SCIENTIFIC POTENTIAL OF EINSTEIN TELESCOPE

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Einstein gravitational-wave Telescope (ET) is a design study funded by the European Commission to explore the technological challenges of and scientific benefits from building a third generation gravitational wave detector. The three-year study, which concluded earlier this year, has formulated the conceptual design of an observatory that can support the implementation of new technology for the next two to three decades. The goal of this talk is to introduce the audience to the overall aims and objectives of the project and to enumerate ET's potential to influence our understanding fundamental physics, astrophysics and cosmology.

1 Introduction

Interferometric gravitational wave (GW) detectors, Laser Interferometer Gravitational-Wave Observatory (LIGO) in the US, Virgo, GEO600 and TAMA, have successfully operated at design sensitivities for a year or more [1,2]. They have demonstrated that it is possible to build and run these highly sensitive instruments with a large duty cycle [3]. While no signal has so far been observed in any of these detectors, their data have been used to break new ground on several astronomical sources [4,5,6,7].

The network of advanced detectors, which includes advanced LIGO [8], advanced Virgo [9], Large Cryogenic Gravitational Telescope [10] (to be built in Kamioka mines in Japan) and GEO-HF [11] (GEO High Frequency), is expected to make the first direct detection of GW sometime during this decade. This will be a new milestone for observational astronomy that will facilitate the study of formations and interactions of neutron stars (NSs) and black holes (BHs) in the Universe.

Direct detection of GW will allow the study of phenomena associated with strong gravitational fields and relativisiic gravity that are otherwise not accessible to us. They will allow new tests of general theory of relativity in regimes where one might expect to see departure from standard predictions. The study of GW sources will by itself establish as a new field of observational astronomy. However, there is much more to be benefitted beyond the mere study of phenomena associated with GW sources. Just as stars, GW sources are markers in space, sometimes with precisely known distances. They could, therefore, serve to study the structure and dynamics of the Universe and hence a new tool for cosmology.

Advanced detectors will study NSNS, NSBH and BHBH binaries at distances of 200 Mpc, 600 Mpc and 3 Gpc, respectively, within which the nominal event rates are about 40 per year for NSNS binaries and similar, but much more uncertain, rates for NSBH and BHBH binaries [12]. The signal-to-noise ratio (SNR) for most of the sources detected by advanced detectors will be around 10. This should already make it possible to carry out a number of accurate measurements that will impact fundamental physics and astrophysics [13]. For instance, it should be possible to measure the Hubble constant to within 1% if NSNS and NSBH binaries are progenitors of short-hard gamma ray bursts (GRBs) and confirm the presence of tails of gravitational waves by observing BHBH mergers [14].

Third generation detectors, such as the Einstein Telescope (ET), will have ten times greater SNR for the same events and their reach will increase to $z \simeq 2$, for NSNS binaries, $z \simeq 6$ for NSBH binaries and $z \simeq 17$ for BHBH binaries (cf. Fig. 3). They will help address a variety of issues associated with phenomena that have remained as enigmas for several years to decades after their initial discovery. More than anything else, ET might well unveil new physics beyond the standard models of particle physics and cosmology.

The purpose of this talk is to discuss the science potential of ET and how it will be a powerful new tool for observing phenomena associated with strong field, relativistic gravity. The design study has already provided useful insight on what really will be the benefit of building a third generation GW detector [15]. However, the *full* science potential of ET and the challenges posed by science exploitation, remain unexplored. Yet what has been investigated is already very exciting and should provide the impetus for further studies. The talk will begin with a brief description of the technical aspects of the design and different sensitivity options, followed by a discussion of ET's science potential.

2 ET Sensitivity

The ET design study was commissioned by the European Commission to scope out the technological feasibility of building a 3rd generation detector and to explore its science potential. The study team set itself the goal of designing a detector that is better than advanced detectors ten times in strain sensitivity and reaches down to 1 Hz rather than the 10-20 Hz low frequency limit of advanced detectors. It was soon realized that the infrastructure, in which advanced detectors will have been housed for more than 20 years since their inception, will be highly inadequate in realizing the sensitivity of a 3rd generation detector. ET will be more than just a detector; it will be a facility that will house a 3rd generation observatory but with infrastructure that can

