PROJECT PERIODIC REPORT

Grant Agreement number: 211743

Project acronym: ET

Project Title: ET—Einstein gravitational-wave Telescope

Funding Scheme: Collaborative project

Date of the latest version of Annex I against which the assessment will be made: 25/06/2008

Periodic report: 1st

Internal periodic sub-report: 3rd (18 months)

Period covered: from: 5/05/2008 to: 31/10/2009

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Declaration by the project coordinator

I, as coordinator of this project and in line with my obligation as stated in Article II.2.3 of the Grant Agreement declare that :

- The attached periodic report represents an accurate description of the work carried out in this project for this reporting period
- The project (tick as appropriate):

X	has fully achieved its objectives and technical goals for the period;
	has achieved most of its objectives and technical goals for the period with relatively minor deviations[1];
	has failed to achieve critical objectives and/or is not at all on schedule.

- The public Website is up to date
- To my best knowledge, the financial statements which are being submitted as part of this report are in line with the actual work carried out and are consistent with the report on the resources used for the project (section 3.6) and if applicable with the certificate on financial statement.
- All beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organizations and SMEs, have declared to have verified their legal status. Any changes have been reported under section 5 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

Name of Coordinator: Jacques Colas

Date: 26 November 2009

Signature of Coordinator: ……………………………………………………………………………

[1] If either of these boxes is ticked, the report should reflect these and any remedial actions taken

Contents

1. Publishable summary

The Einstein Telescope (ET) project is a conceptual design study of a third generation gravitational wave (GW) interferometric observatory. The aim of ET is to realize an observatory that will open the era of the precision GW astronomy and astrophysics. This should be obtained by improving, of about one order of magnitude, the sensitivity of the advanced GW detectors, currently under preparation, especially in the low frequency range (~1-10Hz). The keywords to obtain this ambitious target are to locate the observatory in an underground site, to suppress the seismic noise disturbances, and cryogenics, to suppress the thermal noise fluctuations. Many are the objectives of the ET design study and several are the cross-dependences between them. By choosing the appropriate design and technologies it is possible to tune the sensitivity of a GW detector, enhancing its performances in restricted frequency ranges; the design study aims to better evaluate the potential science reaches of such as observatory, according to the possible sensitivities and to address the design options and technological developments in order to optimize the science targets. A primary target of the ET design study is to define the requirements that an underground location should satisfy to be compliant with the ET requested sensitivity and to provide a list of potential site candidates. In this definition, ET aims to evaluate the rough cost of the infrastructures. An important objective of this study is the definition of the major technologies to be adopted in the ET observatory and to stimulate the R&D activities in the GW scientific community. The final result of the ET design study is a conceptual design of the major infrastructures of the observatory and of the most important components of the interferometer.

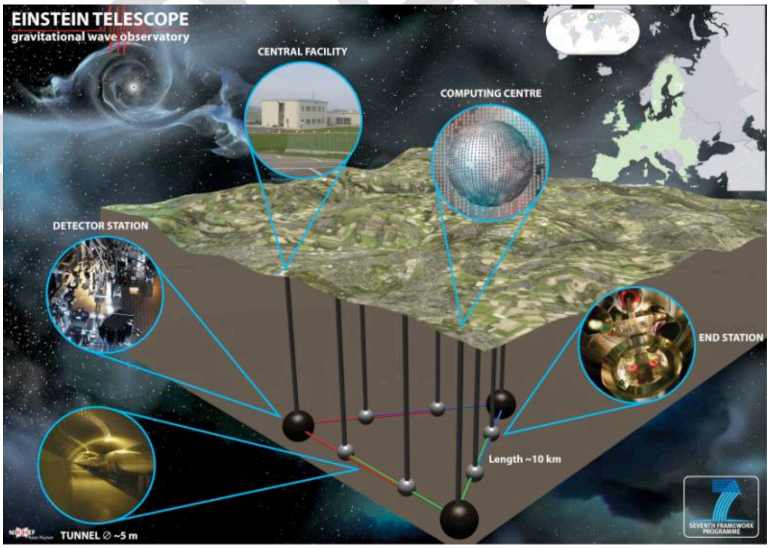


Figure 1 - Pictorial representation of the Einstein Telescope underground observatory

The ET design study officially started the 5th of May 2008. The main activities have been devoted to set up the scientific and management organization of this collaboration. The four scientific working groups, dedicated to the main technical aspects of this project (WP1 – Site and infrastructures, WP2 – Suspensions and thermal noise, WP3 – Geometry and Topology, WP4 – Astrophysics issues), have been formed and a chairman has been identified for each of them. The scientific activities started in each group, with meetings dedicated to the realization of the task list reported in the Annex I and to the identification of new possible activities. A large effort has been devoted to the enlargement of the scientific community involved in ET, contacting the scientists potentially interested in the project. In order to reach this objective an appealing and rich web site has been realized: http://www.et-gw.eu/ and a multitude of mailing lists has been set-up (http://www.et-gw.eu/mailing-lists) to network together the scientists interested to the project (science-team-et@ego-gw.it) and/or in one or more of the four working groups. The feedback of the gravitational wave community has been very positive and about 220 scientists registered to the ET *science team*.

Two general meetings have been organized, the first in collaboration with the ILIAS-GWA FP6 initiative to inherit the legacy of this project. This contributed to have the large participation (more than 110 scientists) at this ET kick-off event. The four working groups are continuing in parallel their activity as reported in the web page devoted to the WG meetings (http://www.et-gw.eu/working-packages-meetings).

The first achievement of the ET design study the production (WP4) of a *Science Vision* document that summarize the scientific potentialities of such as observatory. In the following list, a brief summary is extracted from that document:

Astrophysics: Measure in great detail the physical parameters of compact stars [i.e., neutron stars (NS) and black holes (BH)] in a binary system: constrain the equation-of-state of NS and solve the enigma of gamma ray bursts (GRB).

General Relativity: Test general relativity by comparing observations of massive binary star systems with numerical relativity (NR) predictions and constrain alternative theories of gravity (such as the Brans–Dicke theory) through the observation of NS–BH coalescences.

Cosmology: Measure cosmological parameters from standard sirens of gravity and probe the primordial Universe through the measurement of the GW stochastic background.

Astroparticle physics: Measure or constrain the neutrino and graviton masses through the detection of the GW emitted in a supernova.

As previously mentioned, a primary target of the study is the definition of the site requirements and the preparation of a list of possible candidates. The seismic noise at the selected site affects the performances of the ET observatory both by shaking the mirror suspensions point and by moving directly the mirror through the Newtonian attraction force between the test mass and the soil (so-called Newtonian or gravity gradient noise). Both the effects have been studied and a refined gravity gradient noise analytical model has been developed and cross-checked with a finite element model. Currently, if an enough deep underground site is selected, thanks to the good attenuation of the seismic and Newtonian noise, the very low frequency region (~2-3Hz) seems accessible. The selection of the site requires the evaluation of several parameters, like the geological characteristics of the soil, the human activities in the neighboring and the typical environmental conditions (wind, ocean waves, …). For this reason, an investigation on all these aspects, based on the data available on several databases is started.

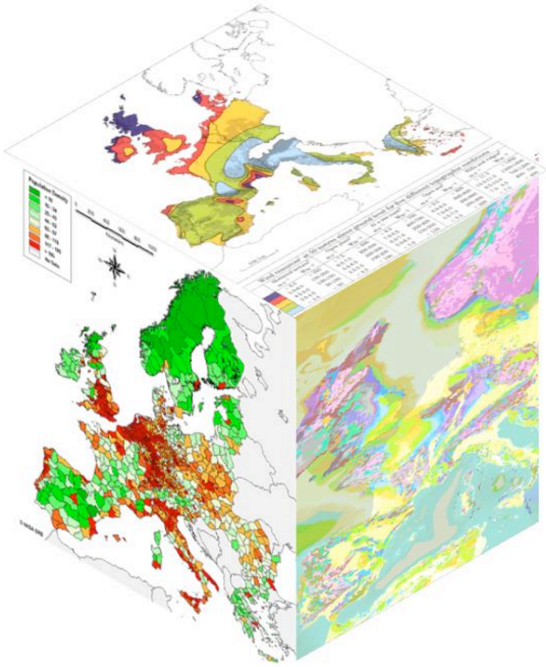


Figure 2 - Several aspects must be evaluated to select a list of candidates for the realization of the ET site; geological conformation of the subsoil (right panel), human generated noise (population density, right panel) and environmental conditions (wind maps, top panel)

Residual seismic noise, that could spoils the detector sensitivity, must be suppressed by a filtering system. Scientists working in the ET-WP2 demonstrated the effectiveness of a passive filtering design and its compliance with the ET requirements through a detailed study of the Virgo Super-Attenuator (SA), as shown in Figure 3. Furthermore, a new thermal noise model able to evaluate the role of the upper stages in the filtering chain has been developed by ET scientists.

To realize a detector with the performances requested for the ET observatory, many technologies must be pushed at the limit and conflicting requirements could make the implementation in a single interferometer of all the desired solutions impossible. For example, to have a cryogenic interferometer having good performances at low frequency and, simultaneously, supporting Megawatts of light power circulating in the Fabry-Perot cavities, could be too hard. For this reason a Xylophone solution, where two (or more) interferometers, each specialized in a frequency band, are realizing the single ET observatory, has been evaluated. This option seems very appealing, as shown in Figure 4.

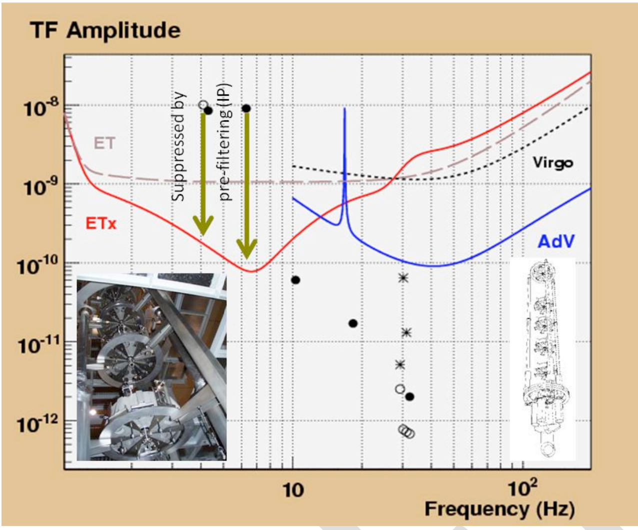


Figure 3 - Demonstration of the compliance of the passive filtering "à la Virgo" with the ET requirements, starting from few Hertz. In the small picture a photo of the Virgo Super-Attenuator (SA) is reported.

