH coalescences has revealed a previously unknown population of stellar-mass BHs, much heavier than those detected through the observation of X-ray binaries, and has shown that BBH exist, and coalesce within a Hubble time at a detectable rate. Concerning fundamental physics, cosmology and General Relativity, the observation of the GWs and the gamma-ray burst from the BNS merger GW170817 proved that the speed of GWs is the same as the speed of light to about one part in 10^{15}; the GW signal, together with the electromagnetic determination of the redshift of the source, provided the first measurement of the Hubble constant with GWs; the tail of the waveform of the first observed event, GW150914, showed oscillations consistent with the prediction from General Relativity from the quasi-normal modes of the final BH; several possible deviations from GR (graviton mass, post-Newtonian coefficients, modified dispersion relations, etc.) could be tested and bounded.

Extraordinary as they are, these results can however be considered only as a first step toward our exploration of the Universe with GWs. Third-generation GW detectors, like the ET, will bring the gravitational wave astronomy revolution to a full realisation. Thanks to an order of magnitude better sensitivity and a wider accessible frequency band 3G detectors will allow us to address a huge number of key issues related to astrophysics, fundamental physics and cosmology. An example of the extraordinary potential of 3G detectors is provided by Fig. 1.1. The figure shows the detector reach, in term of cosmological redshift, as a function of the total mass of a coalescing binary. We see that the coalescence of compact binaries

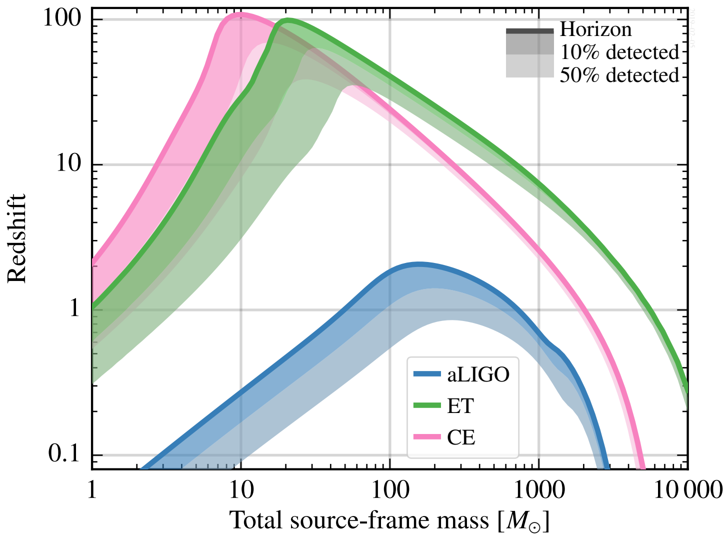

Figure 1.1: Astrophysical reach for equal-mass, nonspinning binaries for Advanced LIGO, Einstein Telescope and Cosmic Explorer.

with total mass $(20-100)$ $M_\odot$, as typical of BBH or BH-NS binaries, will be visible by ET up to redshift $z \sim 20$ and higher, probing the dark era of the Universe preceding the birth of the first stars. In particular, BBH mergers seen at such distances would necessarily have a primordial origin. By comparison, in the catalog of detections from the O1 and O2 Advanced LIGO/Virgo runs, the farthest BBH event is at $z \simeq 0.5$ and, at final target sensitivity, 2G detectors should reach $z \simeq 1$. The range of BH masses accessible will also greatly increase; as we see from Fig. 1.1, ET will be able to detect BHs with masses up to several times 10^3 $M_\odot$, out to $z \sim 1-5$.

For BNS, whose total mass is around $3\,M_\odot$, ET will reach $z \simeq 2-3$; by comparison, the BNS GW170817 was at $z \simeq 0.01$ and, at final target sensitivity, 2G detectors should reach $z \simeq 0.2$. The corresponding detection rates will be impressive, in the order of $O(10^6)$ BBH and $O(10^5)$ BNS coalescences per year; depending on the network of electromagnetic facilities operating at the time of 3G detectors, over a few years one might collect $O(10^2-10^3)$ BNS GW events with observed electromagnetic counterpart. The signal-to-noise ratio of many of these events will be huge, even for events at cosmological distances.

The combination of distances and masses explored, sheer number of detections, and detections with very high signal-to-noise ratio will provide a wealth of data that have the potential of triggering revolutions in astrophysics, cosmology and fundamental physics.

Beside coalescing binary systems, ET will be able to detect several other kinds of signals, such as stochastic backgrounds of GWs, signals from isolated pulsars, or supernovae, with a sensitivity that improves by orders of magnitude compared to 2G detectors. Many of the possible achievements of ET, and other planned 3G detectors like Cosmic Explorer in the U.S., are only possible through gravitational waves. For others, GW detectors are complementary to facilities exploiting electromagnetic radiation or other messengers, such as neutrinos and cosmic rays. The combined observations through GWs, electromagnetic signals, neutrinos and/or cosmic rays, will give us a multi-messenger picture of many phenomena of the Universe. Schematically, we can identify the following main items as part of the ET science case:

- Astrophysics:
  - black hole properties: origin (stellar vs. primordial), evolution, demography;
  - neutron star properties: interior structure (QCD at ultra-high densities, exotic states of matter), demography;

  - multi-messenger astronomy: nucleosynthesis, physics of jets, cosmic rays accelerations, role of neutrinos;
  - detection of new astrophysical sources of GWs: core collapse supernovae, isolated neutron stars, stochastic background of astrophysical origin.
- Fundamental physics and cosmology:
  - the nature of compact objects: near-horizon physics, tests of no-hair theorem, exotic compact objects;
  - dark matter: primordial BHs, axion clouds, dark matter accreting on compact objects;
  - dark energy and modifications of gravity on cosmological scales;
  - stochastic backgrounds of cosmological origin and connections with high-energy physics (inflation, phase transitions, cosmic strings).

It should be stressed, however, that many questions cross the borders between domains outlined above. For instance, understanding whether the BHs observed by GW detectors are of stellar or primordial origin obviously has an astrophysical interest, but a primordial origin would have deep consequences on our understanding of early Universe physics, inflation, etc., subjects that belong to the domain of cosmology and of fundamental physics. As another example, determining the equation of state in the core of neutron stars is of great importance both in astrophysics and for understanding the theory of strong interactions, QCD, in the regime of ultra-high density, where phase transitions can take place.

In the following we briefly discuss some of the science that ET will be able to address[1].

1.1 Black hole binaries

Observationally, BHs have been first identified through X-ray binaries - binary systems in which a BH accretes matter from a companion star. The remarkable GW detections of Advanced LIGO/Virgo in the O1 and O2 runs have then revealed a whole new population of stellar-mass binary BHs with much higher masses, $O(20-80)\mathrm{M}_\odot$. With BBH and BH-NS coalescence, 3G detectors will explore the Universe to depths that go well beyond what can be reached by electromagnetic observations not only of single astrophysical sources, but even of whole galaxies.[2] *ET will uncover the full population of coalescing stellar and intermediate mass BHs in the Universe, over the whole epoch since the end of the cosmological dark ages.* This will allow ET to answer several key questions about the origin and evolution of BBH systems. For instance:

(1) The observations of BBH across the whole epoch of star formation would contain evidence, accessible in no other way, of the cosmic history of stellar evolution, including the earliest populations of stars formed in the Universe.

(2) The observations of BBH probe the physics of BH formation in situations which lead to mergers. ET will provide some events with extraordinarily well-measured properties, alongside large samples of mergers from which statistical population characteristics can be extracted.

(3) By comparing the redshift dependence of the BBH merger rate with the cosmic star formation rate it will be possible to disentangle the contribution of BHs of stellar origin from that of possible BHs of primordial origin. *Showing that at least a fraction of the observed BHs are of primordial origin would be a discovery of fundamental importance not only in astrophysics but also from the point of view of fundamental physics.*

(4) The discovery of luminous quasars at redshift as large as $z \sim 7$ suggests the existence, at redshifts

[1] For more detailed information on the ET science case and full references the reader is referred to M. Maggiore *et al.*, ‘Science Case for the Einstein Telescope’, `https://arxiv.org/abs/1912.02622`.

[2] To understand how this is possible, it is useful to recall that a BBH coalescence such as the first detected event, GW150914, converted into GWs an energy of $3\mathrm{M}_\odot c^2$ in just the last few milliseconds of the coalescence. The peak luminosity of the event, 3.6×10^{56} erg/s, or $200\,\mathrm{M}_\odot c^2/\mathrm{s}$, was an order of magnitude larger than the estimated combined electromagnetic luminosity of all star and galaxies in the observable Universe!

$z > 7$, of a population of 'seed' BHs in the range $(10^2 - 10^5)\,M_\odot$, from which supermassive BHs have grown through gas accretion. ET has the sensitivity necessary to detect BH binary systems containing a BH with mass between $O(10^2)\,M_\odot$ and a few times $10^3\,M_\odot$. *Discovering BHs in this mass range and understanding their role as seed BHs would provide the key to understanding stellar and galactic evolution.*

1.2 Neutron stars

Neutron stars are extraordinary laboratories for studying the fundamental properties of matter under conditions far from the realm accessible to experiments and first-principles theoretical calculations. In NSs, intense gravity compresses matter to several times the density of an atomic nucleus. Predicting the composition of such matter and the multi-body interactions that provide the pressure to prevent collapse to a BH requires large extrapolations from known physics, and has been a longstanding scientific frontier. Neutron stars provide a unique window onto the behavior of QCD, the fundamental theory of strong interactions, in a regime complementary to the higher temperatures and lower baryon densities accessible in collider experiments that probe the quark-gluon plasma.

The fundamental properties of NS matter give rise to characteristic imprints in the GW signals from NS, both in binary coalescences and in the GW signal from individual asymmetric NSs, making GWs unique probes of subatomic physics in unexplored regimes. A 3G GW detector with a high sensitivity and large frequency bandwidth such as ET will be critical to shed light on important fundamental physics questions.

1.2.1 Coalescing neutron star binaries

With 2G detectors, the first observed BNS coalescence GW170817 demonstrated that useful limits on the NSs' tidal deformability, a characteristic parameter that depends on the properties of matter in their interiors, could be extracted from the inspiral part of the GW signal. However, despite the proximity of GW170817, the inferred constraints on the equation of state of NS matter are too weak to discriminate between all realistic models, nor do they offer new insights about the possibility of phase transitions (e.g. to a deconfined quark phase) in the inner core. To determine in detail the nature of matter and interactions in NS interiors requires measuring tidal deformability with an order of magnitude higher accuracy. In addition, such high-fidelity measurements must be obtained for a population of NSs spanning a wide range of masses to map out the parameter dependencies and identify potential signatures of phase transitions. Both can be achieved with ET, which will detect a huge number of BNS and NS-BH coalescences per year as quantified above, and will observe their signal with up to tenfold higher accuracy.

A further unique capability of 3G detectors such as ET is the possibility of exploring in detail the signal after the inspiral part of the coalescence, which, for BNS, is at frequencies too high for 2G detectors, but will be within the bandwidth of ET for BNS within a few hundreds of Mpc. Witnessing the tidal disruption of a NS will yield further insights into the properties of NS matter under extreme gravity, and tracking the violent collision of two NSs and its aftermath will provide an exceptional window onto fundamental properties of matter in a completely unexplored regime, at higher temperatures and yet greater densities than encountered in individual NSs.