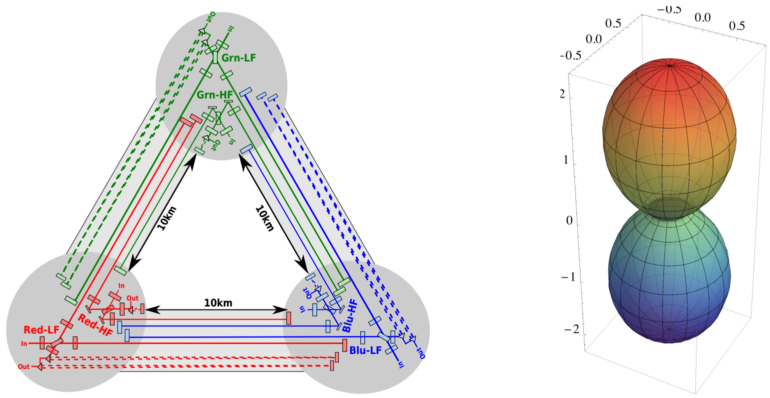

Figure 1: *Left*: Schematic full view of the optical layout of the ET Observatory. It consists of 3 pairs of km-scale interferometers positioned such that they form a triangular shape. Each interferometer pair represents one wide-band detector, in which one interferometer is optimized for gravitational waves at low frequencies (i.e., $< 100\,\mathrm{Hz}$) and the other for high frequencies (i.e., $> 100\,\mathrm{Hz}$). *Right:* The joint antenna pattern of the three interferometers to sources from around the sky. ET has virtually full sky coverage.

support new designs and improvements for several decades.

A factor ten in strain sensitivity is achieved by a combination of increased arm lengths (10 km arms as opposed to 3-4 km arms afforded by the current infrastructures), seismically quieter underground environments to mitigate seismic noise, higher arm cavity laser powers to confront photon shot noise and cryogenic mirrors cooled down to 10 K to reduce thermal noise.

2.1 Arm lengths and topology

In the long-wavelength approximation, the strain sensitivity of an interferometer increases in direct proportion to the length of its arms. The arm lengths of current (large) detectors is either 3 or 4 km. The strain sensitivity of an interferometer with 10 km arms will be 2.5 to 3 greater. Current ground-based detectors are L-shaped interferometers since an opening angle of 90 degrees maximizes their sensitivity. However, careful considerations taking into account continuous operation, ability to resolve the two independent wave polarizations and minimizing the infrastructure costs, favours the construction of a triangular configuration.

The advantage of a triangular topology is that each side of the triangle can be deployed twice to build, in effect, three V-shaped interferometers with an opening angle of 60 degrees and rotated relative to each other by 120 degrees (see the panel on the left in Fig. 1). An opening angle of 60 degrees means that the sensitivity reduces to $\sqrt{3}/2$ that of an L-shaped detector; the three detectors in the triangle enhance the sensitivity by a factor of $\sqrt{3}$ and so an overall gain in sensitivity of $3/2$. The panel on the right in Fig. 1 shows the antenna pattern of the triangular network. The triangular ET has virtually complete sky coverage and it has no blind spots. Its reach to sources lying in the plane of the triangle will be a third of its reach to sources lying overhead!

The three V-shaped interferometers are, of course, equivalent in sensitivity to two L-shaped interferometers with arms that are only three-quarters in size of the triangular arms and rotated relative to each other by 45 degrees. However, the responses of the three detectors in a triangle can be used to construct a *null stream* that is *not* possible with the two L-shaped interferometers. It turns out that the sum of the responses of the three detectors in a triangle (for that matter any closed topology) is completely devoid of any gravitational wave. This is the closest that one can get to measuring the "dark current" in interferometers. The null stream will be an invaluable tool to characterize the background.