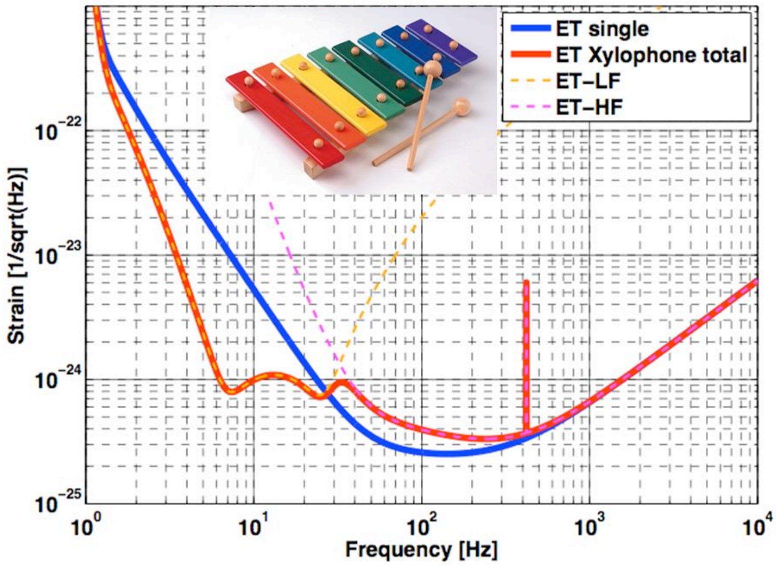


Figure 4 - Sensitivities of the ET observatory if implemented through a single wide frequency range detector (Blue line) or through a Xylophone design (Red line) through two specialized interferometers

2. Project objectives for the period

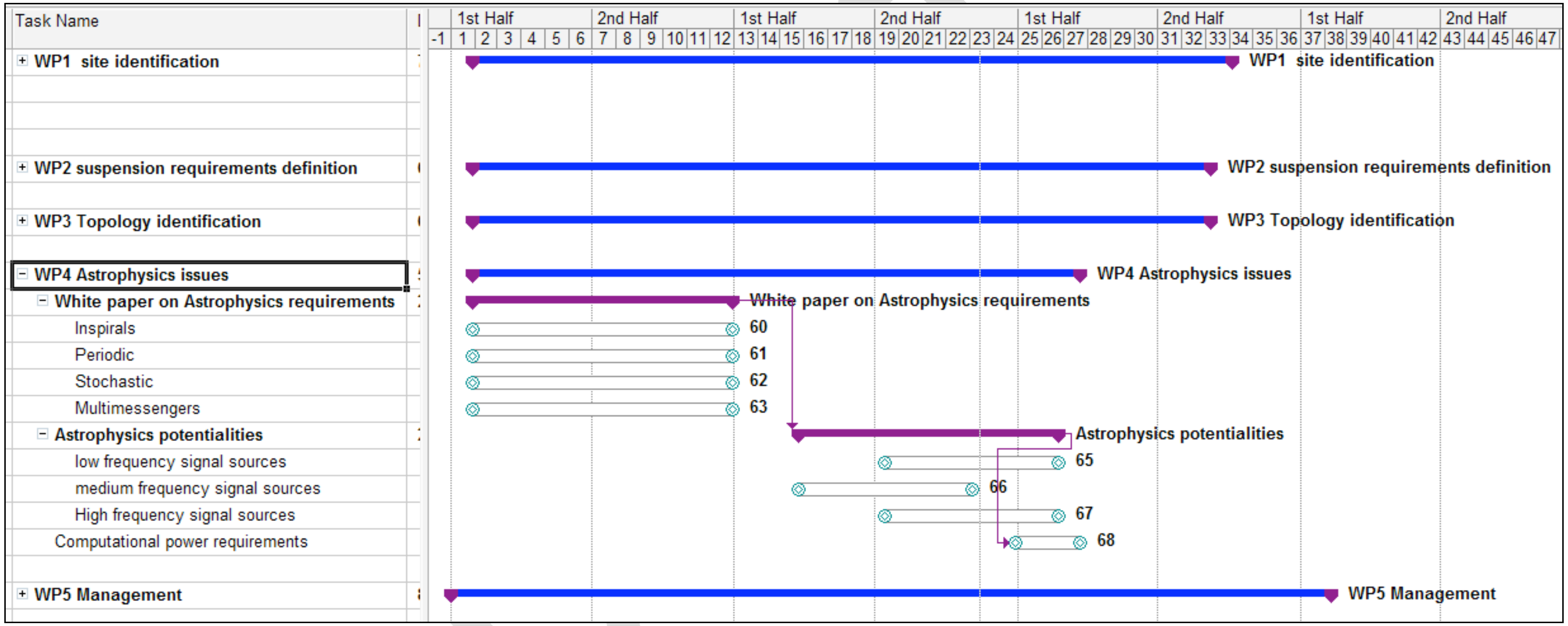
The objectives in the first 18th months are mainly devoted to the realization of the common tools and of the shared knowledge to start to produce the effective ET design. Beyond the constitution of all the working bodies, the first objectives of the project were the refinement of the ET science case; this objective as been obtained thanks to the synergies between all the working packages. In fact WP4, who effectively realized the science case refinement, has been supported in this activity by WP3 that realized the new ET sensitivity curves. These curves have been calculated using noise models developed by WP1 and WP2. The realization of a set of realistic ET sensitivity curves is a major macro-objective for the project, because its accomplishment is related to the completion of many of the tasks and subtasks indicated in the following list and extracted from the ET gantt diagram included in Annex I. Two major objectives of the WP5 have been obtained: (a) the realization of the ET Science Team, that now counts about 220 scientists and (2) allocating the ET project in the roadmap of the gravitational wave detectors in the world, obtained through the inclusion of the ET observatory in the GWIC roadmap.

The technical objectives, embedded in the following list of tasks belonging to the first phase of the ET design study project, have been almost completely reached; the major complexity of the control strategy issues will push to deeper investigate this issue.

- Set-up of the working groups and allocation of the task duties
- Definition of the detector infrastructure requirements (WP1)
  - Tolerance Study
  - Seismic noise completion
  - Newtonian noise evaluation
  - White book on site requirements
- Material intrinsic requirements (cryogenic temperature) – (WP2)
- Seismic attenuation requirements (WP2)
- Identification of the control strategy (WP2)
- Attenuation strategy choice (WP2)
- Test masses requirements (WP2)
- Suspension fibre design (WP2)
- Test mass cooling strategy (WP2)
- Analysis of the available and developing technologies (WP3)
- Cross-compatibility of the available and development technologies (WP3)
- Detector topology modeling (WP3)
- Detector geometry modeling (WP3)
- Detector geometry and topology decision process (WP3)
- White paper on Astrophysics requirements (WP4)
- Set-up of the management bodies (Governing council and Executive Board)
- Set-up of the management and administration tools and web server

3.4. WP4 - Astrophysics issues

3.4.1. WP4: timing of the work package



3.4.2. WP4: work progresses and achievements

3.4.2.1. *Activity report*

Working Package 4 (WP4) is tasked to address the ET science goals and the associated data analysis and computational challenges. In the frequency window of ET we can expect a wide variety of sources. The sensitivity will be deep enough to address a range of problems in fundamental physics, cosmology and astrophysics. WP4 has a membership of nearly 80 researchers from across the world, most participants being from Europe, with expertise in relativistic astrophysics, cosmology and general relativity. A little over 25% of the members are outside the list of ET beneficiary institutions.

The group's activity began with a presentation of the science goals to the community in May 2008 at the Gravitational-Wave Advanced Detectors Workshop in Isola-d'Elba, Italy. Sathyaprakash and Schutz presented the broad science goals for the ET, enumerating the tremendous science opportunities posed by a detector of this kind. After several months of consultation, the group began its activity in September 2009 by identifying the goals that must be achieved during the Design Study and recognized the importance of producing an ET Vision Document during the first year of the Study. The purpose of the document was to identify and explore in greater depth potentially interesting scientific problems. Groups of individuals were then identified to address different tasks and were assigned the task of producing the vision document. The progress was reviewed periodically during face-to-face and ET general meetings held in November 2008 (Pisa), March 2009 (Cardiff) and June 2009 (phone meeting). The agenda and the presentations made at these meetings can be seen at: https://workarea.et-gw.eu/et/WG4-Astrophysics/meetings. The document was further revised based on inputs at the phone meeting and the general meeting in October 2009.

The vision document, authored by about 25 authors from across the globe, is now complete and a mature draft is available at https://workarea.et-gw.eu/et/WG4-Astrophysics/visdoc. We will discuss in this report some of the salient science potentials of ET identified in the document. Two important tasks for WP4 over the next year are (a) trade studies with different sensitivity curves by liaising with other working groups to better understand the science potential of a more realistic ET sensitivity and (b) the development of the ET Mock Data Challenge (ET-MDC) whose goal is to produce mock data sets that can be used to address the data analysis and computational challenges.

(a) Trade Studies: Working Packages 1, 2 and 3 are now in the process of producing plausible sensitivity curves for ET. The ET frequency range and sensitivity pose serious and unprecedented technological challenges. The goal is to get the best possible sensitivity in the range 1 Hz to 10 kHz but compromises might have to be made based on the level of technical challenge, the cost to meet those challenges, site selection, etc. The ultimate design should be based on the scientific merit of the different trade-offs. WP4 has undertaken to study the cost to benefit ratio of the various design sensitivities.

(b) ET Mock Data Challenge: An early result that came of the study was that ET would be a signal-dominated detector with millions of signals from binary neutron stars and binary black holes at cosmological red shifts of 2 to 8 when the Universe was only a small fraction of its current age. Identifying useful signals, subtracting the foreground and digging deeper into the noise, poses challenges in data analysis and computation that are unprecedented in ground-based gravitational-wave detectors. The signal recognition problem in ET is not unlike the Laser Interferometer Space Antenna (LISA) for which many novel algorithms have been produced and tested with a mock data challenge. A data challenge similar to that of LISA is now being prepared to fully address the data analysis and computational problems. In fact, we have already begun producing simple data sets that mimic the expected signal populations on top of the noise background and have begun to analyze the same.

3.4.2.2. *Scientific Achievements*

Introduction

The Science potential of ET depends on the type of sources it can detect, their rate of occurrence and the science they promise to uncover. ET sources fall into four categories: (i) Inspiralling and merging binaries, (ii) neutron star quakes and supernovae, (iii) rapidly spinning neutron stars with mountains or other asymmetries and (iv) quantum fluctuations and phase transitions in the primordial Universe and populations of astronomical sources. In what follows we will review each of these sources and their science potential.