The coalescence events of BNS and NS-BH systems also have key significance as the principal production site of elements heavier than iron in the cosmos. Heavy elements can be synthesized from the neutron-rich material expelled during the merger or tidal disruption of NSs or through winds from the remnant accretion disk. The subsequent radioactive decay of the freshly synthesized elements leads to an electromagnetic transient known as a kilonova. Multi-messenger observations of a large sample of BNS will provide the unique opportunity to study heavy element formation at its production site, to determine how the initial conditions of an astrophysical binary system map to the final nucleosynthetic yields, and the extent to which different BNS progenitors contribute to the cosmic abundances over time.

1.2.2 Continuous waves from spinning neutron stars

A spinning NS, isolated or in a binary system, if asymmetric with respect to its rotational axis, can also emit continuous semi-periodic GWs. Such asymmetry can derive from frozen deformations produced right after its violent birth, from a strong enough inner magnetic field, or from non-axisymmetric motions or density perturbations. No continuous gravitational wave signal has so far been observed by Advanced LIGO/Virgo. *The detection of continuous GWs from NS by ET would be a fundamental breakthrough, that would provide clues about the condition of formation of isolated NS, their spin, thermal evolution and magnetic field. Furthermore, observing such signals with ET's exquisite sensitivity would again give information on the inner structure of NS and on the corresponding aspects of nuclear and particle physics, such as the existence of exotic matter in the NS core.* The maximum degree of deformation that a NS can sustain depends on the equation of state: for standard equations of state the maximum value of the ellipticity is $\varepsilon_{max} \sim 10^{-6}$, but for exotic objects, containing hyperons or quark matter, is expected to be much higher, $\varepsilon_{max} \sim 10^{-4} - 10^{-3}$. In practice, it is difficult to predict the actual deformation of a specific NS, that can depend on the star's history and could be well below the maximum sustainable value. ET will be sensitive to ellipticities of the order of few times 10^{-10} for the nearest millisecond pulsars, and of $\sim 10^{-6} - 10^{-7}$ for young pulsars. It is quite impressive to realize that detecting GWs due to an eccentricity of, say, $\varepsilon = 10^{-10}$ in a NS means that we would detect the effect due to a "mountain" on a NS, with a height of about $10^{-10} \times 10\,\text{km} = 10^{-3}\,\text{mm}$.

The maximum distance at which a continuous wave source would be detected depends on both the ellipticity and the rotational frequency of the NS. For instance, a neutron star spinning at 50 Hz (and then emitting a continuous GW signal at 100 Hz) would be detectable by ET in the whole Galaxy as long as its ellipticity is larger than 10^{-7}. Given the expected variety of ellipticities in NS (which depend also on their past history) the limits obtained from the whole Galactic population will be much more significant than current upper limits from specific pulsars. Very fast spinning and highly distorted neutron stars, such as newborn magnetars produced in core collapses or as post-merger remnants of coalescing binaries, could lead to detectable emission at even higher frequencies. In this case the signal can only be observed for a shorter time, since these objects are characterized by a very high spin-down and the signal frequency eventually leaves the detector sensitivity band within a few days. However, at birth they could have ellipticities as large as 10^{-3} so, even taking into account uncertainties in the data analysis due to the very large initial parameter space (initial frequency, spin-down, braking index), these objects could still be detected out to distances of tens of megaparsecs.

1.3 Multi-messenger astrophysics: synergies with other GW detectors, electromagnetic/neutrino observatories and cosmic-ray detectors

ET, with its triangular configuration corresponding to three nested interferometers, is designed to have an extraordinary science output even when operated as a single GW detector. However, a further enhancement of its capabilities will take place when making use of the synergies with other detectors that could be operating at the same time.

1.3.1 Networks of 3G gravitational-wave detectors

The first obvious synergy is with other 3G detectors, like the Cosmic Explorer (CE) under study in the US, and to a lesser extent upgraded version of the current 2G detectors. The most important improvement of a network of three 3G detectors, compared to a single detector, concerns the accuracy in the localization of the sources. For the continuous GWs emitted by spinning NSs a single ET detector already provides a very accurate parameter estimation - including position - thanks to the very specific modulation of the signals due to Doppler effect induced by the Earth motion. For coalescing BNS or lightweight BBH systems a single ET detector still has some localization capability since, for a low-mass system such as a binary NS, the signal stays in the detector bandwidth for a long time, of order of a few days, and the modulation due to the Earth's motion allows us to localize the source. In this case an average angular resolution would be around $150\,\text{deg}^2$ for a binary NS at $z = 0.1$, but can become of order of just a few deg^2 for the best localized sources. Even for BH-NS binaries, in the best cases, ET alone can provide a localization better than $10\,\text{deg}^2$. No significant localization will be available for massive BBH, that because of their higher total mass will stay in the detector bandwidth for a much shorter time. A network of three GW detectors, in contrast, will have quite good localization accuracy for all types of binary coalescences; for example a large fraction of BNS will have sky localization smaller than 1 deg^2 up to $z = 0.5$. In terms of science output, this means that a 3G detector network will be able to provide good localization information to electromagnetic telescopes, for the search of electromagnetic counterparts.

On the other hand, the different sensitivity curves planned for ET and CE imply that, from other points of view, these detectors will be complementary. For instance, as can be seen from Fig. 1.1, ET will be able to detect heavier systems, with total masses higher than $10^3\ M_\odot$ (thanks to its sensitivity in the low frequency regime), while CE has a greater reach for light systems such as BNS. The different sensitivity curves also mean that, for a given astrophysical system, the signal-to-noise ratio is accumulated differently in ET and in CE, providing complementary information.

1.3.2 Joint gravitational and electromagnetic observations

The discovery and electromagnetic follow-up of GW170817 showed the enormous potential of gravitational-wave observations for multi-messenger astrophysics. The gravitational-wave observations combined with the results from the extensive multi-wavelength observational campaign (still undergoing) had a huge impact on our knowledge of the physics of compact objects, relativistic jets, nucleosynthesis, and cosmology. Identifying the electromagnetic signatures of the gravitational-wave sources enables to maximize the science return from a gravitational-wave detection. Several future observatories, with a large involvement of the European community, will have strong synergies with ET. SKA, LSST, the THESEUS mission concept, and CTA will be able to observe large regions of the sky from the radio, optical to the X-ray and very high energy gamma rays, going to deeper sensitivity than current observatories; a 40-meter class telescope such as ELT and a satellite like ATHENA will be able to characterize the source in the optical and X-ray band respectively.

The ET lower frequency capability enables the accumulation of a significant signal-to-noise ratio before the merger, making possible an early detection and warning for the electromagnetic followup. Requiring a signal-to-noise ratio of $\geq$ 12 and a sky localization smaller than $100\,\text{deg}^2$, ET can send an early warning alert between 1 and 20 hours before the merger (with the mean of the distribution at about 5 hours) for signals at 40 Mpc. At 200 Mpc, about 30% of the detectable signals would accumulate enough SNR for early warning between 1 to 6 hours prior to the merger; about 10% of the detectable sources within 400 Mpc can still be announced with an early warning on the order of an hour. This enables the detection of early electromagnetic emission, which is fundamental to understand the physics of the engine and the merger remnant.

A single ET detector, even in the absence of good source localization, will still be able to perform joint observations with gamma-ray burst detectors, through the observation of a temporally coincident GRB. In turn, this can allow for the measurement of the redshift of the source when the high-energy satellite is capable to precisely localize it. Indeed, GRB satellites such as "Swift" regularly alert ground based spectrographs to obtain the redshifts of the host galaxies of the detected GRBs.

The discovery of the gamma-ray emission associated with GW170817 and the following afterglow observations significantly improved our knowledge of short GRB jets. However, only a detector such as ET will provide the unprecedented capability to completely probe short GRB jet properties by exploring up to high redshift a large population of neutron star mergers observed perpendicular to the orbital plane (on-axis) and off-axis. Mission concepts such as THESEUS will be able to detect $20-40$ on-axis short GRB/year with a localization accuracy of $1-5$ arcmin up to a redshift $z \simeq 5$. After each detection, the rapid alert system will enable to point ground-based spectrographs, such as the ones in ELT and satellites such as ATHENA. THESEUS will give the precise position of the source, and ET and the multi-wavelength follow-up will allow us to connect detailed information of the progenitors and merger remnant properties to the jet and environment properties. It will be possible to build a statistical sample of binary neutron star mergers able to probe the shape of the jet structure, if it is universal, and investigate what is the typical opening angle for short GRBs. It will be possible to constrain the luminosity function of short GRBs and its relation to the jet structure and the intrinsic luminosity evolution, and to understand what is the efficiency of the jet to break through the material surrounding the BNS mergers. Finally, we will understand the role of NS-BH binaries as progenitor of short GRBs. ET will be crucial to identify the nature of the binary neutron star merger remnant (black-hole, unstable or stable neutron star) and how this is connected to the short GRB central engine and afterglow properties.

1.3.3 Neutrinos and cosmic rays

Shock-accelerated particles (protons and nuclei) interacting with matter and photons produce neutrinos. The astrophysical sources of gravitational-wave transient signals associated with gamma-ray bursts, soft gamma-ray repeaters (SGRs), and core-collapse supernovae are expected to emit neutrinos. While gravitational waves produced by the bulk motion of matter carry information on the astrophysical source dynamics, neutrinos give direct information on interactions between accelerated particles with matter and radiation surrounding the sources. GWs and neutrinos probe the innermost regions of the source typically opaque to the electromagnetic emission. GRBs and SGRs are expected to emit high energy cosmic neutrinos (HEN) from MeV to PeV. In the GRBs, TeV-PeV HENs are expected to be produced in the baryon-loaded jets during the prompt gamma-ray emission, and PeV-EeV HENs during the afterglow phase. In SGRs, the HEN production is expected from protons accelerated by the sudden magnetic reconfiguration.

When ET will be operational, the upcoming multi-cubic-kilometer neutrino detector KM3NET, and the 10 km^3 facility in the Southern hemisphere IceCube-Gen2 are expected to observe the sky. The sensitivity of the neutrino detectors will make the simultaneous detection of neutrinos and GWs from on-axis short GRBs possible. The high-energy neutrinos would serve as a powerful probe of cosmic-ray acceleration in GRBs and of the physics of relativistic jets associated with NS–NS and NS-BH mergers. For long GRBs and SGRs, the joint detection is less likely and more uncertain. Some models predict that GRBs produce Ultra-High Energy Cosmic Rays (UHECR). In the case of cosmic ray, the astrophysical source identification is complicated by the cosmic ray deflection and the time delay between the arrival of cosmic rays and photons, GW and neutrinos imparted by magnetic fields in the galaxy hosting the source, our Galaxy, and in the intergalactic medium. In this context, ET together with gamma-ray observatories, such as Fermi, HESS, MAGIC, VERITAS, Fermi, CTA and neutrino detectors will make it possible to probe the GRB population, their progenitors, and the jet properties and composition. This will be crucial to probe the role of GRBs as possible sources of UHECRs.

Core-collapse supernovae emit low-energy neutrinos, as proved on February 23, 1987, when neutrinos with energies of a few tens of MeV emitted by the supernova SN1987A, which exploded in the nearby Large Magellanic Cloud, were recorded simultaneously by the Kamiokande-II, IMB, and Baksan detectors a few hours before its optical counterpart was discovered. Simultaneous detection of GWs and neutrinos from the core collapse of massive stars would open remarkable perspectives in multi-messenger astronomy. They are unique probes to reveal the inner mechanisms of the explosion, the dynamics of the remnant (possibly a newborn neutron star) and the physics of the post-shock region. The current and future low-energy neutrino detectors Super-K/Hyper-K, DUNE, JUNO, IceCube, the LVD, SNO+ and KamLAND are expected to detect neutrinos from the core-collapse SNe, whose GW signal will be detectable by ET. The GW signals detected by ET from the core-collapse and its remnant (a BH or a new born magnetar) are also expected to help searching for sub-threshold neutrino events.