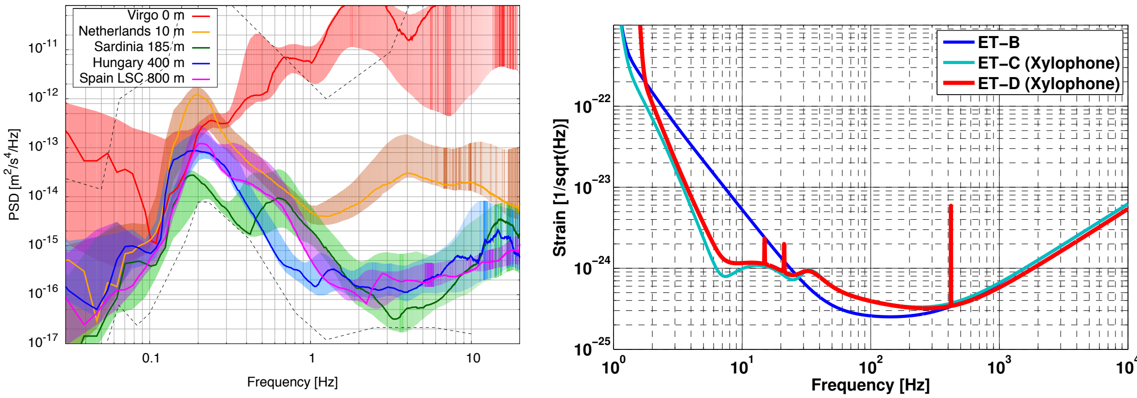

Figure 2: *Left:* The spectrum of horizontal motion over one-week period at Cascina, where Virgo is located, is compared to those measured at several underground locations in Europe. The solid lines correspond to the mode, while the upper and lower limits of the transparent regions are the PSD levels that weren't exceeded for 90% and 10% of the time respectively. *Right:* The sensitivity of ET for two possible options of the xylophone configuration (ET-C and ET-D) is compared with the standard one V-shaped interferometer (ET-B).

2.2 Going underground

Achieving good low frequency sensitivity requires mitigation of gravity gradients that are far too high on ground. They can be circumvented either by getting into space (the option pursued by the Laser Interferometer Space Antenna) or by going underground. To be useful, any underground site must be seismically quiet. Figure 2 shows the seismic noise in several European underground sites compared to the seismic noise at Cascina, where Virgo is located. Clearly, underground environments are several orders of magnitude quieter than ground-based ones.

Achieving a good sensitivity over a broad frequency range from 1 Hz to 10 kHz with the same technology is impractical. The technology required for better high frequency (i.e. $> 100\,\mathrm{Hz}$) sensitivity – higher laser powers – is in direct conflict with that required for improving the low frequency (i.e. $< 100\,\mathrm{Hz}$) sensitivity, namely low thermal and radiation pressure noises. Thus it is not prudent to build a single detector that meets the design goal in the entire frequency band. Instead, the design study concluded that it is best to build separate interferometers for the low and high frequency regions.

2.3 Megawatt lasers, squeezed light and cryogenic mirrors

The key to high frequency sensitivity is high laser power. Above $\sim 100\,\mathrm{Hz}$, the main source of noise is the photon shot noise, which can be reduced by simply using as high a power in the cavity as possible. ET aims to achieve the required 3 MW of power by using inherently more powerful input lasers (500 W as opposed to the 180 W in advanced interferometers). Furthermore, the use of non-classical light, squeezed light, leads to further improvement in sensitivity [16]. Indeed, ET design assumes a squeezing factor of 10 dB, which is equivalent to shot noise reduction resulting from an increase in laser power of a factor of 10.

Although, higher laser power works well at frequencies above 100 Hz, it has the adverse effect of worsening the sensitivity in the 10-100 Hz. This is due to enhanced thermal noise in mirror substrates and coating. Thus, it is not sensible to achieve the sensitivity goal over the entire band with a single interferometer. The current thinking is to build a pair of interferometers in each V of the triangle, one using high laser powers and the other with lower laser powers and cryogenic mirrors to mitigate thermal noise.

Figure 2, right panel, plots the strain sensitivity (per $\sqrt{\mathrm{Hz}}$) for two xylophone configurations [17] (ET-C and ET-D). They deploy a pair of interferometers to achieve good broadband sensitivity. Also shown is the sensitivity of a conventional configuration (ET-B) that deploys only one interferometer in each V of the triangle. Apart from the frequency range from 20 to 200 Hz, where ET-B is slightly better than ET-C or ET-D, the xylophone configuration quite significantly wins over ET-B in the low frequency range.

3 ET's science objectives

ET's distance reach for inspiralling and merging black holes for ET-B sensitivity is shown in the left panel of Fig. 3. The long- and short-dashed curves correspond to the observed total mass $M_{\rm obs}$ and the solid and dotted curves correspond to the intrinsic total mass $M_{\rm int}$; the two are related by $M_{\rm int} = M_{\rm obs}/(1+z)$. The solid and short-dashed curves are for non-spinning binaries consisting of two equal masses, while the dotted and long-dashed curves are the same except that the component black holes are both assumed to have a dimensionless spin magnitude of 0.75.