Compact Binary Coalescences

A binary consisting of a pair of compact stars, i.e. neutron stars (NS) and black holes (BH), evolves by emitting gravitational radiation. The adiabatic evolution of a compact binary, during which the emission of gravitational waves causes the component stars of the system to *slowly* spiral-in towards each other, has been computed very accurately using the post-Newtonian (PN) expansion of the Einstein equations. The amplitude and frequency of the emitted radiation increase with time resembling that of a *chirp* signal. Ultra-strong gravitational fields and relativistic motion dictate the last few seconds of the life of a compact binary. As the two stars *plunge* towards each other at close to the speed of light, for a brief moment, the gravitational luminosity of the system exceeds that of all the stars in all the galaxies in the Universe. The two stars eventually merge to form either a NS or BH, which is initially highly distorted. The merged object settles down to a quiescent state by radiating in gravitational waves the deformations inherited during the process of merger. The radiation emitted in the process arises as a result of the quasi-normal mode (QNM) oscillations of the NS or BH. A careful measurement of the QNM frequencies and damping times can be a powerful test of general relativity, if the final object is a BH, or a tool for nuclear physics to infer the equation-of-state of ultra-dense nuclear matter, if the final object is a NS.

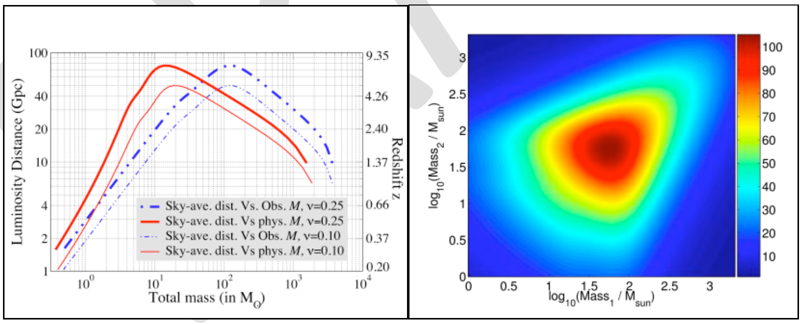


Figure 23: The panel on the left shows the range of the Einstein Telescope for inspiral signals from binaries as a function of the intrinsic (red solid line) and observed (blue dashed line) total mass. We assume that a source is visible if it produces an SNR of at least 8 in ET. The panel on the right shows in the plane of component masses the SNR for binaries at a distance of 3 Gpc.

Expected ET distance reach and coalescence rates: The sky-position averaged distance up to which ET might detect inspiral signals from coalescing binaries with an SNR of 8 is shown in Figure 23. We plot the range both as a function of the intrinsic (red solid lines) and observed (blue dashed lines) total mass. A binary comprising two 1.4 solar mass neutron stars (BNS) can be observed from a red-shift of $z = 2$, and that comprising a 1.4 solar mass neutron star and a 10 solar mass-black hole (NS-BH) from $z = 4$. The distance reach of ET for compact binaries is so large that one expects to observe millions mergers each year. In what follows we will discuss some of the most important scientific benefits of observing a population of binary merger events in ET.

Cosmography with ET: In astronomy, standard candles are sources whose distance from the Earth can be inferred from their apparent luminosity and other observed properties such as their time variability, spectra, etc. They are essential tools for measuring the matter energy content of the Universe, its expansion rate and the large-scale geometry. There are no perfect standard candles in astronomy and none that works even approximately at all distances. Astronomers have built a *cosmic distance ladder* by using several distance calibrators such as Cepheid variables, Tully-Fisher relation, type Ia supernovae, etc. Cosmologists have long sought for standard candles that can work on large distance scales without being dependent on the lower rungs of cosmic distance ladder. In 1986, Schutz pointed out that gravitational astronomy could provide a self-calibrating standard candle, or, more appropriately, a *standard siren*, in the form of a chirping signal from the coalescence of compact stars in a binary.

The basic reason for this is the amplitude of gravitational waves from such a system depends only on the ratio of a certain combination of the binary masses and the luminosity distance. For chirping signals, gravitational-wave observations can measure both the amplitude of the signal and the masses very accurately and hence infer the luminosity distance. The detector response depends only on a small number of signal parameters, which can all be measured either directly or indirectly. The signal is insensitive to the composition of the component stars and there is no complicated modelling that involves the structure of the stars or their environments. Consequently, the measurement of the luminosity distance is precise, except for statistical errors, whose magnitude depends on the signal-to-noise ratio (SNR), and systematic errors due to weak gravitational lensing.

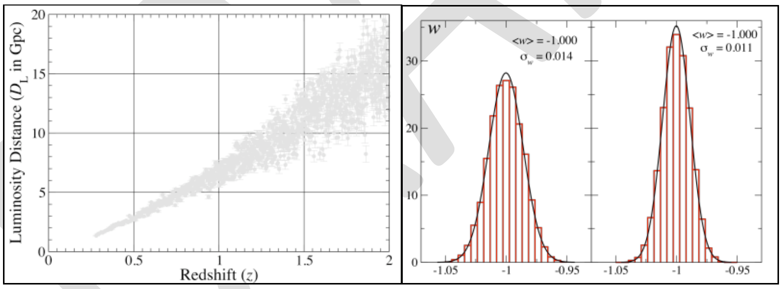


Figure 24: A realization of measured values of the luminosity distance and redshift to coalescence sources (left panel) and the expected error in the measurement of the w parameter with and without weak gravitational lensing. The error in w without gravitational lensing is 1.1% but lensing increases that only to 1.4%. ET's accuracy in w is as good as some of the dedicated dark energy missions.

ET should detect millions of binary neutron star inspirals each year. A small fraction of these events might be observed as gamma-ray bursts, helping to measure both the luminosity distance D_L to and the redshift z of the source. The relationship between and z depends on the cosmological parameters via an equation of the type:

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{(1+z')^{-3/2} dz'}{[\Omega_M + \Omega_\Lambda (1+z')^{3w}]^{1/2}},$$

Here H_0, Ω_M, and Ω_Λ are, respectively, the present values of the Hubble parameter, dark matter and dark energy densities and w is a parameter characterizing the dark energy equation-of-state. By fitting the measured values of the luminosity distance and redshift to a cosmological model Sathyaprakash, Schutz and Van Den Broeck, have shown that it should be possible to infer the dark energy equation-of-state to within 1.5% without the need to correct for errors in luminosity caused by weak-lensing (see Figure 24). This compares with the 3%-10% that can be achieved with LISA and 5% with the proposed dedicated missions to measure the dark energy equation-of-state.

Black hole seeds and galaxy formation: It is widely accepted that the massive black holes (MBHs) found in the centres of many galaxies grow from initial seeds through the processes of accretion and mergers (see Figure 25) following mergers between their host dark matter halos. However, little is known about the seeds from which these black holes grow. Open questions include: *How and when did they form*? *What are their masses*? *Where are they*? Current observations are consistent with both *light seed* scenarios, in which 100 solar mass black hole seeds form at redshift z of about 20 from the collapse of Population III stars, and *heavy seed* scenarios, in which black holes of mass 10^5 solar mass form from direct collapse of dust clouds. Mergers between MBHs in merging dark matter halos will generate gravitational waves. These are a major source for LISA, but LISA will only see mergers with total mass greater than about 1,000 solar masses. LISA is able to probe black hole seeds only in the heavy seed scenario and does not have the power to discriminate between the light and heavy scenarios.

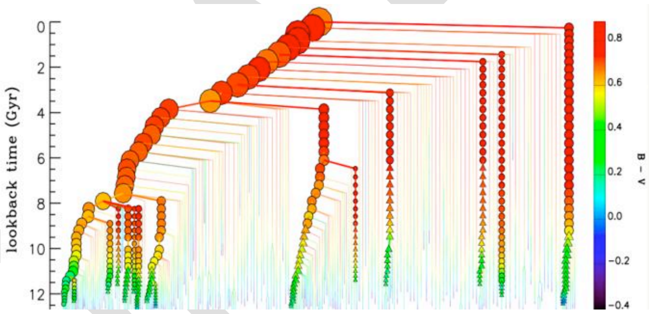


Figure 25 A cartoon showing how hierarchical merging of small black hole seeds produce super-massive black holes we see today at galactic nuclei (courtesy A. Sessana).

The Einstein Telescope will have sensitivity in the 1-50 Hz band in which gravitational waves from mergers involving 10-100 solar mass black holes lie. It will, therefore, provide complementary information to LISA and could directly observe the first epoch of mergers between light seeds. Present estimates, based on Monte Carlo simulations of galaxy merger trees, suggest that ET could detect between a few and a few tens of seed black hole merger events over three years of operation. Several of these events will be at high redshift z ~ 5, by which time it is unlikely that 100 solar mass black holes could have formed by other routes. ET and LISA in conjunction probe the whole merger history of dark matter halos containing black holes in the $10\text{-}10^6$ solar masses, which will provide detailed information on the hierarchical assembly of galaxies.

ET on its own is not able to measure the distance to a seed black hole merger. However, if an additional interferometer with a long baseline with ET is in operation concurrently, the network will be able to determine the luminosity distance of a source to 40% precision and the redshifted total mass of the system to less than 1%. Using a concordance cosmology, this distance estimate can be used to infer the source's redshift with comparable accuracy. Therefore, it should be possible to say that the z ~ 5 events are of *low mass* and at *high redshift*, and hence provide convincing evidence of Pop III seed mergers.

A single detection by ET will rule out the heavy seed model. With several detections, we will be able to make statements about Pop III seed black hole properties, such as their mass distribution, their early accretion history etc. These observations cannot be made be any other existing or proposed detector – it is science that is unique to ET. Such observations will be vital to our understanding of the assembly of structure in the Universe, and of the close link between black holes residing in the centres of galaxies and their hosts.

Testing the uniqueness theorem of black hole spacetimes: It is generally accepted that the massive compact objects observed in the centres of most galaxies are massive, rotating black holes described by the Kerr metric of General Relativity. This belief comes in part from the uniqueness theorem, which is the result that the Kerr metric is the unique end state of gravitational collapse. However, this theorem is based on several assumptions – the spacetime is vacuum, axisymmetric and stationary; there is a horizon in the spacetime; and there are no closed timelike curves. If one of these assumptions were violated, then objects that deviate from the Kerr metric could exist.

In black hole binary systems where the mass of one object is much bigger than the other, many gravitational wave cycles are emitted while the smaller object is in the strong field region close to the larger object. These gravitational waves encode a map of the spacetime structure in the vicinity of the large black hole, which can be used to measure properties of the central object. Using such observations to measure spacetime structure has been explored extensively in the context of extreme-mass-ratio inspirals (binaries of 10 solar mass objects with 10^6 solar mass objects) for LISA. There is an analogous source for ground-based detectors, namely the inspiral of a 1 solar mass object into a 100 solar mass black hole. We refer to these as intermediate-mass-ratio inspirals (IMRIs).