1.3.4 Multi-band GW observations with LISA

Another potential very interesting synergy could take place with the space interferometer LISA, should ET be operational by the time that LISA will take data (launch scheduled for 2034, operational from 2036 for a nominal duration of four years), or up to a few years after the end of the mission. This would allow multi-band GW observations, i.e. the observation of GW signals in widely different frequency bands. In particular, from the rate of BH coalescences inferred by the Advanced LIGO/Virgo O1 and O2 runs, we expect that LISA, in a 4 yr mission, will detect several tens of stellar-mass BBH. Months to years later, several of these events will cross into the ET window, where they will coalesce. For instance, the first observed GW event, GW150914, would have been detected by LISA a few years before coalescence, if at that time LISA had already been in orbit.

Multi-band observations would have many benefits: a joint LISA-ET detection would provide sky localization of the source with an error of only a few square degrees, and would make it possible to alert telescopes and look for an electromagnetic counterpart, both in the pre-merger and post-merger phases (which in principle is not expected for BBH coalescences, but could be present in BH-NS binaries); it would improve parameter estimation, reducing the error on the luminosity distance to the source and on the initial spins and allowing to measure with extreme precision the sky position, mass and spin of the final BH. LISA and ET observations of such events would be highly complementary; for instance LISA, by observing the long inspiral phase, will measure very accurately the masses of the initial BHs, while ET would detect the last few cycles and the merger, and would therefore measure the final masses and spin from the ringdown of the final BH. Consistency tests between the inspiral part of the waveform and the merger-ringdown part, of the type performed for the first detection GW150914, would then provide very stringent tests of General Relativity. Furthermore, the early warning provided by LISA on particularly interesting events might allow real time optimization of ET to improve sensitivity to the ringdown signal.

1.4 Fundamental physics and cosmology

The direct detection of gravitational waves has started to give us access to the genuinely strong-field dynamics of spacetime. This is illustrated in Fig. 1.2, which shows how different kinds of observations (past, current, and future) will give us access to different regimes, in terms of spacetime curvature R and gravitational potential Φ (which for binary systems can be traded for v^2/c^2, where v is the characteristic speed of the binary and c is the speed of light).

Observations of GWs from binary BH and binary NS coalescences with Advanced LIGO and Advanced Virgo have enabled us to probe for the first time the regime where both R and v/c are large. By observing the inspiral phase we could test the predictions of GR (as encoded in the post-Newtonian coefficients) to a precision of about 10%. By observing the full inspiral-merger-ringdown process of binary black holes, we could perform a first study of the dynamics of vacuum spacetime. The observation of the binary neutron star inspiral GW170817 also gave us our empirical access to the interaction of spacetime with high-density matter. Because of the large distances that GWs have to travel from source to observer, we were able to strongly constrain possible dispersion that might occur; the latter led to an impressive bound on the mass of the graviton of $m_g \leq 5 \times 10^{-23}\,\mathrm{eV}/c^2$. These examples notwithstanding, on the whole the existing detectors lack the sensitivity to put very strong constraints on possible deviations from Einstein's theory, particularly regarding the strong-field dynamics at the source, corresponding to the top right edge of Fig. 1.2. The situation will be quite different with the Einstein Telescope. One reason is the much larger detection rate; especially for the purposes of fundamental physics, information from multiple sources can often be combined, and the measurement accuracy on common observables tends to improve with the square root of the number of detections. For example, the post-Newtonian coefficients that govern binary inspiral will be determined with sub-percent to sub-permille accuracy. However, the fact that the same GW source will be much louder in ET will also give us access to qualitatively new effects. Below we discuss in turn capabilities of ET in probing the properties of gravity, as well as unraveling the nature of

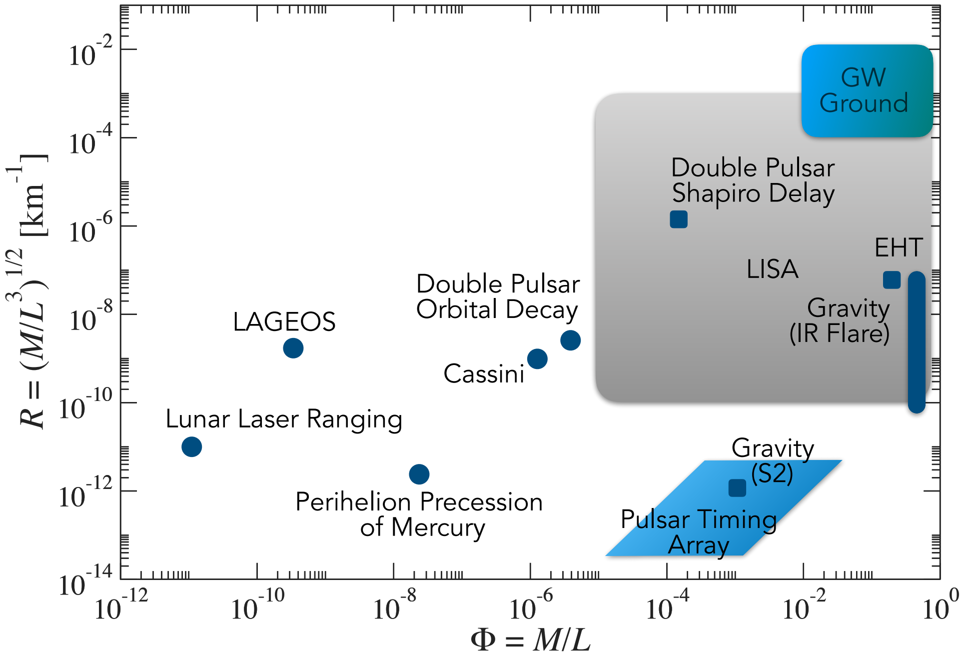

Figure 1.2: Probing gravity at all scales: illustration of the reach in spacetime curvature versus potential energy targeted by different kinds of observations. M and L are the characteristic mass and length involved in the system or process being observed. The genuinely strong-field dynamics of spacetime manifests itself in the top right of the diagram. The label EHT refers to the Event Horizon Telescope. Image from the '3G Science Book' by the the GWIC 3G Science Case Team, and the International 3G Science Team Consortium (in preparation, 2020).

ultra-compact objects, with potentially game-changing implications for our understanding of black holes, the make-up of dark matter, dark energy, and maybe even quantum gravity itself.

1.4.1 Physics near the black hole horizon

Testing the GR predictions for space-time dynamics near the horizon. Black holes are one of the most extraordinary predictions of General Relativity. They are identified through their most striking property: in the case of stellar mass black holes, a mass $O(10-100)\,M_\odot$ is concentrated in an extremely small volume; for instance, the Schwarzschild radius of a non-rotating BH with mass $10M_\odot$ is about 30 km. However, how certain can we be that the massive compact objects that we saw with 2G detectors are really the standard black holes of classical General Relativity?

General Relativity gives detailed and specific predictions on the nature of BHs that a 3G detector such as ET will be able to test. The celebrated no-hair theorem of GR states that, in a stationary situation, a BH is determined by just two numbers: its mass and its spin (plus the electric charge, which however is not relevant in an astrophysical context, where it is quickly neutralized). However, when a BH is perturbed, it reacts in a very specific manner, relaxing to its stationary configuration by oscillating in a superposition of quasi-normal modes, which are damped by the emission of GWs. The fact that an elastic body has normal modes is a familiar notion from elementary mechanics. It is however quite fascinating to realize that a BH, which is a pure space-time configuration, also has its quasi-normal modes. These represent pure space-time oscillations, in a regime of strong gravity, and, in a sense, describe the elasticity of space-time in a most extreme situation, in the region close to the BH horizon. The theory of BH quasi-normal modes is a classic chapter of GR, and in particular predicts the spectrum of frequencies and damping times of the quasi-normal modes as a function of the mass and spin of the BH. Highly perturbed black holes arise as the remnants of binary BH or NS mergers, and relax to the final stationary BH configuration

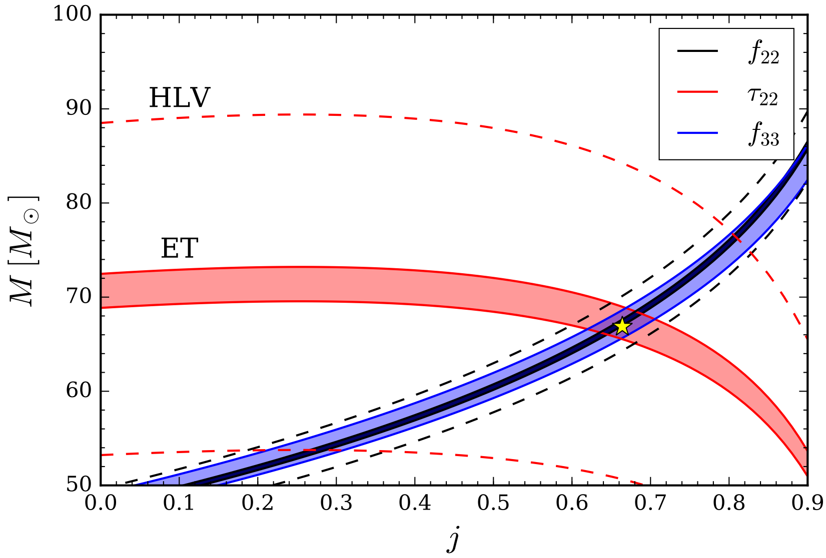

Figure 1.3: Testing the nature of black holes by using two quasi-normal modes and checking that the characteristic frequencies f_{22} and f_{33} and the damping time τ_{22} are consistent with each other, given that for ordinary black holes these can only depend on two numbers, the final mass M and final spin j. The estimates are for the "ringdown" of the remnant black hole arising from a binary similar to the source of GW150914. The dashed curves marked HLV are the 95% confidence regions one would obtain from Advanced LIGO-Virgo, while the colored bands are for ET. The star indicates the true values of M and j.

through GW emission in the quasi-normal modes, in the so-called 'ringdown' phase of the coalescence, where the waveform is given by a superposition of damped sinusoids. Indeed, for the first observed BBH coalescence, GW150914, the final ringdown phase was just discernable, and was shown to be broadly consistent with the prediction of GR for the value of the parameters inferred from the inspiral part of the waveform. Fig. 1.3 illustrates the difference in the accuracy of such a test between 2G and 3G detectors, for a single source such as GW150914. Furthermore, the accuracy of the measurement scales as $1/\sqrt{N}$, where N is the number of detections; as we saw, ET will detect $N \sim O(10^5 - 10^6)$ BH binaries, compared to several hundreds expected for 2G detectors.

Exploring the possibility of exotic compact objects. The observation of quasi-normal modes, besides providing a spectacular test of GR in the strong-field, near-horizon regime, could also potentially lead to the discovery of different types of compact objects. Indeed, various exotic compact objects have been proposed that may act as "black hole mimickers", such as boson stars, gravastars, etc. When such objects are part of a binary system that undergoes coalescence, they can make their presence known through various possible imprints on the GW signal emitted. Already during the inspiral phase, these objects may get tidally deformed in a way that would be impossible for a standard, classical black hole. Unlike second generation detectors, ET will for instance be able to distinguish neutron stars from boson stars even for the most compact models of the latter. Another possibility is that an exotic object could be identified through an anomalous spin-induced quadrupole moment, which would again not be accessible with current detectors, but measurable with ET to the percent level.