It is immediately apparent that ET will be sensitivity to BHBH binaries of intrinsic total mass 10-20$M_\odot$ at a redshift of $z \sim 10$ and beyond. NSNS binaries could be seen when the star formation in the Universe is at its peak at $z \sim 2$. NSBH binaries comprising of a 1.4 $M_\odot$ NS and a 10 $M_\odot$ BH can be detected from redshifts of at least $z \sim 6.5$. Together with the fact that the inspiral phase of compact binaries are standard sirens [18] means that ET will be able to explore not only the properties of the sources themselves but can also act as a tool to probe the properties of the Universe. Intermediate mass black holes of intrinsic total mass in the range 10^2-$10^4 M_\odot$ can be seen in the redshift range of 1 to 10, thus offering a unique probe to uncover a host of questions related to their existence and their role in the formation and evolution of galaxies.

Also shown in Fig. 3, right panel, are the sensitivities of initial LIGO, Virgo, advanced LIGO and ET (two versions, ET-B and ET-D), to continuous waves from rotating, asymmetric neutron stars, for an integration period of five years. Inverted black triangles give the upper limit on the amplitude of GW of known pulsars derived by assuming that their observed spin-down rate is entirely due to the emission of GW – Vela, Crab, B1951+32 and J0537-69 being specific examples. The horizontal line shows the limit on the amplitude of GW from pulsars obtained from statistical arguments. ET-D (red curve) will be sensitive to intrinsic GW amplitudes greater than $h \sim 10^{-27}$ in the frequency range 6 Hz to 3 kHz, and a factor 3 better in the range 20 Hz to 1 kHz. It is particularly important that ET is able to reach sensitivity levels that are two to four orders of magnitude lower than the spin-down limits, where one might have a real chance of detecting a signal.

The rest of this paper enumerates ET's science goals in fundamental physics, astrophysics and cosmology.

Probing fundamental physics with ET

3.1 Is the nature of gravitational radiation as predicted by Einstein's theory?

ET will allow a test of the wave generation formula beyond the quadrupole approximation [19]. It could accurately measure the GW propagation speed by coincident observation of GW and EM radiation from NSNS binary coalescences at $z \sim 2$ and constrain the graviton mass [20].

3.2 Are black hole spacetimes uniquely given by the Kerr geometry?

By measuring different quasi-normal modes, ET will test if the spacetime geometry of a BH is uniquely described by its mass and spin [21]. Additionally, ET can measure the multipole moments of a source from the radiation emitted as a stellar-mass BH spirals into an intermediate-mass BH and confirm if the different moments depend only on the massive BH's mass and spin [22,23].

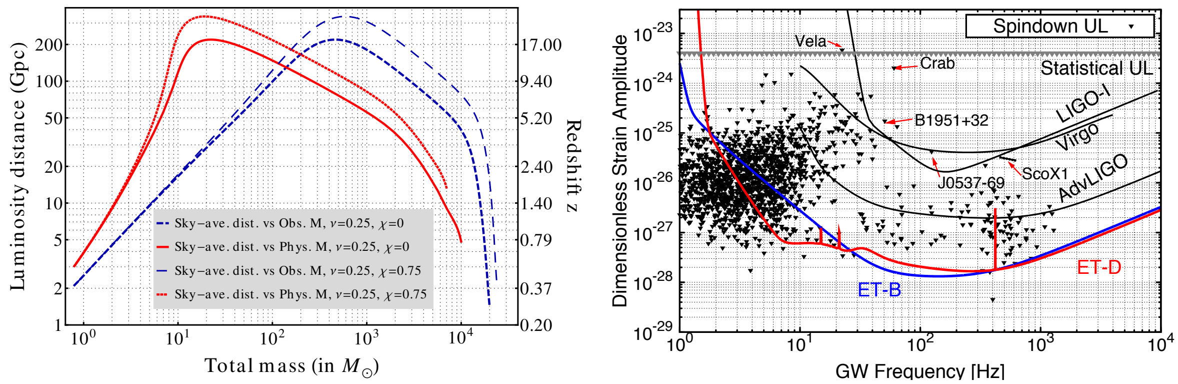

Figure 3: Plots show the distance reach of ET for compact binary mergers as a function of the total mass (left) and its sensitivity to GWs from known pulsars (right). See the text for details.

3.3 What is the physics of gravitational collapse?

ET can study supernovae and explore if they leave behind a massive object that is trapped inside an event horizon or lead to a naked singularity, or some other exotic object. ET could well reveal a new class of objects and phenomena, for instance *silent supernovae* [24] and other gravitationally unstable transients.