Explicit calculations have not yet been done for ET, but they do exist for Advanced LIGO. Extrapolating from those results, ET could see IMRI events out to a redshift z ~ 3 and could detect as many as several hundred events per year, although a few to a few tens is more likely. ET will observe these events for more cycles than Advanced LIGO, due to its better low-frequency performance, which is very important for the precision of spacetime mapping measurements.

Testing the black hole no-hair theorem: The uniqueness of Kerr black holes as the end state of collapse is sometimes referred to as the "no-hair theorem". A Kerr black hole has "no-hair" since the entire spacetime structure, characterized by "multipole moments", is determined by just two parameters, the black hole mass M and its spin magnitude S. It has been demonstrated that gravitational wave observations can measure the multipole moments independently of one another. We can therefore directly verify that they satisfy the Kerr relationship

$$M_l + \mathrm{i}S_l = M(\mathrm{i}S/M)^l$$

We need only to measure three multipole moments to rule out an object as a Kerr black hole. IMRI observations with Advanced LIGO could detect an $O(1)$ deviation in the quadrupole moment of an object. The precision achievable with ET should be at least a factor of 10 better than this due to the improved low-frequency performance. To put this in perspective, one alternative to black holes, boson stars, have quadrupole moments two orders of magnitude bigger than black holes of the same mass and spin. Any deviations from the no-hair theorem that are detected will have profound implications for our understanding of relativity and of black holes. Persistent deviations from the theory may lead to important insights in the search for a Fundamental Theory that unifies all four forces of nature.

Are there naked singularities? One of the assumptions of the uniqueness theorem is that a horizon exists in the spacetime. This arises from a belief embodied by the "Cosmic Censorship Hypothesis" (CCH), which states that any singularity will be enclosed by a horizon. The CCH arises from a desire for predictability in the Universe – when physics breaks down at a singularity, we do not want information from that to propagate into the rest of the Universe. However, the CCH is unproven and therefore "naked" singularities not enclosed within a horizon may still exist. Gravitational wave observations provide a unique way to look for these exotic objects. Observations may be indirect, via detection of a violation of the "no-hair" theorem. However, they may also be direct – if a horizon is not present in the spacetime, the gravitational waves will not cut-off when the object crosses the horizon, which will be a clear smoking gun signature for the absence of a clothing horizon in the system.

The Einstein Telescope will provide much more stringent constraints on potential violations of the CCH than are possible with Advanced LIGO. ET observations will therefore play an important role in answering the question as to whether naked singularities exist, which could have profound implications for our understanding of various aspects of the theory of relativity.

Properties of neutron stars and their populations: The Einstein telescope will provide a large sample of binary coalescences with the precise measurement of their masses, arrival times (see Figure 26) and redshifts. This will be an extremely valuable tool for analysis of the cosmic compact object formation history. The measurement of their masses will yield information on the metallicity evolution as well as evolution of most massive stars. The Einstein telescope will yield a cosmic compact object census up to redshift z=2, and will yield information about black holes and neutron star formed even at earlier epochs because of the delays between formation and coalescence.

There are two distinct routes to form BH binary. The first, conventional way, is to start with binary system of two main sequence stars and trace their evolution. There are several big uncertainties in this process. The first one is the initial mass ratio function: what is the distribution of the mass ratio in the binary of two main sequence stars, how it depends on the metallicity and spectral type. The second, and probably the biggest uncertainty, is related to the "common envelope" evolution, where the NS (or BH) and Helium core are emerged and evolve in the gaseous environment of the star. In this stage the NS/BH could merge with Helium core on the time scale etc., and binary is not formed. The third uncertainty is related to the direction and magnitude of the kick exerted on the newly born BH from the asymmetric supernova explosion. All the above is reflected in the uncertainties on the rate of such binaries and hence ET could shed light on the formation and evolution of binaries in ways not obtainable in any other way.

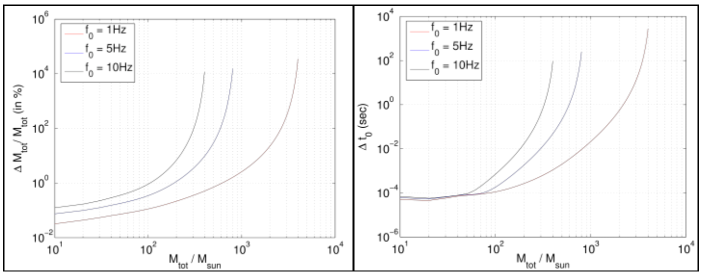


Figure 26: The accuracy in the measurement of the total mass of the binary (left) and the time -of-arrival (right) for different lower frequency cut-offs in ET.

Equation-of-state of neutron stars from binary coalescences: The central densities of isolated neutron stars can range up to ten times nuclear saturation density, and during the merger and coalescence of two neutron stars the maximum density will rise even further before the remnant object collapses to a black hole. The behaviour of bulk matter at these densities is not well understood, and measurements of gravitational wave signals from neutron star sources can usefully constrain the EOS at the these densities.

Quantum chromodynamics is expected to be a complete description of matter at these energies; the uncertainty in theoretical understanding comes from the many-body-problem with strong interactions. The description of bulk neutral matter in terms of hadrons, such as protons and neutrons, may need to be expanded to accommodate new particles that are formed at these energies, such as hyperons, pions, and kaons. In fact the appropriate degrees of freedom describing cold matter at very high density may no longer be hadrons but the quarks and gluons themselves, in some form of quark matter.

While isolated and inspiralling neutron stars are well described by the ground state of matter, i.e. with a “cold” EOS, the temperatures reached in the coalescence as a result of strong shocks will be significantly higher – of the order of 10^{10}-10^{12} K. Yet, just as measurements of the hot out-of-equilibrium ion collisions at the Brookhaven’s Relativistic Heavy Ion Collider experiments constrain the ground state of dense nuclear matter so could gravitational wave signals from the collisions of neutron stars. This is illustrated in **Figure 27**, which plots the spectra of gravitational waves from binary inspiral and merger expected to be frequently detected in ET. It is clear that the spectrum of the merger phase is pretty sensitive to the EOS of the nuclear matter as well as to the masses of the component stars. While the EOSs considered here are not realistic, they span, in some sense, the extremes of the range of possibilities. Most importantly, they show that the gravitational-wave signal will be very sensitive to the masses of the stars and their EOS.

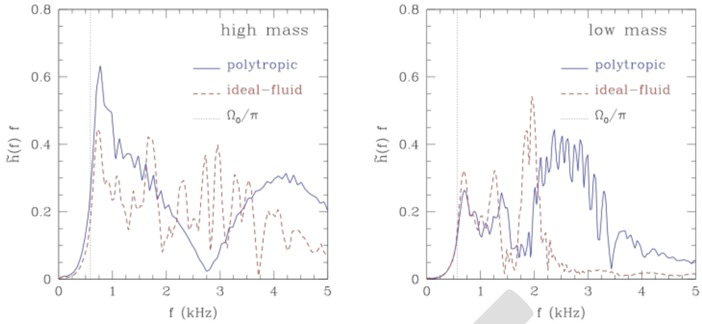


Figure 27: Left panel shows a comparison of the gravitational-wave spectra for a high-mass binary with a total mass of 3.2 $M_{\odot}$, when evolved with a "cold"' EOS (labeled polytropic) or with a "hot" EOS (labeled ideal-fluid). Right panel is the same as the left panel but for a low-mass binary with a total mass 2.9 $M_{\odot}$.

The inspiral phase, not just the merger phase, might also provide important information on the EOS. For most of the inspiral phase the stars are well modeled as point particles. However, as they approach each other an EOS-dependent tidal deformation modifies their orbits, changing the late inspiral waveform. The measurability of this effect in gravitational wave detectors can be estimated using numerical simulations of binary neutron stars with varying EOS. A set of numerical simulations by Read et al. predicts that for binary neutron stars within 100 Mpc, by observing the modifications in the inspiral phase of the signal caused by tidal deformations, ET should be able to measure the radius of a neutron star to within 0.5-1.0 km. This compares favorably to the range in predicted radius for different EOS of roughly 9-16 km, implying that ET should be well positioned to measure the EOS of neutron stars from rare close-by coalescence events. ET will provide very strong signals at reasonable rates; for example, at an effective distance of 100 Mpc ET would observe a binary neutron star merger with an SNR of over 900. This makes it possible to precisely measure the masses and small departures from point particle behaviour.

What are the progenitors of gamma-ray bursts? Gamma-ray bursts (GRBs) are the most luminous explosions currently known emitting more energy in just a few seconds than a typical star would in its entire life. GRBs are classified as either *short-hard* or *long-soft* bursts, depending on their duration and spectra. Through follow-up observations of the x-ray, optical and radio afterglow emission of GRBs it has been possible to determine their sky-location, redshift and host galaxy. Long GRBs are always associated with late-type star-forming host galaxies. A handful of long GRBs have also been associated with supernovae. It is, therefore, thought that core-collapse supernovae are the progenitors of long GRBs.

Short GRBs are observed at lower redshifts than long GRBs. They are associated with a variety of galaxy types, including early-type elliptical and lenticular galaxies, without active star forming regions. Currently, it is widely thought that merger of neutron star binaries or neutron star-black hole binaries are the progenitors of most short-hard GRBs. Simultaneous gamma-ray and gravitational wave detections would settle the issue and open the way to more detailed modeling of these systems. ET has the potential to detect such a large number of these systems that it will help in identifying different populations, shed light on the physical mechanism behind the intense gamma-ray flashes and enable a very detailed study of the progenitors.

Numerical relativity simulations: Following breakthroughs in 2005, it is now possible to numerically solve the full Einstein equations for the last orbits, merger and ringdown of comparable mass black-hole-binary systems, and to calculate the emitted GW signal. Subsequent dramatic progress has lead both to simulations of rapidly increasing numerical accuracy and physical fidelity, and to the inclusion of larger numbers of GW cycles before merger, allowing full GR waveforms to be in principle useful for searches of black-hole binaries of ever lower mass. Results from numerical simulations of BH coalescence aid gravitational-wave astronomy in a number of ways, the consequences of which are still being explored. These include *template banks* to search for complete inspiral-merger-ringdown waveforms, the *mass and spin of the final black hole* that will be critical for strong field tests of general relativity, etc.