If the outcome of a coalescence is different from a BH, this might leave an imprint on the ringdown phase, and could be tested by measuring quasi-normal mode frequencies and life-times, as in Fig. 1.3. For exotic compact objects where the modifications take place only at scales much shorter than the so-called light-ring (as in the case of quantum gravity effects discussed below), the ringdown signal will be very similar to a BH, but after the ringdown has died down, exotic compact objects may continue to emit bursts of gravitational waves at regular time intervals, called *echoes*.

Signals from quantum gravity? Prompted by Hawking's information paradox, modifications of the structure of space-time at the horizon scale have been proposed, such as firewalls and fuzzballs, for which the classical horizon is removed through macroscopic quantum effects. From a particle physics perspective, one is used to the fact that, at energies E much below the Planck energy scale $M_{\rm Pl}$, quantum gravity effects are suppressed by powers of $E/M_{\rm Pl}$, and therefore, given that the Planck scale $M_{\rm Pl}$ is of order 10^{19} GeV, they are totally unaccessible at accelerators, even in any foreseeable future. Equivalently, at a macroscopic length-scale L, quantum gravity effects are suppressed by powers of $l_{\rm Pl}/L$, where $l_{\rm Pl} \sim 10^{-35}$ m is the Planck length. In contrast, near the BH horizon, where the characteristic length-scale L is given by the Schwarzschild radius R_S, effects due to quantum gravity are governed by a factor $\log(l_{\rm Pl}/R_S)$, and can manifest themselves through a series of echos after the initial ringdown signal, emitted with a time delay $\tau_{\rm echo} \simeq (R_S/c)\log(R_S/l_{\rm Pl})$. For instance, for a final object with mass $M = 60{\rm M}_{\odot}$, one has $\tau_{\rm echo} \simeq 16\tau_{\rm BH}$, where $\tau_{\rm BH} \simeq 3$ ms is the fundamental damping time of a Schwarzschild BH with this mass. Such signals are potentially within the reach of ET, which raises the tantalizing possibility of accessing quantum gravity effects at ET.

To summarize, *the transition from second generation observatories to Einstein Telescope will lead to a qualitative leap in our ability to probe both the nature of gravity in the strong field regime and the structure of compact objects, and could even lead to exploring the quantum gravity regime.*

1.4.2 The nature of dark matter

Understanding the nature of dark matter and of dark energy is one of the crucial problems in astrophysics, cosmology and fundamental physics. ET will be able to address both questions. Observations with ET will allow us to attack the problem of the origin of dark matter from several different angles. A part of the dark matter could be composed of *primordial* black holes in the mass range $\sim 0.1-100M_{\odot}$. Primordial BHs could be seeded by fluctuations generated during the last stages of inflation, which then collapsed in later epochs as a consequence of drops in the pressure of the cosmic fluid, e.g. during the QCD quark-hadron transition. Their mass distribution depends on the precise model of inflation and on the epoch when they collapsed. The large number of mergers that ET will see, together with its ability to access a broad range of masses, would allow us to map the black hole mass distribution and identify an excess of black holes in certain mass intervals. For black holes with masses well below a solar mass, no plausible astrophysical formation mechanism is available, so that their detection would point to the existence of primordial black holes. A unique advantage of ET is the possibility of observing stellar mass black hole mergers at redshifts of $\sim 10-20$, before any stars had formed that could create black holes in the usual way; should such an event be observed then (irrespective of masses) the objects involved are bound to be of primordial origin.

If most of the dark matter occurs in the form of particles beyond the Standard Model, then also in that case gravitational wave observations can be used to search for them. Black holes could not only accrete dark matter particles, but also be subject to gravitational drag, which in a binary system would accumulate over the course of many orbits. If ET will be operational during the same period as LISA, joint LISA-ET observations of the same source will then be of great value. There is also the possibility that dark matter particles are captured in astrophysical objects and thermalize with the star. The presence of a dark matter core in a neutron star might again have an imprint upon the GW signal during binary inspiral and merger. In some models, the accumulation of dark matter may lead to the formation of a black hole inside a neutron star, which then accretes the remaining neutron star matter, leading to black holes of $(1-2)M_{\odot}$ that could be observed by ET.

Finally, ultralight bosons have been proposed in various extensions of the Standard Model, and also as dark matter candidates. If their Compton wavelength is comparable to the horizon size of a stellar or supermassive rotating black hole (*i.e.* for particle masses of $10^{-21}-10^{-11}$ eV), they can extract rotational kinetic energy from the black hole through "superradiance" to feed the formation of a bosonic "cloud" with mass up to $\sim 10\%$ of the black hole. These clouds annihilate over a much longer timescale than their formation, through the emission of nearly monochromatic gravitational waves, which could be detected either directly or as a stochastic background from a large number of such objects throughout the Universe. Additionally, measuring the distribution of black hole masses and spins can yield an indication of the prevalence of superradiance through light scalars. Moreover, the presence of such clouds will again have an effect on binary orbital motion. In this way GWs have the potential to provide a unique probe into an ultralight, weakly coupled regime of particle physics that can not easily be accessed in accelerator experiments.

To summarize, ET has the potential of discovering several dark-matter candidates that will be inaccessible by any other means.

1.4.3 The nature of dark energy

ET will be an outstanding discovery machine for studying the nature of dark energy, using binary NSs and binary BHs as cosmological probes. Indeed, a remarkable feature of the GWs emitted in the coalescence of compact binaries is that their signal provides an absolute measurement of the luminosity distance to the source. The relation between the luminosity distance d_L and redshift z of the source carries crucial cosmological information and is among the main observables of modern cosmology.

In the low redshift limit $z \ll 1$ accessible to 2G detectors, the relation between d_L and z reduces to the Hubble law $d_L(z) \simeq H_0^{-1} z$. Hence the observation of standard sirens at low redshifts can provide a measurement of H_0. The possibility of measuring H_0 has already been demonstrated with GW170817, from which a value $H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ was obtained. With $O(100)$ standard sirens with counterpart, a measurement of H_0 at the 1% level could already be possible with 2G detectors. This would allow us to arbitrate the current discrepancy between the value of the Hubble parameter H_0 obtained from late-Universe probes, and the value inferred from early-Universe probes, which has currently reached the 5.3σ level and can be an indication of deviations from ΛCDM, the standard cosmological model.

With ET, given the expected huge number of detections and the very high signal-to-noise ratios of nearby events, a sub-percent level accuracy on H_0 could be reached. However, a much higher potential for discovery is provided by the fact that ET will have access to standard sirens at much larger redshifts, where the luminosity distance-redshift relation will be sensitive to effects induced by a non-trivial dark energy sector and by modifications of General Relativity on cosmological scales. This would allow us to obtain a measurement of the dark energy equation of state from GW observations. Actually, the situation for 3G detectors is even more interesting due to a phenomenon of modified GW propagation. Indeed, in generic theories where dark energy is dynamical and gravity is modified at cosmological scales, the propagation of GWs over cosmological distances is also modified. As a result, the GW amplitude becomes inversely proportional to a “GW luminosity distance” $d_L^{\mathrm{gw}}(z)$, different from the standard electromagnetic one $d_L^{\mathrm{em}}(z)$; the ratio $d_L^{\mathrm{gw}}(z)/d_L^{\mathrm{em}}(z)$ carries distinctive imprints of the dark-energy sector of the theory. This behavior turns out to be completely generic to modified gravity models. For most models, the deviations from GR can be parametrized in terms of two parameters (Ξ_0, n) defined by $d_L^{\mathrm{gw}}(z)/d_L^{\mathrm{em}}(z) = \Xi_0 + (1-\Xi_0)(1+z)^{-n}$. Measuring modified GW propagation through its effect on the GW luminosity distance is a very powerful probe for the dark energy sector, which cannot be accessed at all with electromagnetic observations. With a few hundred standard sirens with counterpart, ET will constrain Ξ_0 to below 1%, a level significantly smaller than the deviation from GR foreseen by various alternative gravity theories. Indeed, the sector of tensor perturbations over a cosmological background can only be explored with GW detectors, and can lead to significant surprises. For instance, one can have a cosmological model that is observationally indistinguishable from ΛCDM in terms of current electromagnetic observations, but still predicts a value of Ξ_0 as large as $\Xi_0 \simeq 1.8$, representing a 80% deviation from ΛCDM. Such a large effect could be detectable even with just a single standard siren at ET. The study of standard sirens is among the issues that will benefit from the triangle configuration, which allows the separate measurement of the two polarization amplitudes, breaking the degeneracy between distance and inclination of the orbit, and therefore providing a significantly more accurate measurement of the distance to the source. *In summary, the sector of cosmological tensor perturbations is virgin territory that can only be explored by third-generation GW detectors such as ET, and which could offer the most powerful window for understanding the nature of dark energy and modifications of General Relativity at cosmological scales.*

1.4.4 Toward the Big Bang: stochastic backgrounds of GWs

The weakness of the gravitational interaction, which is responsible for the fact that GW detection is such a challenging enterprise, also implies that the observed GW signals carry uncorrupted information about their production mechanism. This is particularly significant for stochastic backgrounds of GWs of cosmological origin. For comparison, in the early Universe photons were kept in equilibrium with the primordial plasma by the electromagnetic interaction, and decoupled from it at a redshift $z \simeq 1090$, when the Universe already had a rather low temperature $T \simeq 0.26\,\text{eV}$. The photons that we observe today from the cosmic microwave background therefore give a snapshot of the Universe at this decoupling epoch, while all information about earlier epochs was obliterated by the photon collisions with the primordial plasma. Neutrinos, which interact through weak interactions, decoupled when the Universe had a temperature $T \simeq 1\,\text{MeV}$. By contrast, GWs were decoupled from the primordial plasma at all temperatures below the Planck scale $\sim 10^{19}\,\text{GeV}$, corresponding to a far earlier epoch, and energies far exceeding those accessible to particle accelerators. Gravitational waves from the early times of the universe imprint a signature on the B-mode of the cosmic microwave background, the analysis of which can provide valuable indirect indications of early physical processes. *The direct observation of a stochastic background of gravitational waves of cosmological origin would provide us with an unaltered direct snapshot of the earliest moments after the Big Bang that could not be obtained like this with any other probe.*

In order to detect a stochastic background one has to perform cross-correlation among the outputs of pairs of detectors, as would be possible with a single ET observatory, which is made of three non-parallel detectors. On the cosmological side, while the background generated by the amplification of quantum vacuum fluctuations due to the inflationary expansion is expected to be too low to be detected by 3G detectors, there are several other inflation-related mechanisms that can produce detectable signals. For example, large GW amplitudes are naturally produced in inflationary models where there are secondary fields coupled to the inflaton. On the other hand, also scenarios alternative to inflation, such as pre-Big-Bang models inspired by string theory, or models where the inflaton is coupled to an axion field, predict a spectrum which grows with frequency, resulting in a potentially detectable signal in the ET bandwidth. Another source of GWs is expected during the preheating period of the Universe, following closely the end of inflation. In particular, when "preheat" fields are coupled to the inflaton, these may undergo a non-perturbative excitation after inflation with the consequent generation of GWs. The amplitude of these backgrounds can be very large, and there are scenarios that can peak at frequencies in the Einstein Telescope range. The statistical properties (and, particularly, its deviation from Gaussianity) of the cosmological stochastic GW background will be another possible target for 3G detectors that will allow to distinguish a cosmological background from other stochastic signals.