3.4 What is the equation of state of matter at supra-nuclear densities as might be found in NS cores?

The equation of state (EoS) of NSs affects the late-time evolution of NSNS and NSBH binaries. By matching the observed radiation from the coalescence of such sources to theoretical predictions ET will deduce the EoS of NS cores [25,26].

3.5 What is the maximum mass of a neutron star?

The maximum mass of a white dwarf is $\simeq 1.4\,M_\odot$ as determined by the electron degeneracy pressure. The maximum mass of a NS is an additional test of the nature of matter at extremely high densities; it is currently unknown and should be determined by ET by accurately constructing their mass function from millions of NSNS binaries [27].

ET's impact on astrophysics and multimessenger astronomy

3.6 What is the mass function of BHs and NSs and their redshift distribution?

ET will measure masses and spins of millions of NSs and BHs in binary systems and will thereby obtain a census of these objects as a function of redshift. This will be a very valuable tool for understanding a host of questions in astronomy related to redshift evolution of compact objects [28].

3.7 What are the progenitors of gamma-ray bursts?

GRBs are the most luminous electromagnetic sources in the Universe. While advanced detectors might provide some clues as to their origin, ET will provide a large statistical sample of events that could be used to understand GRB progenitors and to test their astrophysical models [27].

3.8 How do compact binaries form and evolve?

The process by which main sequence binary stars evolve into compact binaries (that is, NSNS, NSBH and BHBH) could be understood by ET's observation of millions of coalescing binaries with different masses, mass ratios and spins and mapping the observed population to astrophysical models [29].

3.9 What is the physical mechanism behind supernovae and how asymmetric is the gravitational collapse that ensues?

Supernovae are complex processes whose modelling requires many different inputs, including relativistic magneto-hydrodynamics, general relativity and nuclear and particle physics [30]. ET's observation of supernovae in coincidence with the detection of neutrinos could provide the data necessary to constrain models and help understand the process by which stars collapse to form NSs and BHs.

3.10 Do relativistic instabilities occur in young NSs and if so what is their role in the evolution of NSs?

Non-linearities of general relativity could cause instabilities in NSs that lead to parametric amplification of GWs. ET's observations of the formation of NSs can explore if such instabilities occur in young NSs and how that might affect their spin frequencies [26].

3.11 Why are spin frequencies of NSs in low-mass X-ray binaries bounded?

ET will verify if gravitational radiation back-reaction torque is responsible for the observed upper limit on NS spin frequencies in low-mass X-ray binaries [31].

3.12 What is the nature of the NS crust and its interaction with the core?

ET should detect NS ellipticities that are few $\times 10^{-10}$ (for sources within a distance of 1 kpc) or larger depending on their spin frequency and their distance from earth. Such observations can be used to deduce the property of NS crusts. ET might also detect GWs that are expected to be emitted when pulsars glitch and magnetars flare and thereby help understand crust-core interaction that is believed to transfer angular momentum from the core to crust [32].

3.13 What is the population of GW sources at high redshifts?

A large population of point sources would produce a confusion background that would be detectable by ET if the energy density of the background is large enough. Detection of confusion backgrounds can be used to understand the nature and population of GW sources in the Universe.

ET as a new cosmological tool

3.14 What are the luminosity distances of cosmological sources?

Compact binaries are an astronomer's ideal *standard candles* or, more appropriately, *sirens.* Gravitational wave observations can alone determine both the apparent and absolute luminosity of a source and hence deduce their luminosity distance. With ET, these self-calibrating standard sirens can be used to calibrate the cosmic distance ladder [33].

3.15 What is the EoS of dark energy and how does it vary with redshift?

ET could observe thousands of coalescing NSNS and NSBH systems in coincidence with optical or gamma-ray observations and hence measure both the luminosity distance and redshift. ET will, therefore, facilitate precision measurement of the dark energy EoS and its variation with redshift [34].

3.16 How did the black holes at galactic nuclei form and evolve?

ET can verify if seeds of galaxy formation were intermediate BHs of hundreds to thousands of solar masses and map their merger history up to redshifts of $z \sim 5$–15 depending on the total mass and mass ratio of progenitor binaries [23].

3.17 What were the physical conditions in the primeval Universe and what phase transitions occurred in its early history?

Stochastic GW backgrounds could be produced by quantum processes in the primordial Universe or during phase transitions in its early history. ET will be sensitive to background densities $\rho_{\mathrm{GW}} \sim 10^{-12}\,\rho_c$, where ρ_c is the critical density of the Universe [35].

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