It has been shown that the numerical accuracy of current numerical relativity simulations is sufficient for both detection and parameter-estimation with Initial and Advanced LIGO and Virgo. For ET, where SNRs could often exceed 100, however, this is no longer the case, and more accurate waveforms will be required. Following the rapid progress in numerical simulations in the last four years, it seems quite reasonable to expect sufficient accuracy for ET requirements within the next 5-10 years. This includes greater accuracy in the calculation of subdominant harmonics, which is still a challenge in most codes.

Of more difficulty will be simulations of binaries with much larger mass ratios. To date, long simulations (greater than 10 inspiral cycles) have been performed only for binaries with mass ratios up to 1:6. The computational requirements at present scale at best linearly with the mass ratio, and this makes long simulations of mass ratios above 1:10 difficult, and out of current reach for mass ratios of 1:100. Simulating those cases in full general relativity will require real breakthroughs in either numerical techniques or the formulation of the problem, or both. Intense efforts are underway to address all of these issues and it is expected that accurate numerical-relativity-based template banks can be produced well within the time frame of the design and construction of ET.

Cosmological evolution of compact object populations: The formation and evolution of compact binaries in the Universe is an open problem of great interest in astrophysics. Understanding this phenomenon requires input from nuclear physics, hydrodynamics, relativistic gravity, stellar evolution, etc. ET will provide a large sample of compact binary coalescences with accurate measurement of the component masses and spins and optical follow-up of such events will provide their redshift. Optical and infrared observations could also inform us of the history of star formation. Combining the data from these observations will help us unravel the physical processes involved in the formation and evolution of compact binaries throughout the cosmic history.

The coalescence rate as a function of the redshift is influenced by a number of different factors: the star formation rate history $SFR(z)$, the binary fraction $f_b(z)$, the formation efficiency of a given type of binary, i.e. the fraction of number of binaries that lead to formation of coalescing compact object binary, and their distribution of merger times. These quantities may depend on the redshift since the stellar populations evolve with cosmic time.

The star formation rate is known to increase strongly up to redshifts of z=2, and there is a debate about its behavior at higher redshifts. At redshift z=2 the star formation rate is estimated to be a factor of 10 larger than the present rate at z=0. The main factor that may affect the evolution of binaries as a function of redshift is the change in the distribution of metallicity. Metallicity strongly affects the mass loss rate in stars, and hence has a strong influence on the mass spectrum of compact objects. The lower the metallicity the higher the maximum mass of a black hole that may be formed in the course of stellar evolution. This leads to stabilization of mass transfers and therefore to an increase in the formation rate of compact object binaries.

There are two distinct routes to form a BH binary. The first, conventional, route is to start with binary system of two main sequence stars and trace their evolution. There are several big uncertainties in this process. The first one is the initial mass ratio function: What is the distribution of the mass ratio in the binary of two main sequence stars? How does it depend on the metallicity and spectral type? The second, probably the biggest, uncertainty is related to the "common envelope" evolution, where a NS/BH and a Helium core emerge and evolve in the gaseous environment of the star. In this stage the NS/BH could merge with the Helium core and a binary is not formed. The third uncertainty is related to the direction and magnitude of the kick exerted on the newly born NS/BH from the asymmetric supernova explosion. All the above is reflected in the large (3 orders of magnitude) uncertainty in the local coalescence rate.

Black hole binaries could also form in the dense environment of galactic nuclei. In galaxies with a super-massive black hole a steep cusp of stars and stellar mass BHs can be formed. BHs, being more massive and compact, will segregate into the central 1 pc region. Other dense regions where black holes could segregate are massive globular clusters and nuclear star clusters in the centers of low-mass galaxies which may not host a super-massive black hole. The densities in such regions could be high enough to have multiple encounters and lead to the formation and hardening of BH binaries.

ET will yield a census of cosmic compact objects up to redshift z=2 for neutron stars and z=8 for black holes. The measurement of the mass spectrum of compact objects will yield information on the metallicity evolution as well as evolution of most massive stars and how and where black hole binaries could form.

Confusion background from compact binaries in ET: With current and advanced interferometers, whose horizon is tens to hundreds of Mpc, the detection of individual binaries is limited by the instrumental noise. ET is expected to reach redshifts of z=2-4 for BNS and NS-BH sources that could lead to problems not foreseen in current detectors. For instance, at redshifts of 1 or more gravitational lensing will be significant which would corrupt luminosity distance measurements and thus the quality of binaries as standard candles to probe cosmology and dark energy. Another problem is the formation of a confusion background from a large population of high-redshift sources

The Table below lists the redshifts within which the number of compact binary mergers is greater than 1 (z_*) and greater than 10 (z_{**}). They are listed for three different values of the lower frequency cutoff of ET (10, 5 and 1 Hz) and for optimistic, realistic and pessimistic estimates of the coalescence rate. $\dot{\rho}^o(z)$ For double neutron star binaries (NS-NS), both z_* and z_{**} are well within the horizon of the planned Einstein Telescope, if its low-frequency cutoff is at 1 Hz. If the low-frequency cutoff is at 5 Hz, we expect the popcorn background to occur before the detection horizon, and more likely around z_* ~ 0.25-0.4, unless our most pessimistic coalescence rates are accurate. The transition to a Gaussian stochastic background most likely occurs at z_{**} ~ 0.6-1.2, but can fall beyond the detection horizon if binary coalescence rates are too low.

TABLE II: Threshold between resolved and unresolved NS-NS binaries (left) and NS-BH binaries (right) for different estimates of the source rate $\dot{\rho}_c^o$ and detector lower frequency bound f_L. No value means that the number of sources at the detector is always < 1 or < 10.

f_L	$\dot{\rho}_c^o$	z_*	z_{**}	f_L	$\dot{\rho}_c^o$,	z_*	z_{**}
10	0.01	-	-	10	0.001	-	-
	0.4	0.8-0.9	-		0.04	-	-
	1	0.5-0.6	> 2		1	1.1-1.4	-
	10	0.2	0.5-0.6		10	-	-
5	0.01	-	-	5	0.001	-	-
	0.4	0.4	1-1.2		0.04	-	-
	1	0.25	0.6-0.7		1	0.5	> 1.6
	10	0.1	0.25		10	-	-
1	0.01	0.3	0.8	1	0.001	> 2.3	-
	0.4	0.08	0.2		0.04	0.3	0.8-0.9
	1	0.06	0.13		1	0.1	0.2
	10	0.03	0.06		10	-	-

The conclusions for NS-BH binaries are similar to those for NS-NS. If the lower frequency cutoff is 1 Hz, z_* and z_{**} are both more likely to occur well below the horizon. For a 5 Hz cutoff, however, there is not likely to be enough sources to create a Gaussian stochastic background (or even a popcorn background), except for the most optimistic coalescence rates. As a consequence, NS-BH binaries may always be resolved provided that we can separate them with adequate data analysis strategies in the popcorn regime. This result motivates very careful analysis of how data would be analyzed. Experience from the Mock LISA Data Challenges, and ideas developed for the Big Bang Observatory (a future space-based project in the USA), prove that disentangling multiple signals in a gravitational-wave detector's data stream is certainly possible. Unless the coalescence rate is well above our current estimates, the foreground from the extragalactic population of double neutron stars is well below the instrumental noise, and shouldn't affect the detection of other sources.

Neutron Star Mountains and other Continuous Wave Sources:

The Universe might consist of astronomical systems that shine in the gravitational window for weeks or years. Such signals are expected to be produced by rapidly rotating non-axisymmetric neutron stars which are either isolated or in binary systems. Their amplitude is constant (or roughly constant) and frequency varies relatively slowly over the observation time. There are a number of mechanisms, which may cause a star to emit gravitational waves. These include deformations of the neutron star crust, precession, magnetic fields, internal oscillation modes of the neutron star fluid etc.

Isolated neutron stars: There are at present hundreds of pulsars known from either radio or X-ray observations. The parameters of many of these systems, i.e. the sky location and frequency evolution, have been accurately measured. A gravitational wave emission due to a non-negligible ellipticity occurs at twice the rotational frequency of the star. These two assumptions constrain the expected gravitational waveform up to an unknown initial phase, amplitude and polarization angle. It is then easy to search over these unknown parameters and to either measure the amplitude h_0 or in the case that no signals are detected, to set upper limits on it. The benchmark for these searches is the indirect upper bound on h_0 set by assuming that all of the kinetic energy of the star lost in the spindown is channeled into gravitational radiation. A straightforward calculation leads to the so-called spindown limit h_0^{sd}:

$$h_0^{sd} = 8.06 \times 10^{-19} \frac{I_{38}}{d_{kpc}} \sqrt{\frac{|\dot{\nu}|}{\nu}}$$

Here I_{38} is the moment inertia of the star in units of 10^{38} kg m^2, d_{kpc} is the distance to the star in kpc, $\dot{\nu}$ is the spindown rate and ν is the spin frequency. This assumption is not expected to hold for any of the known pulsars where electromagnetic braking explains most of the spindown. Nevertheless, the spindown limit still a very useful benchmark for quantifying the astrophysical relevance potential targets and search results. This procedure has been carried out for a number of known pulsars using data from the LIGO, GEO and Virgo detectors. One highlight from these results is beating the spindown limit for the Crab pulsar where the gravitational wave luminosity is constrained to be less than 2% of the spindown luminosity. A useful benchmark for the detectability is given by

$$h_0 = 11.4 \sqrt{\frac{S_n(f)}{D T_{obs}}}$$

Here $S_n(f)$ is the detector noise power-spectral density at a frequency f, T_{obs} is the observation time, and D is the number of detectors. The factor of 11.4 corresponds to a false alarm rate of 1% and a false dismissal rate of 10%. **Figure 28** shows (left panel) the detectable amplitude for Initial and Advanced LIGO, Virgo and ET, and spindown limits for various known pulsars.

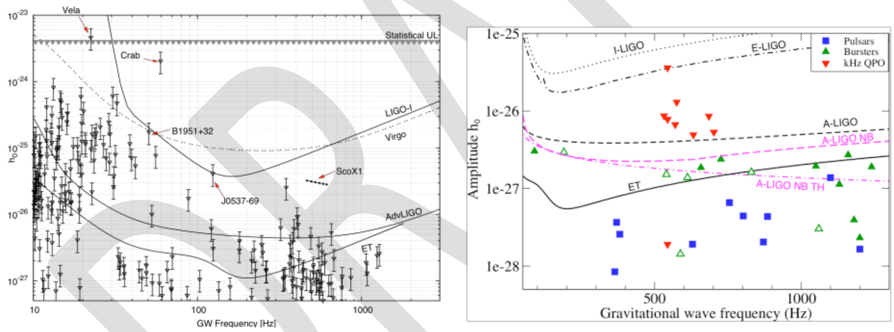


Figure 28 The left hand plot shows upper limits and the spindown limits for the known pulsars (adapted from R.Prix, 2006). The right hand plot shows the sensitivity of various detectors and the spin-balance limit for the accreting neutron stars.