Strong first order phase transitions are another potential source of a stochastic background. As the Universe expands, its temperature drops and it may undergo a series of phase transitions followed by spontaneous breaking of symmetries. If a phase transition is of first order, a stochastic GW background may be produced as true vacuum bubbles collide and convert the entire Universe to the symmetry-broken phase. In the Standard Model of particle physics, the electroweak and the QCD transitions are just cross-overs, hence any generated gravitational wave signal is not expected to be detectable. However, there are many extensions of the Standard Model (e.g., with additional scalar singlet or doublet, spontaneously broken conformal symmetry, Peccei-Quinn like symmetries, or phase transitions in a hidden sector) which predict strong first-order phase transitions, not necessarily tied to either the electroweak or the QCD phase transition.

Phase transitions followed by spontaneous breaking of symmetries may leave behind topological defects as relics of the previous more symmetric phase of the Universe. In the context of Grand Unified Theories, one-dimensional defects called cosmic strings are generically formed. Cosmic string loops oscillate periodically in time, emitting GWs which depend on a single parameter, the string tension μ, related to the energy scale η of the symmetry breaking through $G\mu \sim 10^{-6}(\eta/10^{16}\,\text{GeV})^2$. Cosmic strings may also emit bursts of beamed gravitational radiation. The incoherent superposition of these bursts generates a stationary and almost Gaussian stochastic GW background. Occasionally there may also be sharp and high-amplitude bursts of GWs above this stochastic background. ET will be able to improve on 2G bounds on $G\mu$ by up to 8 orders of magnitudes: with just one year of data one can detect or exclude values of $G\mu$ down to $10^{-17} - 10^{-18}$, depending on the loop distribution.

In addition to the cosmological background, an astrophysical contribution will result from the superposition of a large number of unresolved sources too faint to be detected individually. Examples include short-lived burst sources, such as core collapses to neutron stars or black holes, oscillation modes of (proto)-neutron stars, or the final stage of compact binary mergers; periodic long lived sources, typically pulsars; or the early inspiral phase of compact binaries, whose frequency evolves slowly compared to the observation time. The strongest astrophysical background in the frequency region of terrestrial detectors is expected to be due to the coalescence of BBH and BNS systems. To separate the cosmological and the astrophysical backgrounds the first step will be to use any distinct spectral dependence of the average (monopole) amplitude Ω_{GW}. However, the better angular resolution of 3G detectors will most probably allow us to spot the anisotropies (directionality dependence) of the astrophysical background. Such anisotropies contain information about the angular distribution of the sources and can be used as a tool for source separation as well as a tracer of astrophysical or cosmological structure. The detection of the anisotropies will give the possibility to relate the properties of GW sources with those of their host galaxies, and in particular their cross-correlation will provide a handle to discriminate the origin of black holes. On the other hand the effects imprinted in the angular power spectrum of the stochastic background, due to the GW distortion by the intervening Large Scale Structure distribution, like Kaiser, Doppler and gravitational potential effects, can be used to study the Large Scale Structure and make precision cosmology with 3G detectors.

2 Instrumentation, Site and Infrastructure

2.1 Detector instrumentation

The Einstein Telescope will be a new gravitational wave observatory with a unique design. A project of this scale must be based on well proven and experimentally tested technologies. On the other hand, to achieve the sensitivity that the Einstein Telescope project aims for, it will be necessary to exploit many state-of-the-art technologies and drive them to their physical limits. The Einstein Telescope combines the proven concepts from current detectors such as LIGO and Virgo with advanced upgrades, such as cryogenic mirrors, in a infrastructure designed to accommodate several technology upgrades over a period of 50 years.

2.1.1 Optical layout and interferometery

The Einstein Telescope aims at providing a significant increase in scientific reach through a tenfold improvement of the detector sensitivity in a wide frequency band, and, in addition, by extending the range of the detector to lower frequencies. The overall improvement can only be achieved by significantly

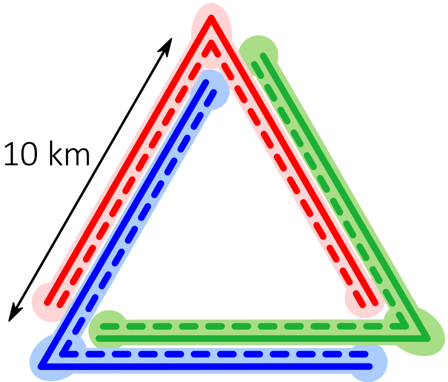

Figure 2.1: The Einstein Telescope will consist of three nested detectors (shown in blue, green and red) in a triangular arrangement. Each detector consists of two interferometers, one optimised for low-frequency (solid) and one for high-frequency sensitivity (dashed).

increasing the length of the detector beyond the size of currently available instruments (i.e. 3 km for advanced Virgo and KAGRA, and 4 km for advanced LIGO) and going to an underground location, where the seismic noise, and hence the level of Newtonian noise, is lower than at the surface. By increasing the arm length to 10 km the influence of unavoidable displacement noises can be lowered to allow a significant improvement in sensitivity. Observing gravitational waves at frequencies well below the limits of current detectors will also require advanced technologies such as cryogenic mirrors and active noise cancellation.

The Einstein Telescope is a single-site observatory that will consist of three nested detectors, arranged in a triangular pattern as shown in figure 2.1. The triangle shape, similar to the space-based LISA detector, represents the smallest layout for a single-site observatory that is equally sensitive to both polarizations of the gravitational wave signal. It also provides redundancy for continuous data taking during maintenance or upgrades of a single detector, and has the potential for exploiting elaborate data analysis techniques developed for LISA such as null-streams for noise identification and removal.

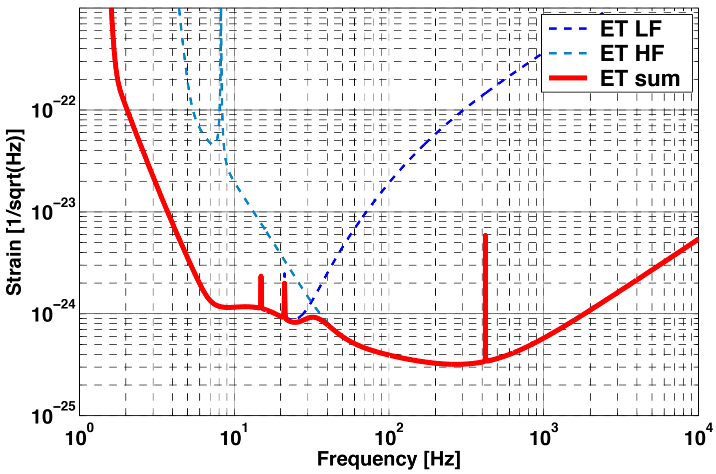

Figure 2.2: Sensitivity of the Einstein Telescope. The sensitivity of the low-frequency cryogenic interferometer is shown in the dashed dark blue curve and the one of the high-frequency room temperature one in a dashed blue-green tone. The resulting total detector sensitivity is shown as the solid bright red curve.

A configuration covering multiple-spectral bands

In contrast to all currently existing detectors, each of the three ET detectors will be composed of two interferometers, one specialized for the detection of low-frequency gravitational waves and the other for high-frequency waves. The sensitivity goal for each interferometer is shown in figure 2.2. This so-called *xylophone* configuration separates the high laser power required for good high-frequency performance from the cryogenic mirror suspension systems employed for a good low-frequency sensitivity into two separate, parallel systems. In order to achieve a sufficient sensitivity at high frequencies the light power in the arms of the high-frequency interferometer needs to be in the megawatt range. Thermal noise considerations on the other hand require cryogenic optics to reach the sensitivity goal at low frequencies. Operating cryogenic optics at a level of several megawatts of light power presents a serious technological challenge that is extremely hard to master. Even for the best mirrors that state-of-the-art coating technology can produce, the residual absorption of only about one ppm leads to an absorbed power of several watts at a circulating light power level in the megawatt range. The resulting thickness of the suspension fibres, which would be needed to remove the heat, would spoil the performance of the ultra low loss suspension.

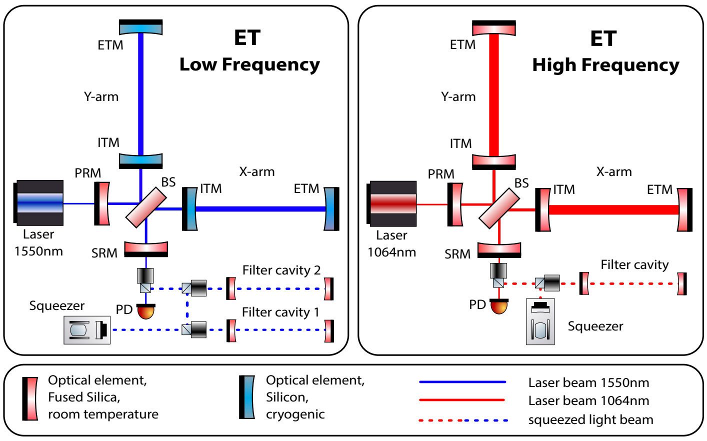

Figure 2.3: Simplified sketch of the ET low- and high-frequency core interferometers of a single ET-detector.

The interferometer dedicated to detecting high-frequency gravitational waves (ET-HF) in the range from about 30 Hz to 10 kHz will be operated at room temperature, will use fused silica optics with a diameter of about 60 cm and a mass of about 200 kg each, will have a light power of about 3 megawatts in the interferometer arms, and will run with an interferometer configuration optimized for high frequencies (tuned Resonant Sideband Extraction). The cryogenic, low-frequency interferometer (ET-LF), operated at a temperature of 10-20 K and aimed at the frequency range from 1.5 Hz to 30 Hz, will use signal recycling tuned to maximise low-frequency sensitivity, will have a light power of 18 kW in the interferometer arms, and silicon mirrors with a diameter of about 45 cm and a mass of about 200 kg. A simplified sketch of the optical layout is shown in figure 2.3. The xylophone configuration addresses two other challenges as well:

Control noises: Many noise sources limiting the second generation GW detectors at the low frequency end become more challenging with increased optical power: classical radiation pressure forces and torques originating from residual misalignments and beam jitter dominate the dynamics of the interferometer mirrors and hence the local and global control loops. The xylophone concept will help ET to achieve its unprecedented low-frequency sensitivity target, by minimising the radiation pressure driven forces on the mirrors of the ET-LF detector.

Shot noise vs radiation pressure noise: Due to the fact that the shot noise contribution scales inversely with the square root of the optical power, but the photon radiation pressure noise contribution on the other hand scales proportional to the square root of the optical power, it will be hard to obtain the desired bandwidth with a single detector. The xylophone allows us to optimise quantum noise through operating the high and low frequency interferometers at very different optical powers.

Core optics

The core optics are the four main mirrors making up the Fabry-Perot arm cavities and are the heart of the ET interferometers. To ensure the best optics, the three ingredients of a mirror, i.e. substrate, polishing and coating, must be manufactured using state-of-the-art technology. The temperature at which the mirror is operated has a strong impact on the technological choices to be made. ET will require larger mirrors than current generation detectors. The large mirror mass will not only reduce radiation pressure effects but will also allow us to use larger sized beam spots on the mirror surfaces for lowering thermal noise effects.