Low-mass X-ray binaries: Observations of accreting neutron stars lead to perhaps the most important reason why, irrespective of the mechanism at work, at least some neutron stars might be actually emitting detectable gravitational waves. This is the observation that even the fastest accreting neutron stars spin at rates much lower than the expected break-up frequency. The current record is 716 Hz, while the theoretically expected upper limit is more than 1 kHz. Bildsten has suggested that this limit occurs because of the balance between the spin-up torque due to the accreting matter, and the spindown torque due to gravitational wave emission. A short calculation assuming a link between the observed X-ray luminosity with the accretion rate, and taking the mountain scenario for the emission mechanism leads to an estimate of the GW amplitude from accreting neutron stars of various kinds as shown on the right hand plot of **Figure 28**. ET promises to be an excellent probe for accreting neutron stars with kilohertz quasi-periodic oscillation frequencies.

High Energy Transients and Gravitational Wave Bursts

The brightest sources in the sky are transients resulting from catastrophic events – the collapse of massive stars, stellar quakes, etc. ET might observe some of these events if the source quadrupole moment changes sufficiently rapidly.

Probing Core-Collapse Supernova Physics: Stellar collapse is the most energetic event in the Universe, with the liberation of some 10^{53} erg of gravitational energy in the compression of a massive star's iron core to a neutron star. Most of this energy (99%) is emitted in neutrinos and only about 10^{51} erg could go into energy of the core-collapse supernova (CC-SN) explosion. CC-SNe (SN types II, Ib, Ic) are about 10 times more frequent than thermonuclear type-Ia SNe. A SN explosion pollutes the interstellar medium with the nucleosynthetic products of stellar evolution (CC-SNe are the Universe's primary source of oxygen) and enriches the universe with rare heavy isotopes via the *r*-process. The perturbation caused by an SN in its vicinity can trigger the formation of stellar systems and stellar collapse and CC-SNe are the birth sites of neutron stars (NSs) and stellar-mass black holes (BHs).

The Supernova Problem and GW observations: The precise mechanism of explosion operating in CC-SNe is unknown. When the inner part of the collapsing iron core reaches densities close to those in atomic nuclei, the strong force leads to a stiffening of the nuclear equation of state (EOS), resulting in *core bounce* of the inner core into the still infalling outer core. A shock wave is formed that propagates outward in mass and radius, but quickly loses energy due to the breakup of heavy nuclei and neutrinos that carry away energy from the post shock layer. The shock stalls, turns into an accretion shock and must be *revived* to drive a CC-SN explosion. If this does not happen, a BH will form on an accretion timescale of 2 s. *What is the mechanism of shock revival?* This is the fundamental question and primary unsolved problem of CC-SN theory.

Indications are strong that the CC-SN mechanism involves a multitude of multi-dimensional processes, including rotation, convection/turbulence, and various hydrodynamic instabilities of the stalled shock and in the proto-NS. This opens up the possibility of probing the supernova mechanism with gravitational waves. Gravitational waves, even more so then neutrinos, carry direct dynamical information from the supernova engine deep inside a dying massive star, a region generally inaccessible by the traditional means of observational astronomy. Gravitational waves from a core-collapse event have the potential of putting very strong constraints on the CC-SN mechanisms. With initial and certainly second-generation interferometric GW detectors, this should be possible for an event in the Milky Way ($D \sim$ 10-15 kpc) and the Magellanic Clouds ($D \sim$ 50-70 kpc) but even optimistic estimates of the CC-SN rate in this region do not predict more than 1-2 events per century. This number roughly doubles if one includes the entire local group ($D \sim$ 1 Mpc). In the region from 3-5 Mpc a number of starburst galaxies increase the predicted and observed integrate SN rate to about 0.5 per year. At a distance of 10 Mpc the rate is greater than 1 per year.

Supernova Science with ET: In a core collapse event GW strains in the range $h \sim 10^{-22} - 10^{-24}$ can be emitted for SNe at 1 Mpc. Most of the emission takes place at frequencies of 200 Hz-1 kHz but the various explosion scenarios exhibit unique spectral distributions and vary in total emitted energies. In addition, there is likely to be a low-frequency GW-memory-type component with large h up to 10^{-22} for events at 1 Mpc at frequencies 0-20 Hz. Figure 29 summarizes the observational capabilities of ET and examines each of the main generation processes of gravitational waves. ET as currently envisioned is sufficiently sensitive to detect GW from various CC-SN scenarios out to 2-4 Mpc. If the high-frequency sensitivity was increased by a factor of ~ 2-3, detection out to 10 Mpc may be possible. Even without this improvement, ET may see multiple CC-SNe during its lifetime and would have the power to provide strong hints for a particular SN mechanism and/or smoking-gun evidence against another – crucial astrophysics information that is unlikely to be attainable in other ways. At ET's implementation, megaton-class neutrino detectors will be operative and, having a range similar to ET, will be able to provide coincident observations, narrowing down the time of the GW emission to about 1 ms. In addition, deep high-cadence optical transient surveys will be operative and targeting near-universe transients, providing additional coincident data as well as additional astrophysics output such as progenitor type, associated mass, explosion morphology, total energy in explosion, etc..

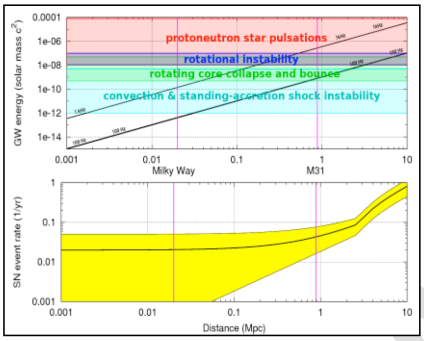


Figure 29: The upper plot displays the minimum GW energy that a supernova core collapse is required to radiate in order to be detectable by the Einstein telescope. We give two estimates assuming that the GW signature is described by a sine-Gaussian burst waveform. We consider two cases with a low frequency of 100 Hz and high frequency of 1 kHz content. The minimum GW energy is given as a function of the source distance. We also indicate the expected range of radiated GW energy for several processes. The lower plot shows an estimate of the cumulative event rate (with error bars) obtained from the star formation rate computed over a catalog of nearby galaxies.

Constraining the CC-SN mechanism will mean a breakthrough in our understanding of the large range of phenomena associated with stellar collapse, CC-SNe, BH and NS formation and GRBs. However, the astrophysics and physics information provided by GWs observed from a CC event with ET goes beyond this: These GWs carry also information on the high-density nuclear EOS, explosion asymmetries and pulsar kicks, the formation of a BH in a failing CC-SN, and can help uncover rare events such as the accretion-induced collapse of a white dwarf to a NS or weak or failing CC-SNe that have very weak or absent EM signatures.

Soft Gamma Repeater flares: A significant fraction, up to 15%, of short, hard gamma-ray bursts may be associated with flaring activity in soft gamma-repeaters (SGRs). These sources often undergo sporadic periods of activity that last from days to months where they emit short bursts of hard X-rays and soft gamma-rays with luminosities $L \sim 10^{41}$ erg s^{-1} and photon energies in the range 10-30 keV. Occasionally, they exhibit enormous, giant flares with luminosities as large as $L \sim 10^{47}$ erg s^{-1}. It is generally believed that SGRs belong to a class of neutron stars – magnetars with extraordinarily large magnetic fields in the range $10^{14\text{-}16}$ G – where the flaring activity is due to sudden, violent reconfigurations of complex magnetic field topologies.

Gravitational wave observations can provide an extremely powerful tool to identify SGRs as short-hard GRB progenitors. First, we note that the failure to detect the signature of a compact binary coalescence from GRBs, at distances where such a signal is expected, can provide compelling evidence for the SGR progenitor scenario. Indeed, observations by the initial LIGO detectors recently excluded the coalescence of a binary neutron star system in M31 at more than 99% confidence as the progenitor for GRB 070201. Furthermore, a binary neutron star merger is excluded at distances less than 3.5 Mpc with 90% confidence. If, however, the progenitor had been an SGR flare, the LIGO observations imply an upper bound on the isotropic energy released as an unmodeled gravitational wave burst of 7.5 □ 10^{50} erg, within the bounds permitted by existing models.

The non-detection of an expected inspiral gravitational wave signature, however, is not the only way that an instrument like ET can provide evidence for the SGR progenitor scenario. SGR flares could be a source of quasi-periodic oscillations, with quadrupolar components in the 10-40 Hz range. Observations of these shear mode oscillations in gravitational waves, with no accompanying inspiral signal, would only be explicable under the SGR scenario. It is also possible that non-radial oscillatory modes would become excited by tectonic activity associated with a giant SGR flare. These modes will then be damped by gravitational wave emission, resulting in a characteristic ring-down signal. Various families of oscillatory modes, such as fluid, pressure and purely space-time modes may be excited. Andersson and Kokkotas show that simultaneous gravitational wave observations of all three of these families can be used to place tight constraints on the neutron star equation of state. The pressure and space-time modes, however, tend to have frequencies well above 4 kHz making the fluid-mode, with frequencies expected in the range 1-3 kHz, the most accessible to gravitational wave observations. Again, gravitational wave observations of fluid modes would point directly to an SGR giant flare as the progenitor.

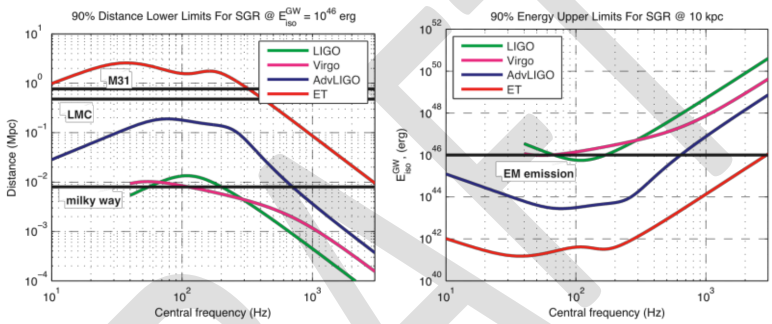


Figure 30 Left panel: 90%-confidence lower limit on distance for burst sources assuming the energy in gravitational waves is 10^{46} erg for an SGR progenitor scenario. Starting from the lower edge of the figure, the solid horizontal black lines show the distances, respectively, to the center of our galaxy, the large Magellanic cloud and M31. Right panel: predicted 90% upper limits on isotropically emitted gravitational wave energy from a Galactic SGR flare. The solid black horizontal line shows the expected upper limit of from 10^{46} erg energetic arguments alone.