The mirror substrates must meet some demanding optical and mechanical specifications, and should be available in large sizes with surfaces polished to sub-atomic level accuracy. Due to these constraints, only a few specific materials are considered:

Fused silica is the substrate of choice for all the current room temperature interferometers. Due to its use for first and second generation gravitational wave detectors, this material has been extensively characterised at room temperature. Moreover the polishing and coating technologies are now highly developed for this material. Serving as a pathfinder for ET, the upgrade of Advanced Virgo, called Advanced Virgo+ will use fused silica test masses with a diameter of 55 cm and a weight of 100 kg.

Silicon is the preferred candidate material for the test masses for the cryogenic ET low-frequency interferometers. Unlike fused silica, silicon is not transparent at a laser wavelength of 1064 nm and so the operating wavelength of the LF interferometers has to be shifted to 1550 nm. In contrast to fused silica, silicon has excellent mechanical and thermal properties at cryogenic temperatures and is easily available in relatively high quality due to the large market of the semiconductor industry. The maximum available diameter and purity of silicon depends on the fabrication process. The two main growing processes for single crystal silicon used by the semiconductor industry are the Czochralski (CZ) and the Float Zone (FZ) methods. CZ silicon is grown from a silicon melt in a fused silica crucible, resulting in relatively large samples with moderate purity. Using the CZ growth technique, silicon ingots up to 45 cm in diameter can be produced, though 30 cm is still the dominant wafer diameter in the semiconductor industry. The FZ process purifies CZ grown ingots but only works to a diameter up to 20 cm. Impurities from the crucible in the CZ process can be reduced by applying a magnetic field, the so called magnetic Czochralski (mCz) growth technique. Still FZ silicon contains significantly lower concentrations of impurities. In the recent years the optical properties of silicon have been thoroughly characterised. According to the latest measurements, mCZ is the most suitable approach for ET as it can combine large diameter ingots (45 cm diameter) with very low impurities and absorption at the 20 ppm/cm level. This level of absorption is promising but further developments are required, and the effects of residual birefringence intrinsic to crystalline materials have to be evaluated.

A backup substrate choice could be sapphire as a candidate material for ET-LF. Sapphire is already used in the Japanese cryogenic interferometer KAGRA, though much smaller in size than what is required for ET, but extensive experience has been acquired on operating those mirrors in cold conditions. Like for silicon, large sapphire boules with excellent optical properties still have to be demonstrated.

Polishing of the surfaces of fused silica substrates is well mastered thanks to the current generation of room temperature interferometers as well as EUV lithography optics and hence presents minimal risks. For the Einstein Telescope main mirrors, the already-demonstrated surface quality such as surface height errors below 0.3 nm RMS for low spatial frequencies (also called figure error) and below 0.1 nm RMS for the micro-roughness will be enough, albeit it must be achieved on a larger area since the ET mirrors will be bigger.

Polishing of silicon does not carry any difficulties as this substrate material is heavily used for X-ray mirrors, but a demonstrator meeting all the ET polishing specifications will have to be produced. Experiences from polishing companies indicate that silicon could be polished the same way as fused silica and similar surface figure accuracy can be achieved (using also ion beam figuring to reach sub-nanometer surface height errors). However, the very low micro-roughness is likely to be more challenging compared to fused silica.

Thin optical coatings, a few microns in thickness, must be added to the surfaces of the mirrors to make them highly reflective for the used laser wavelength. Since the thermal noise from these coatings will limit the sensitivity of current room-temperature detectors at their most sensitive frequencies, it is essential to reduce coating thermal noise to achieve the ET design sensitivity. To meet the goal of a factor of 25 improvement in strain sensitivity over the Advanced LIGO design at 10 Hz, ET-LF requires a reduction in coating displacement thermal noise by at least a factor of 10 with respect to Advanced LIGO. A large fraction of this improvement can be obtained from operating at low temperature and through the use of larger laser beam spots on the mirrors. The target for ET-HF is a factor of 8 reduction at 100 Hz for the contribution of the thermal noise to the strain amplitude spectral density (ASD) compared to the Advanced LIGO design. Accounting for the larger laser beam in ET-HF and longer arm length, this sets a requirement of a reduction in displacement induced thermal noise by a factor of about 2 from the coating materials, which should already be achieved for the upgrades of Advanced LIGO and Virgo by 2024.

Significant progress has been made towards the development of coatings suitable for low temperatures in ET-LF. There are several highly-promising routes to meeting the coating thermal noise and optical absorption requirements. However, further studies are required optimising the trade-off between coating absorption requirements, suspension thermal noise, ultimate mirror temperature and substrate thermoelastic noise. Achieving significant reductions in coating thermal noise at room temperature may be more challenging than at low temperature. Work in this area is ongoing, both for ET and for upgrades to the Advanced LIGO and Advanced Virgo detectors.

Michelson interferometer

Each individual interferometer has a classical dual-recycled Michelson topology with arm cavities. This is a mature technique, well tested by second-generation detectors, Advanced LIGO and Advanced Virgo. More elaborate topologies like speedmeter interferometers fit equally well into the planned infrastructure but are not considered for the initial installation, as they have not yet reached the required level of maturity.

Each of the ET interferometers will require a novel high power laser system with low intrinsic noise called the high power laser (HPL) in the following. The ET-HF HPL has to operate in a single-frequency continuous-wave (cw) mode at a wavelength of 1064 nm and needs to deliver 700 W in a linearly polarized fundamental spatial HG_{00} mode. With the assumption of roughly 30% loss in the injection path this leaves 500 W at the input of the main interferometer. The higher-order mode content of this laser should be below 10% and the polarization purity at least 1/10. The ET-LF HPL needs to operate in a single-frequency continuous-wave (cw) mode at a wavelength of approximately 1550 nm with similar spatial and polarization purities as the ET-HP HPL. This different wavelength for ET-LF results from the material choice for the test masses. A laser power of 5 W is required to allow for 3 W to be injected into the main interferometer. Both laser systems have to achieve demanding noise requirements for all frequencies in the observation band: a frequency noise in the order of $10\,\mathrm{mHz}/\sqrt{\mathrm{Hz}}$, relative lateral and angular beam fluctuations in the $10^{-6}/\sqrt{\mathrm{Hz}}$ range and a relative laser power noise of roughly $3\times10^{-10}/\sqrt{\mathrm{Hz}}$. These requirements appear to be feasible using current approaches to stabilization.

Advanced detectors have recently been upgraded with *squeezed light* which generates correlations between the phase and the amplitude quadratures. In the shot noise dominated frequency range squeezed light is used which shows lower phase fluctuations (at the cost of the amplitude fluctuations) in comparison to classical laser light in the interferometer arms. In the low-frequency, radiation pressure dominated range the fluctuations need to be lowered in the amplitude quadrature. Providing the right spectral dependence of the so-called *squeezing angle* can be achieved by reflecting squeezed light off a filter cavity. For ET we assume 15 dB initial squeezing level at the squeezing source and an effective squeezing level of 10 dB to be available (equivalent to a shot noise reduction from a laser power increase by a factor of 10).

The squeezing level, and with it the sensitivity improvement that can be reached, depends on the optical losses in the squeezer, the filtering optics, the interferometer, and all optical devices on the way to the photodetector, including the photodetector efficiency itself. It will therefore be essential to keep the optical losses as low as possible. These levels of squeezing, and maintaining the low losses required to preserve the squeezing, will require technology development.

2.1.2 Seismic isolation and suspension

Seismic isolation refers to the stage(s) of isolation systems directly connected to the ground. It fulfills two main functions: to suppress the seismic noise over a wide range of frequencies including at and below the resonance frequencies of the suspension system; and to reduce the RMS input motion to the suspension systems, particularly at the suspension resonances and the micro-seismic peak(s). It also provides large-scale and slow position control of the test-masses.

The baseline for ET consists in using a longer Virgo-style Superattenuator. The increased length (17 m) reduces the normal mode frequencies, pushing the seismic wall down to ~ 2 Hz. The main advantage for such a choice is that it employs a design thoroughly tested during many years of operation in Virgo and it requires relatively little R&D to be adapted to ET. It therefore represents a safe pathway towards a 3G configuration.

A possible alternative to be investigated via a dedicated R&D program is the coupling of a Superattenuator to an inertial platform controlled in all 6 degrees of freedom. This configuration would make use of a combination of technologies and expertise developed in the GW field in the last decade. The inertial platform would support the Superattenuator, an approach that was envisaged for use in Virgo. The Superattenuators are supported on a rigid platform resting on 3 elastic feet that can be actuated by piezo actuators in order to actively control of the ground tilt. The ET design would extend this concept to also improve horizontal performance. An advantage of this alternate could be relaxed requirements on the physical infrastructure, providing an advantageous cost and risk trade.

Thermal noise of the mirror suspensions

The main requirements of a gravitational wave mirror suspension are to reduce seismic noise input from the ground and to provide a mechanism to steer the mirror via electromagnetic/electrostatic forces for alignment and control. This must all be done while minimising the thermal noise arising from the suspension. Suspension thermal noise arises due to mechanical dissipation in the materials which make up the suspension (Brownian noise) or through thermoelastic noise, the coupling of statistical temperature fluctuations through the thermo-mechanical properties of the suspension materials such as the thermal expansion coefficient and the Young's modulus.

High-frequency suspension: The current room temperature interferometers (Advanced LIGO, Advanced Virgo, GEO) utilise fused silica as a material to suspend the test masses. The suspensions were initially pioneered in GEO 600 around 1990-2000 (5.6 kg optics), upscaled for use in Advanced LIGO and Advanced Virgo (both 40 kg optics) between 2000-2012, with installation occurring from 2015 onwards. Fused silica is the material of choice as it can be pulled into long thin fibres, can be welded to form monolithic structures, has extremely low internal friction, and has a breaking strength in excess of 4 GPa. The ET-HF suspension mirror mass will be increased to 200 kg to provide lower suspension thermal noise and also reduction of radiation pressure noise. Building on the heritage and experience of many years in the field, there is a mature technology for room temperature suspensions. The Heraeus Suprasil family of synthetic glasses will be utilised, and initial work has shown that fibres of suitable geometry can be pulled and welded. While the fused silica solution is already well developed, there needs to be work devoted towards the demonstration of a full scale ET HF prototype. Key areas of future R&D include the testing of a full scale prototype suspension with fused silica fibres with operating stresses of around 1 - 1.5 GPa; activities to prove the stress-corrosion properties of fused silica, and the techniques required to bond/attach the ear/fibres to the test mass; the demonstration of sensors and actuators with sufficient sensitivity for suspension local control and damping; and the demonstration of mitigating excess charges in electrostatic actuation.

Low-frequency suspension: In addition to providing a low seismic/thermal noise platform, the ET low frequency suspension also has to fulfill a second crucial duty - to extract the thermal load that is put into the optical component by the laser beam and residual ambient thermal radiation ($\simeq 40$ mW). The materials of choice are crystalline materials that have a very high thermal conductivity at low temperatures and also display low mechanical loss. In particular, both silicon and sapphire are excellent materials in the temperature region of interest (10 - 20 K). Sapphire has a higher thermal conductivity than silicon below 20 K. Sapphire fibres for heat extraction have been investigated in detail by Japanese groups for KAGRA. At low temperatures the mechanical loss of the suspension, which defines the thermal noise performance, is a key driver for the suspension design. Heavy test masses will be utilised, with the addition of low temperature to provide enhanced thermal noise performance. Thermoelastic noise drops away sharply with decreasing temperature, and indeed for silicon is zero around 120 K and below 20 K. While sapphire is the baseline for KAGRA, the need for large and heavy test masses (200 kg) highlights silicon as a preferred material for ET-LF. Silicon suspension elements are currently under investigation in the form of fibres and ribbon-like geometries. Fabrication techniques include (i) Laser Heated Pedestal Growth, (ii) micro pull down and (iii) etching from wafers. R&D activities are needed on several aspects of the low frequency suspension:

- fibre fabrication techniques, to develop long thin silicon or sapphire fibres, and to join the suspension elements to the ears and test masses;
- detailed FEA modeling of the final stage suspension, in order to estimate the effects of real fibre geometries on the thermal noise performance;
- inertial sensors and actuators, operating at cryogenic temperature, with high sensitivity and large bandwidth;
- prototyping the lower stage suspension, including a fast turnaround tabletop systems and small scale prototypes of 10 m arm length with payload in the 1 kg to 10 kg range.

2.1.3 Vacuum system

In laser interferometers for GW detection the instrument has to be kept under High-Vacuum or Ultra-High-Vacuum (HV, UHV) for several reasons:

- reduce the noise due to residual gas fluctuations along the beam path to an acceptable level;
- isolate test masses and other optical elements from acoustic noise;
- reduce test mass motion excitation due to residual gas fluctuations, i.e. reduce residual gas damping;
- contribute to thermal isolation of test masses and of their support structures;
- contribute to preserve the cleanliness of optical elements.

The power spectral density of gas-induced fluctuations in the optical path length has been calculated choosing conservative beam shape parameters and taking a safety factor of at least 10 with respect to the pressure producing a phase noise at the limit of the best sensitivity for the ultimate detector envisioned for ET. The residual gas composition will be dominated by hydrogen with presence of water and other gases; we will keep the total residual pressure below ca. 10^{-10} mbar, corresponding to a noise level below 10^{-25} $Hz^{-1/2}$. The vacuum system will be extremely clean from heavy organic molecules, both to limit the phase noise and to prevent pollution of the optical components. Hydrocarbon partial pressure shall be at a level below 10^{-14} mbar.

The technologies that were developed and employed in the existing gravitational wave observatories have been shown to meet the stringent requirements of vacuum integrity, very low hydrogen and heavy molecule outgassing, minimal particulate generation, low vibration, and appropriate stray light optical absorbance for successful operation. However, straightforward extrapolation of the costs for extending the interferometer vacuum beam enclosures from the current lengths of 3 - 4 km/arm to $\sim$ 10 km/arm indicates the need for investigation of a range of technologies and materials that could significantly lower the final cost, facilitate construction and increase the life-time of the vacuum systems for next generation observatories.

2.2 Cryogenics

The low-frequency ET detector test masses will be cooled to 10 - 20 K to reduce thermal noise, which presents a limit to the low-frequency sensitivity for the second generation of detectors. The payload, i.e. the last stage of the test mass suspension, will include a mass used to steer the mirror, called marionette, where the thin wires used to suspend a massive silicon (or sapphire) mirror are attached. The payload (including reaction masses) will weigh one ton and it will be cooled in a dedicated cryostat, which will include two radiation shields at 8 K and 80 K. The entire payload and cryostat will be hosted in the lower part of the vacuum towers hosting the long Superattenuators. The need to preserve the high mechanical quality factor of the mirror and the ultra-high quality of the optics necessitates keeping the mirror at low temperature in vacuum while avoiding any mechanical contact or exchange gas. This imposes stringent dimensional requirements on the mirror suspension wires, that represent the only conductive path to transmit the refrigeration power and keep the optical element in thermal equilibrium. In order to minimise the coupling of vibration noise generated by the cooling system, it will be connected to the marionette via extremely soft heat-links of high thermal conductivity (similar links have been developed already in KAGRA). The cooling system is based on pulse-tube technology. Alternatively a system based on superfluid ^{4}He is being studied. Moreover, in order to reduce the thermal radiation from the beam duct to the cold mirror, cryo-shields, tens of meters long, will be installed along the vacuum tubes and appropriate low-emissivity coatings will be deposited on their inner walls.

2.3 Site and Infrastructure

2.3.1 Site requirements and characterisation

The achievable detector sensitivity and duty cycle, infrastructure lifetime, and its construction cost depend strongly on the characteristics of the ET site. This concerns underground parameters such as rock quality, groundwater, and site stability, but also surface parameters such as remoteness of the site, accessibility, and connection to existing infrastructure including public utility. In addition, socio-economic criteria must be considered for a big infrastructure like the Einstein Telescope, and it is important to understand and respect the interest of the local population.

The achievable detector sensitivity, duty cycle and infrastructure lifetime are of prime interest to the science community. The impact of environmental noise on detector sensitivity is discussed in Section 2.3.2. The duty cycle of a detector also depends on its environment since regional earthquakes, but potentially also major storms, railroad traffic and other anthropogenic sources can produce enough ground motion to make a continuous operation of the detector challenging or impossible. In terms of ET's immediate science return, site parameters affecting the sensitivity of the detector are most important, but the infrastructure lifetime determines how many cycles of major detector upgrades, leading to sensitivity improvements, one will be able to realize, which means that infrastructure lifetime plays an equally important role.

The lifetime of an underground infrastructure is above all influenced by groundwater conditions (hydrogeology) and geological stability. Water inflow into tunnels requires water-handling systems, which might act as underground sources of seismic noise. Water that is being moved to the surface typically must be considered waste and pass through a water-treatment plant. The presence of water in the tunnels increases the humidity of the tunnel air, which drives atmospheric corrosion potentially accelerated by the presence of certain elements in groundwater such as chloride, and of microbes, e.g., sulfate-reducing bacteria, leading to microbially induced corrosion. Air humidity is controlled by ventilation systems that may also act as sources of underground seismic noise. With time, drainage systems to prevent water inflow can deteriorate leading to water leaks and tunnel lining deformation, which means that monitoring and maintenance are necessary in aged tunnels.

Geological conditions determine the site stability. The most stringent requirements on differential motion across the tunnels does not come from the tunnel construction itself, but from the hosted detector infrastructure. The vacuum pipe will be mounted as a series of modules welded at their interfaces. Stress on the welding lips needs to remain small over the infrastructure lifetime. For example, across the 15 m modules used in the Virgo detector, only a few millimeters of integrated differential displacement is tolerable. Another requirement comes from the positioning of the optical axis inside the vacuum pipe, which means that one needs to impose a maximum differential displacement across the full tunnel length as well. Drilling of the tunnel through active shear zones must therefore be avoided, and subsidence should be limited by driving the excavation through high-quality rock, or by employing hydraulic pipe-alignment systems like in Virgo.

The characterization of the site is happening in two steps. A preliminary survey of both condidate sites in Sardinia and in the Meuse–Rhine Euroregion is ongoing for site selection, relying mostly on surface measurements, and on a collection of already available site data. A few boreholes are under preparation to obtain at least some information about groundwater conditions, the local geology, and underground seismic spectra. This information will be used to obtain first construction-cost estimates and to predict eventual complications in tunnel construction and maintenance. Characterization of environmental noise over at least one year is important to make accurate noise predictions for ET. Generally, the impact of the candidate sites' environments on the ET sensitivity and operation needs to be assessed and evaluated. Solutions need to be found for waste removal (rock from excavation and tunnel water), and local support needs to be secured for realizing the ET infrastructure and for preserving the site quality. Once the site is chosen, extensive borehole studies of the future ET site will be necessary for construction planning and for a detailed cost estimate.

2.3.2 Newtonian noise and other environmental noise

Several environmental factors can influence the sensitivity of a gravitational-wave detector. Most importantly, seismic fields produce ground vibration that needs to be filtered out by a seismic isolation system for the suspended test masses. Seismic fields also lead to perturbations of the gravity field, which produces another random force on the test masses. Detector noise produced by terrestrial gravity fluctuations is also known as Newtonian noise to distinguish it from the effect of gravitational waves, which are described by general relativity. Similarly, atmospheric gravity fluctuations from acoustic, temperature and humidity fields are sources of Newtonian noise. Acoustic fields also act as sources of vibration of detector structure together with seismic fields. Electromagnetic fluctuations can produce detector noise by coupling with magnetic components of the detector, or by inducing noise at connectors and in cables acting as antennas. Finally, cosmic rays might cause test-mass charging, which then leads to excess noise by altering the dynamics and thus impeding the performance of the seismic isolation system.

None of these environmental factors can be neglected a priori in ET. It is likely that test-mass charging by cosmic rays will not play a role in ET since the underground environment acts as a shield against cosmic rays. Newtonian noise from atmospheric fields is mitigated by constructing ET several hundred meters underground leaving only minor (but likely significant) contributions to Newtonian noise from acoustic fields in the caverns. The seismic isolation system will be designed with the goal to provide sufficient seismic isolation without depending significantly on properties of the seismic field. Electromagnetic fluctuations, either being produced by the detector electronics or associated with Schumann resonances, depend weakly on the site where the detector will be built leaving seismic Newtonian noise as the main site-selection criterion with respect to environmental noise. It is crucial though that the underground environment will not be perturbed by detector infrastructure like the cryogenic system, water pumps, ventilation, and other machinery required to operate the detector. Experience with the Japanese underground detector KAGRA will help to optimize the ET infrastructure design to avoid excess noise.

Only some contributions to seismic Newtonian noise decrease with increasing detector depth. The contributions suppressed underground are mostly associated with seismic surface waves. Contributions from so-called body waves, i.e., seismic waves able to propagate in all directions through Earth, depend weakly on detector depth. In other words, the body-wave contribution sets a lower limit to seismic Newtonian noise, which is reached when the detector is so deep that body waves dominate the local seismic field and surface contributions can be neglected. Underground levels of seismic displacement are therefore a strong site-selection criterion. Newtonian noise in ET from seismic surface waves can also be significant, even many 100 m underground, depending on seismic speeds. However, while there is no known technology that could mitigate effectively Newtonian noise from body waves, surface waves could be easily monitored by seismometer arrays and the seismic data be used to subtract efficiently the associated Newtonian noise from ET data if necessary.

2.3.3 Tunnels and caverns

The design of the underground infrastructure is based on a trade-off between the cost of the realization and the fulfillment of several scientific requirements, such as, the capability of hosting the 6 interferometers, the availability of free space, safety, etc. The main elements are: the tunnels, the caverns, the access routes. Important works are also needed on the surface, with the realization of buildings and roads.

The underground scheme consists of an equilateral triangle of an approximate side length of 11 km. The access is granted in the form of an inclined access tunnel or a vertical shaft, which connects the caverns at the intersection points with the surface. The access tunnels/shafts are the main points of access during construction and operation. Several caverns of various geometry are situated in the vicinity of the intersection points. An additionally lined borehole/service tunnel offside the crucial and vibrational sensitive cavern structure is foreseen for water management during operation.