Current models for SGRs indicate that they will emit less than 10^{46} erg in gravitational waves. **Figure 30** plots 90%-confidence lower limits on the distances to which various detectors will be sensitive to gravitational wave bursts with this energy and we see that, in their most sensitive frequencies, the current generation of interferometers are just able to probe our own galaxy. While advanced LIGO improves this reach substantially, it is only with ET that observations of extra-galactic SGR flares become possible.

It is likely that any vibration in the crust will quickly develop into a global magneto-elastic crust-core oscillation, since these two regions of the star are efficiently coupled by the strong magnetic field. A gravitational wave signal associated with a global magnetar mode could last about a minute (i.e. the typical lifetime of a QPO observed in X-rays), which translates to about a thousand wave cycles. This kind of gravitational wave signal would carry precious information about the (largely unknown) interior properties of magnetars, such as the strength and topology of the magnetic field and the elastic properties of the crust. With an instrument like ET operational, magnetar seismology might turn to a strong synergy between the electromagnetic and gravitational wave neutron star communities.

Gravitational wave observations may also provide valuable clues about the precise nature of the magnetar flare-trigger, which is presently a subject of speculation. The current magnetar model envisages that giant flares may be caused by large-scale star quakes in the magnetar's crust, which is subject to a growing strain due to the secularly evolving magnetic field in the core and the crust. Another possibility could be the triggering of a dynamical hydromagnetic instability somewhere in the core. In both scenarios, the magnetic field (and any matter coupled to it) is likely to undergo a global change, which could potentially have an observable gravitational wave burst-like signature, most likely in the same low-frequency band relevant for the QPOs.

Pulsar glitches: Many radio pulsars exhibit glitches, sudden spin-up events followed by a relaxation period towards stable secular spin-down. Pulsar glitches have a long observational history (beginning shortly after the discovery of the first pulsar) and so far over a hundred pulsars are known to have glitched at least once. Glitches have also been observed in magnetars. The archetypal glitching pulsar is Vela, which exhibits regular large glitches causing fractional spin frequency changes of the order of 10^{-6}.

Despite the wealth of observational data, glitches remain an enigma from a theoretical point of view. It is widely believed that they are related to the existence of supefluids in the interior of mature neutron stars and that they involve a transfer of angular momentum from a superfluid component to the rest of the star, which includes the crust (to which the pulsar mechanism is presumed to be rigidly attached) and the charged matter in the core. A superfluid rotates by forming an array of quantized vortices and it can spin down provided the vortices can move outwards. If ‘pinning’ to the other component impedes vortex migration, then the superfluid cannot keep up with the spin-down due to electromagnetic braking. As a result, a rotational lag develops between the two components until some critical level is reached at which the vortices unpin and transfer angular momentum to the rest of the star, and the two components are driven to corotation.

The nature of the instability causing vortex unpinning and the subsequent stage of relaxation of the system are poorly understood. One might hope that gravitational radiation detected by a glitch event could help unveil the key physics associated with this enigmatic phenomenon. It is likely that a glitch event involves the excitation of some of the inertial modes of the two-component system and the post-glitch relaxation is governed by the coupling of the two components through the vortex-mediated mutual friction force and the magnetic field. In fact, as recent work suggests, the glitch trigger-mechanism may be the result of a superfluid ‘two-stream’ instability setting in through the inertial modes of the system. ET would be an ideal tool for detecting a signal in the 10-100 Hz band which is the relevant one for the inertial modes of a Vela-like pulsar.

Stochastic backgrounds

The superposition of a large number of unresolved sources of gravitational waves produces a stochastic background, which could be detected by cross-correlating two (or more) detectors. We can distinguish between two contributions: a background of cosmological origin, a memory of the early stages of the Universe, and a background of astrophysical origin, a memory of the evolution of the galaxies and star formation.

Cosmological Stochastic Backgrounds: The cosmological stochastic background of GW is a unique window on the very early Universe, as gravitational radiation propagates uninterrupted to us from cosmic events even at the highest temperatures and densities. The detection of any such background would have huge consequences for models of fundamental physics, possibly giving us direct indications of inflation, phase transitions or formation of topological defects. As shown in Figure 31 many types of cosmological stochastic background are potentially above the ET sensitivity curve. It may also be possible to extract detailed information about the cosmological events that produced GW if the spectrum has some characteristic shape.

Inflation: There are many models of inflation, but they all share a few essential features that can be summarized as follows: exponentially expanding the scale factor in a short time; sourcing primordial density perturbations with amplitude $O(10^{-5})$ and an approximately Harrison-Zeldovich spectrum; and finally reheating the Universe to at least the temperature required for primordial nucleosynthesis (order of 10 MeV). For a scale-invariant spectrum, the CMB determination of the scalar amplitude together with the current bound on the ratio $r < 0.2$ of tensor to scalar perturbations translates to a very small value $\Omega_{gw} < 10^{-15}$ for all frequencies accessible to. However, since the CMB bounds apply at frequencies f 10^{-18} Hz, a positive spectral index could change the picture for interferometers. Figure 31, left panel, plots the possible signal for r=0.15, however, such optimistic parameter values are not consistent with simple scalar field inflation models.

Phase Transitions and Reheating: Peaked sources of stochastic background result from an event localized in cosmic time, typically a phase transition. There are many candidates, determined by the details of models in high-energy physics, including reheating after inflation. First order phase transitions proceed by the nucleation of spherical bubbles in a "false vacuum", where the potential energy density inside the bubbles is smaller than that in the false vacuum by an amount e. The bubbles grow rapidly and collide with one another; after collision the remaining bubble walls have a nonzero, rapidly-varying quadrupole moment and radiate gravitational waves. In the latter stages of the transition, gravitational waves may also be sourced by turbulence as the energy difference e is finally converted into heat. The main parameters of the transition are the temperature T_* at which bubble nucleation occurs, and the duration or characteristic timescale, assumed much shorter than a Hubble time. A transition temperature of 10^6-10^7 GeV corresponds to the sensitive range of ET. This could be achieved for phase transitions between metastable SUSY-breaking vacua. Figure 31 plots one scenario, for a hidden sector SUSY-breaking 10^6 GeV.

Reheating and Related Phenomena: At the end of inflation, the Universe is reheated by converting the inflationary energy density into radiation (light particles). This may happen non-perturbatively via parametric resonance, called "preheating", where the fluctuations of fields coupled to the inflaton grow exponentially rapidly. The stochastic GW spectrum produced from preheating after chaotic inflation has a peak value of $\Omega_{gw} \sim 10^{-11}$, however the peak frequency is well above the range of interferometers, unless model parameters take unlikely fine-tuned values.

The rapid decay of "flat directions" (scalar degrees of freedom) in supersymmetric models after inflation is a similar potential source of stochastic GW. Here the characteristic momenta of fluctuations is of order the SUSY-breaking mass scale $m \sim$ TeV, giving a present-day frequency of 100 Hz to 1 kHz. Figure 31 plots the spectra for two choices of parameter values: the lower curve has m = 100 GeV, reheating temperature 10^8 GeV and initial field value F = 2 x 10^{18} GeV; for the upper curve, m = 1 TeV, reheating temperature of 10^9 GeV and initial field value of F = 10^{18} GeV.

Many diverse and exciting phenomena in the physics and cosmology of the early Universe may be probed by ET via the stochastic GW background, either almost immediately if a signal is well above the detection threshold, or with an extended observation period. It may be possible to estimate the parameters, e.g. mass scales and couplings, of the new physics responsible: observational evidence for a cosmological phase transition, or of the temperature of reheating, would be an epoch-making result.

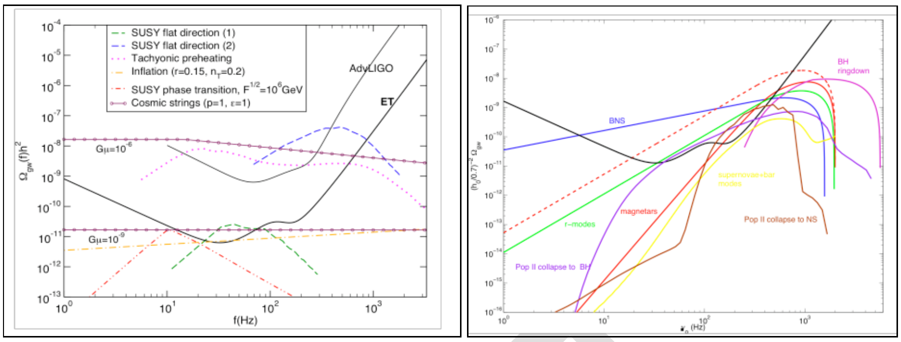


Figure 31: Energy density in gravitational waves from primordial sources (left panel) and of the different contributions to the astrophysical background discussed in the text (right).

Astrophysical Backgrounds: The astrophysical contribution is important for at least two reasons. On the one hand, it may mask the cosmological background in some frequency windows; on the other hand, its detection would put strong constraints on the physical properties of compact objects and their evolution with redshift, such as the mass of neutron stars or black holes, the ellipticity and the magnetic field of neutron stars or the rate of compact binaries.

What is particularly interesting is that using stochastic searches, we are able to put constraints on the mean values and not on the properties of the brightest sources, more likely in the tail of the distributions. The spectrum of the gravitational stochastic background is usually characterized by the dimensionless energy parameter:

$$\Omega_{gw}(\nu_o) = \frac{1}{\rho_c}\frac{d\rho_{gw}}{d\ln\nu_o}$$

Here r_{gw} is the gravitational energy density, n_o the frequency in the observer frame and the r_c is the critical energy density of the Universe. For a stochastic background of astrophysical origin:

$$\Omega_{gw}(\nu_o) = 5.7\times10^{-56}\nu_o\int_{z_{\min}}^{z_{\max}}\frac{\dot{\rho}^o(z)}{(1+z)E(z)}\frac{dE_{gw}}{d\nu}(\nu_o)dz$$

Here is $\dot{\rho}^o(z)$ the number of events in an element of co-moving volume and interval of time in the observer frame, $\frac{dE_{gw}}{d\nu}$ typical the spectral energy density of a single source and $E(z)$ a function that depends on the cosmology. We take the Hubble parameter to be 70 km s^{-1} Mpc^{-1} and a flat Universe with 70% of dark energy and 30% dark matter.