Tunnels

Due to the length of the tunnels, a mechanised excavation method utilising Tunnel Boring Machines (TBMs) are considered for the design stage. It is envisaged to excavate the whole length of the tunnel in one stretch without further points of intermediate access. The inner diameter will be 6.5 m, needed to host 4 vacuum pipes, which must be straight to several cm (and not follow Earth's curvature). The outer diameter could vary in a range between 7.3 m and 8.4 m depending on the type of TBM excavation (shielded or open) and consequently by the kind of lining of the excavated tunnel (segmental pre-cast or shotcrete lining). The concept of the shielded TBM type considers a continuous mining process with parallel installation of a segmental lining, which takes over the support of the rock mass. A single-layer segmental lining with all-rounded preformed elastomer gaskets would be used to control water inflow to the tunnel. Thus the thickness of the reinforced concrete segments is at least 30 cm. Contrary to a shielded TBM, the open TBM is based on applying shotcrete, steel ribs and rock bolts. As part of the excavation concept, rock mass grouting is considered, to decrease the overall inflow of groundwater to the tunnel, since the shotcrete support is more prone to water inflow. The overall thickness of the shotcrete support layers is also of the order of 30 cm thick consisting of two layers. Regardless of the straight direction demanded for the subsequent installation of the vacuum pipes in the tunnels, the TBM excavation implies an inherent meandering of the tunnel axis (<25 cm amplitude) as a reaction to heterogeneous geological conditions while driving.

Caverns

The caverns of the underground laboratory are located at each vertex of the triangle. A sketch of the cavern layout at one vertex is shown in Figure 2.4.

The largest cavern (A) is formed by an intersection of two caverns with an identical shape at an angle of 60°, with lengths of 150 to 200 m. Each of these caverns connects to a 12 m wide and 500 m long tunnel that contains a series of three caverns (C, D, E), and cavern E marks the transition into the 10 km long TBM tunnel. The three caverns (C, D, E) have a spacing of several tens of meters in between them.

Cavern A hosts the main beamsplitter and input output optics for ET-LF, and connects to the main access

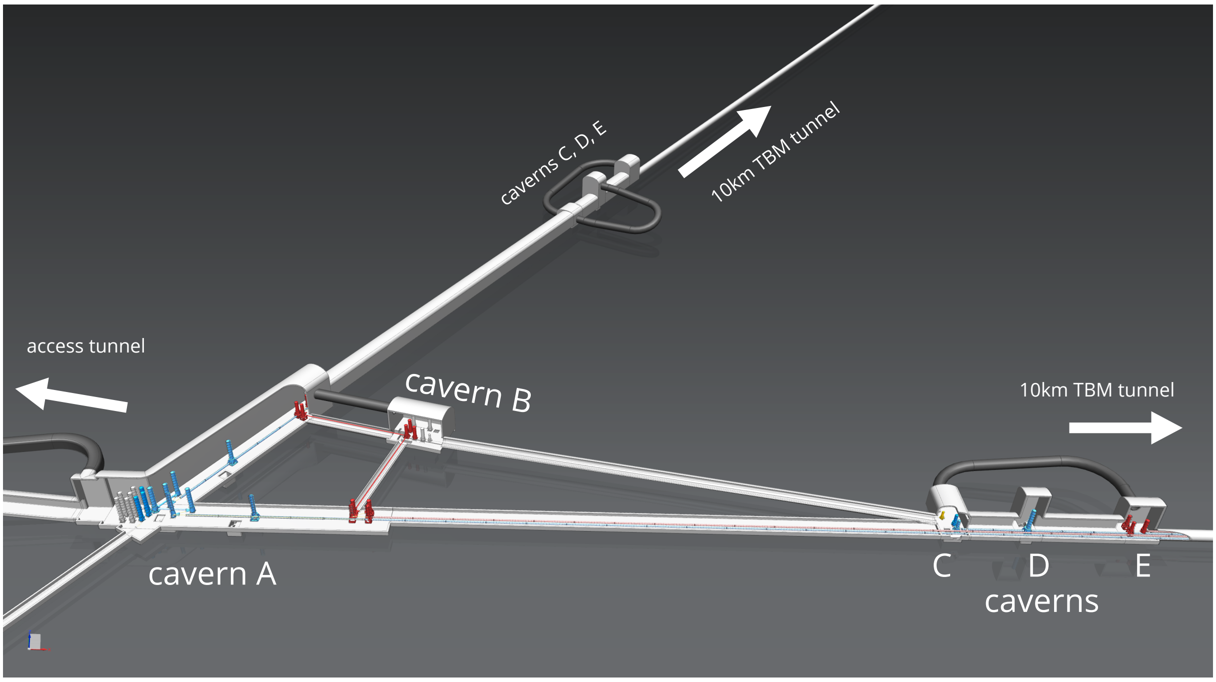

Figure 2.4: Sketch of the cavern layout in one corner of the triangle.

point of the underground structure and to a smaller 1 km long tunnel for the LF filter cavities. In addition, another cavern (B) is located along the bisecting line of the angle between the two main arms. It hosts the main beamsplitter and input-output optics of the ET-HF interferometer. It is linked to the two branches of the cavern A and carries an additional connection tunnel to cavern C that hosts the filter cavity for ET-HF.

The caverns and the connecting tunnel are of various shapes and will be excavated by drill and blast. The design foresees a horseshoe-shaped design of all cavern, tunnels and galleries. The shape of these caverns and tunnels might be redesigned to fit the geomechanical requirements.

Access

The underground infrastructure can be accessed by elongated inclined tunnel ramps or large vertical shafts. The best option may strongly depend on the geography, geology and surface land use and will therefore be finalized after the choice of the site.

Three construction methods are available: access by inclined elongated ramp; access by inclined helical ramp; access by vertical shaft. An “inclined elongated ramp” equally to an “inclined helical ramp” connects the surface with the cavern structure situated a few 100 m below the ground surface. The length of the access tunnel is determined by its slope of max. 10%. It is not required to build the access tunnel in a straight line. Any combination of straight and curved sections is possible. The clearance profile of any inclined tunnel shall support all aspects of construction, mucking, ventilation and safety.

Daylighting shafts are the shortest connection of the surface to the underground structure. The vertical shaft is considered as the single line of access during construction and operation. Nevertheless, for the long-term service, changes to the shaft hauling system are necessary to comply with the demands of the laboratory.

The decision on the best type of access depends on a combination of ecological, logistical (connecting roads), geological/hydro-geological, safety and monetary aspects. Due to further site-dependent impact factors, currently only the monetary aspects of the access have been analysed. Both types of access can be accomplished with standard tunnelling equipment. The shaft solution implies the utilisation of specialised equipment for shaft lowering, while the inclined access tunnel can be excavated with standard tunnelling equipment, as foreseen in any way for the excavation of the underground caverns.

2.3.4 Roads and buildings

The construction of the ET facility will include all the surface technical and general buildings needed for the construction and operation of the research centre. The surface buildings will be located mainly at the access points to the underground infrastructure and consist of laboratories for the construction and the installation, warehouses, clean rooms, mechanical and electrical workshops, control buildings, office buildings, technical buildings for plants, a visitor centre, and access buildings.

2.4 Computing Infrastructure

As with most large experiments, the scale of ET computational challenges is such that the computing infrastructure architecture cannot be solely based on local resources. We expect that most of ET computing will be done off-site in external computing centres, also including much of the low-latency searches. So, the on-site computing infrastructure will be limited to what is needed for detector control, data buffering, preparation and transfer, unless special needs will be discovered (for example, the need for sizable AI clusters to manage some aspect of detector control such as alignment optimization). The physics community at large has a long experience in designing, building and managing global-scale computing infrastructures that can be exploited to cater to such needs; the main GW peculiarity here is the need to generate low-latency alerts for the wider astronomical community.

2.4.1 Computing challenges and strategies

ET will not, even by today's standards, generate a huge data volume with respect to the 1 PB of data per year produced by a 2G interferometer; it is the quantity of valuable scientific information hidden in the data that will grow, and with it the amount of computational power needed to extract it. Factoring in the expected technological developments in computing hardware (Moore's law is starting to fail for CPU performance, whereas its network capacity equivalent is not), it turns out that data management will most likely not be an outstanding issue; computing power itself, however, will be challenging, particularly for Compact Binary Coalescence matched-filter searches and parameter estimation. The better sensitivity implies a larger parameter space to explore, so much larger template libraries have to be used for matched-filter searches; the computing power needed for parameter estimation of course scales with the expected event rate.

Even not taking into account complications such as the analysis of day-long signal candidates, for which the detector moves with respect to the source, a naive extrapolation from current activities gives an increase of *at least* three orders of magnitude in computing power from 2G to 3G data. This is clearly out of reach, and a number of mitigation actions need to be planned (exactly like what is being done today in the HEP community for High-Luminosity LHC).

A community of computing experts needs to be created alongside the GW scientists to optimize code and efficiently exploit heterogeneous hardware and software platforms: plain high throughput facilities for embarrassingly parallel workloads, high performance facilities for lower-level parallelism, hardware accelerators for e.g. Deep Learning training, and possibly, in the decade timescale, also more exotic technologies like quantum computing or neuromorphic processors. Again, this must be done in synergy with the larger physics community, which is facing similar issues. Activities such as mock data challenges will need to be planned very early in the project to explore possible data analysis strategies and optimise the scientific output of the available computing power.

2.4.2 Distributed computing infrastructure

Before and during the Advanced Detectors era, distributed scientific computing activities in the EU and worldwide were mostly driven by LHC requirements, which led to the design and deployment of the WLCG infrastructure. In the timeframe of the initial ET phases, several other collaborations will reach LHC-like scales both in data sample size and computing power requirements, e.g. SKA and CTA, but also outside of the physics community, e.g. with the Human Brain project. Furthermore, High Luminosity LHC runs will increase both its data volume and computing requirements by large factors. We therefore expect that a large scale shared European computing infrastructure will be available to meet the needs of all these collaborations; several R&D projects already exist or are being proposed to develop such an infrastructure. We plan to use the services offered by the European Open Science Cloud (EOSC) as much as possible, since the ET requirements will represent only a fraction of the total computing activities.

Some of the services that will form the framework for an ET Distributed Computing Infrastructure, either coming from the EOSC or evolution of existing services, include:

- archival storage services, with non-reproducible data duplicated over several “core” data centres;
- Data Management services to timely and reliably transfer raw data from the facility to the relevant external data centres, with functionalities for automatic issue detection and data loss recovery;
- network services, provided by national research and education networks (NRENs) and the pan-European data network for the research and education (GÉANT), possibly with dedicated links between the facility and the core data centres and/or a network environment similar to LHC-ONE, for data transfer, access and access to the general purpose network (GPN);
- a data distribution infrastructure based on the concept of Data Lake and cache-based Content Delivery Network;
- cloud access to heterogeneous, distributed High Throughput Computing and High Performance Computing resources and services in a set of core data centres and a network of other resource providers;
- a common authentication and authorisation infrastructure, based on trusted identity providers and an ET authorization service, federated with the equivalent for existing 2G and other 3G collaborations;
- a public alert generation network, with event database services;
- an Open Data platform for general release of public data, compliant with FAIR principles, evolution of the existing Gravitational Wave Open Science Center (GWOSC) infrastructure and integrated with the Virtual Observatory platforms that will be available.

Most of the GW computing workloads are embarrassingly parallel, and hence well suited to be run on conventional high-throughput distributed infrastructures, with the exception of the numerical relativity simulations used to prepare the template libraries. Several currently used analysis pipelines, and Deep Learning algorithm training, can profit from the use of GPUs and hardware accelerators. The exact mix of architectures needed will depend upon what will be available in ten years from now both in terms of computing technology and GW data analysis techniques.

Conclusion

This document provides a summary of the science case for ET, the design and feasibility of the required infrastructure, and the design study of the ET detectors. For a more extensive treatment of the same topics please see the ET Design Report Update 2020, available at: `https://apps.et-gw.eu/tds/?content=3&r=16984`.