Binary Neutron Stars: Double neutron star coalescences, which may radiate about 10^{53} erg in the last seconds of their inspiral trajectory, at frequencies up to 1.4 − 1.6 kHz, may be the most important contribution in the ET frequency range. In the quadrupolar approximation the GW energy spectrum emitted by a binary system is

$$dE_{gw}/d\nu = \frac{(G\pi)^{2/3}}{3}\frac{m_1 m_2}{(m_1+m_2)^{1/3}}\nu^{-1/3}$$

The energy density in the stochastic background caused by a population of binary sources at cosmological distances is shown in Figure 31. The energy density increases as $\nu_0^{2/3}$. ET should detect the background even for the most pessimistic predictions of the coalescence rate, down to $\dot{\rho}^o(z) = 0.035$, roughly equivalent to a galactic rate of 3 My^{-1}, for a signal-to-noise ratio of 3.

Rotating Neutron Stars: Rotating neutron stars with a triaxial shape may have a time varying quadrupole moment and hence radiate GWs at twice the rotational frequency. The total spectral gravitational energy emitted by a NS born with a rotational period P_0, and which decelerates through magnetic dipole torques and GW emission, is also plotted in Figure 31. The majority of neutron stars are born with magnetic fields of the order of 10^{12-13} G and rotational periods of the order of tens or hundreds of millisecond and very likely don't contribute very much to the stochastic background. But the population of newborn magnetars in which super-strong crustal magnetic fields $B \sim 10^{14-16}$ G may have been formed by dynamo action in a proto-neutron star with very small rotational period (of the order of 1 ms) may produce a stochastic background detectable by ET.

For these highly magnetized neutron stars, the distortion induced by the magnetic torque becomes significant, overwhelming the deformation due to the fast rotation. When the deformation of the star is small, the magnetic torque dominates the spindown but as the ellipticity increases GW emission may become the most important process.

Assuming that magnetars represent 10% of the population of neutron stars, the stochastic signal is detectable with ET after an observation time of one year and with a signal to noise ratio of 3. In the saturation regime where the spindown is purely gravitational, the energy density increases as the square of the frequency at low frequencies and reaches a maximum of $\Omega_{gw} \sim 1.3 \times 10^{-8}$ around 1600 Hz, giving a signal detectable by ET with a signal-to-noise ratio of 45.

Relativistic Instabilities: The gravitational-wave background from core collapse supernovae could be pretty large due to a number of proposed post-collapse emission mechanisms. One intriguing mechanism is the bar-mode dynamical instability associated with neutron star formation. These instabilities derive their name from the `bar-like' deformation they induce, transforming a disk-like body into an elongated bar that tumbles end-over-end. The resulting highly non-axisymmetric structure resulting from a compact astrophysical object encountering this instability makes such an object a potentially strong source of gravitational radiation and has been the subject of a number of numerical studies.

Howell et al. have calculated the background signal from this emission process using simulated energy spectra data. Assuming a 20% occurrence of this instability, one finds that the resulting background reaches a maximum of $\Omega_{gw} \sim 4 \times 10^{-10}$ around 800 Hz would be detectable with a SNR of 3 after one year of integration. The optimistic event rate considered here is supported by suggestions that post collapse neutrino emission by the proto-neutron stars can induce contraction through cooling. This leads to increased spins though conservation of angular momentum. The implication here is that the instability can set in tens of milliseconds post collapse, increasing the rate of occurrence.

The stochastic background from r-modes was first investigated by Owen and then reviewed by Ferrari. The spectral energy density of a single source is given by:

$$\frac{dE_{gw}}{d\nu} = \frac{2E_o}{\nu_{\rm sup}^2}\nu \text{ with } \nu \in [0 - \nu_{\rm sup}]$$

Here ν_{sup} is 4/3 of the initial rotational frequency and E_0 is the rotational energy lost within the instability window. For neutron stars the spectrum evolves as $\Omega_{gw} \sim 10^{-12} \xi \nu_o^3$ where ξ is the fraction of neutron stars born near the Keplerian velocity and which enter the instability window, until it reaches a maximum at 900 Hz. ET may be able to detect this signal with an SNR > 3 after a year's integration provided ξ>0.23%. Similar constraints are obtained with the secular bar mode instability at the transition between Maclaurin and Dedekind configurations.

Core Collapse Supernovae: The GW background from core collapse supernovas that result in the formation of black holes was first calculated by Ferrari and others using the relativistic numerical simulations of Stark and later by de Araujo, who found similar results assuming that all the energy goes into the ringdown of the $l=m=2$ dominant quasi normal mode.

The frequency ν_* of this mode is given by

$$\nu_* \approx \frac{c^3}{2\pi G}(1 - 0.63(1-a)^{0.3})\frac{1}{M(\mathrm{M}_\odot)}$$

Here the mass of the BH is a fraction of the mass of the progenitor and where a is the dimensionless spin parameter ranging from 0, for a Schwarzschild BH, to 1 in the extreme Kerr limit. The spectral energy distribution in ringdown modes is

$$\frac{dE_{gw}}{d\nu} = \varepsilon M_{\rm bh} c^2 \delta(\nu - \nu_*(M))$$

Here ε is the efficiency coefficient. Numerical simulations give $\varepsilon = 7 \times 10^{-4}$ for an axisymmetric collapse but it is likely that less symmetric situations result in a more efficient production of gravitational waves. Assuming that stars in the range 30-100 solar mass can produce a BH. Taking a=0.1 and a=0.6, Regimbau et al. find that the energy density ranges between 250 Hz to 5.6 kHz, with a maximum of $\Omega_{gw} \sim \varepsilon \times 10^{-8}$ around 1650 Hz. This means that an efficiency of greater than 0.2% would give a signal detectable in ET with an SNR of 3 after one year of observation.

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3.4.2.3. *Summary of Achievements*

1. Sathyaprakash, Hough, Lueck and Punturo are editors of a Special Issue on 3rd generation gravitational-wave detectors, commissioned by *General Relativity and Gravitation*, Springer Verlag, Heidelberg, Germany. They have invited over 50 international experts to write technical papers on the science potential of and the technological breakthroughs needed for the Einstein Telescope.
2. Bose, O'Shaughnessy, Sathyaprakash and Van Den Broeck have shown that ET will be able to see binary neutron star coalescences out to red shifts of z=2; this will make it possible to resolve the enigma of GRBs. Inspiralling black hole binaries should be seen to red shifts of z=8, thereby allowing to map the binary black hole population at high redshifts.
3. Regimbau and Hughes have shown that the confusion background from neutron star binaries will be well below the baseline ET sensitivity but it is possible that several overlapping signals might be present at any one time. This has implications for ET data analysis. ET should detect the confusion background and shed light on binary neutron star populations in the Universe.

4. Bose, O'Shaughnessy, Sathyaprakash and Van Den Broeck have shown that ET will measure the component masses of a binary neutron-star black hole system so accurately that it should be possible to infer the maximum mass a neutron star could have (a long-standing open problem in fundamental nuclear physics) and whether there is a state of matter intermediate between neutron stars and black holes.
5. Sathyaprakash, Schutz and Van Den Broeck have shown that coincidence observation of GRBs, their afterglows and gravitational waves from binary neutron stars will enable accurate measurements of the Hubble parameter, deceleration parameter and the dark energy equation of state.
6. Sessana, Gair, Mandel and Vecchio, have investigated the potential of ET to detect and measure seed black holes of galaxy formation and growth of structure in the Universe, concluding that ET could detect intermediate mass black holes of masses up to 1,000 solar masses.
7. Bosi has begun to put forward a plan to address the computational and data analysis challenges. Bosi and Ed Porter have computed the computational requirement to search for binary neutron stars and black holes in ET underlining that the possibility to boost the data analysis of GW signals in a many-core environment is very promising for the next decade (now implemented through GPU technology). This will be further investigated in the next months of the project.

3.4.2.4. *Deviations from Annex I and proposed corrective actions*

None

3.4.3. Use of the resources

At Cardiff University Van Den Broeck was appointed during May 2008-August 2009 to work 50% on ET science goals. In August 2009 he was appointed as a faculty at NIKHEF, Amsterdam. In April 2009 Thomas Dent was appointed to work 100% on ET science goals. Sathyaprakash is working 5% on the ET project and coordinates the activities of WP4. At Perugia Leone Bosi has been appointed to work on the computational and data analysis challenges that we face in the context of ET. At CNRS, Annecy, France, Alex Dietz was appointed in July 2009 to work 25% on ET Mock Data Challenge. At Albert-Einstein Institute, Golm, Germany, Sofiane Aoudia has been appointed to work 35% on ET Mock Data Challenge

3.4.4. Publications realized during the period

1. *Observing gravitational waves from the first generation of black holes*, A. Sesana, J. Gair, I. Mandel, A. Vecchio, Astrophys. J. Letters 698 L129-132 (2009) [arXiv:0903.4177].
2. *Probing seed black holes using future gravitational-wave detectors*, J. R Gair, I. Mandel, A. Sesana, A. Vecchio, Class. Quantum Grav. 26, 204009 (2009).
3. *Gravitational-wave confusion background from cosmological compact binaries: Implications for future terrestrial detectors,* T. Regimbau, S. A. Hughes, Phys. Rev. D79, 062002 (2009) [arXiv:0901.2958].
4. *Measuring the neutron star equation of state with gravitational wave observations,* J.S. Read, C. Markakis, M. Shibata, K. Uryu, J.D.E. Creighton, J.L. Friedman, Phys. Rev. D79, 124033 (2009) [arXiv:0901.3258].
5. *Precision cosmology with the Einstein Telescope,* B. Sathyaprakash, B.F. Schutz, C. Van Den Broeck (submitted for publication) [arXiv:0906:4151].
6. *Confusion background from compact binaries*, T. Regimbau, Scott A. Hughes, Proceeding of the 8th Amaldi International Conference on Gravitational Waves, NYC, July 2009 [arXiv:0911.1043].
7. *Tidal deformability of neutron stars with realistic equations of state and their gravitational wave signatures in binary inspiral*, T. Hinderer, B.D. Lackey, R.N. Lang and J.S. Read [arXiv:0911.3535]

In addition members of the Design Study team have been invited to a number of workshops and conferences to talk about ET science potential.

3.4.5. Milestones

The first milestone *Science Requirement Document*, now called *ET Vision Document*, has now been accomplished and archived at: https://workarea.et-gw.eu/et/WG4-Astrophysics/visdoc

Table 7 - WP4 Milestones

MILESTONES					
Milestone no.	Milestone name	Due achievement date from Annex I *	Achieved Yes/No	Actual / Forecast achievement date	Comments
1	Science Requirement Document	M12	Yes	M17	This is now called ET Vision Document.
2	Astrophysics potentials-low frequency sources	M27			
3	Astrophysics potentials-medium frequency sources	M23			
4	Astrophysics potentials-high frequency sources	M27			
5	Computational Requirements	M28			