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Einstein Telescope, the future generation of ground based gravitational wave detectors

Aniello Grado

INAF- Osservatorio Astronomico di Capodimonte Via Moiariello 16 80131 Napoli, Italia

E-mail: aniello.grado@inaf.it

Abstract. The second-generation gravitational wave detectors Advanced LIGO and Advanced Virgo have shown their breakthrough capability to shed light on our understanding of the Universe. Although the steady increase in sensitivity, these detectors will hit in the future limitations due to their hosting infrastructures. This is the reason why a new generation of gravitational wave detectors are under studies. The Einstein Telescope (ET) is a planned European 3^{rd} generation gravitational Wave (GW) Observatory, a new research infrastructure designed to host a detector capable to observe the entire Universe using gravitational waves. ET will be a multi-interferometer observatory aiming to increase a factor ten the sensitivity of previous generation detectors. We will give an overview of the project, describe the main scientific goals and the technological challenges that must be overcome to reach the expected sensitivity.

1. Introduction

Since the first direct detection of a gravitational wave (GW) achieved in 2015, the 2^{nd} generation detectors Advanced LIGO [1] and Advance Virgo [2] have made great strides in the understanding of several astrophysical, cosmological and fundamental physics questions, starting with the proof that binary black holes (BBH) and binary neutron stars (BNS) do exist. Up to now, 90 GWs were detected [3], two generated by the coalescence and merging of BNS, three from NS-BH binaries and eighty-four from BBH. Thanks to these detections it was possible to get information on the population characteristics of such binary compact objects systems; on the nature of the central engine of short gamma ray bursts; it was possible to measure the Hubble constant in a completely new way, as suggested in 1986 by B. Schutz [4]. In addition, it was found evidence of the mechanism that produces heavy elements through the r-process and new insight was obtained on the equation of state of neutron stars, just to give a not exhaustive list.

In the last years there was an escalation in the number of GW detections thanks to the increase in the sensitivity of the detectors that undergo periodic hardware upgrades. This process will proceed until infrastructural limitations will make any further improvement very difficult. For that reason, there is an ongoing effort in Europe, with the Einstein telescope (ET), and in the United States, with Cosmic Explorer (CE), to design the 3^{rd} generation of gravitational waves detectors. In particular, ET will have a sensitivity ten times better compared to the second generation detectors and will be optimized for the detection of gravitational signals at low frequency. This requires the adoption of a certain number of technical and infrastructural solutions as detailed in the following sections. Thanks to these improvements, the expected distances, masses range, detection rate and signal-to-noise ratio of sources detectable by ET will pave the way to new insight into astrophysics, cosmology and fundamental physics. The paper will describe the ET science goals in section 2 while a description of the main technological solutions that will be adopted to meet the required sensitivity will be reported in section 3. The section 4 is devoted to the conclusions.

2. ET science goals

In this section, we will shortly describe the extraordinary capability of ET in observing the Universe in terms of distances, detection rate and signal-to-noise ratio. We will only grasp the surface of the ET scientific potential. For a comprehensive review on the subject see [5].

For what concerns distances, ET will be able to see the coalescence of equal masses BBH, with a total source-frame mass of 20 $M_{\odot}$, up to cosmological redshift z $\sim$ 100, probing the dark era of the Universe before the birth of the first stars [6]. It is worth noting that any detection from a merger of a BBH at distances above z $\sim$ 30 would entail a primordial origin of the source, with all the cosmological implications of such discovery [7]. ET will be capable to determine the BH mass function and its evolution with redshift, in other terms it will be able to understand the BH origin and how the binary systems formed in the different phases of the Universe history [8].

ET will be capable to detect BNSs up to a redshift of $\sim 2 - 3$, i.e at least one order of magnitude larger compared to the distance reachable by 2^{nd} generation detectors for the same kind of sources. Not only the distances but also the expected detection rates per year will be astonishing: of the order of 10^5 - 10^6 for BBH and 10^4 for BNS [9, 10]. The signal-to-noise ratio of many of these events will be huge. With a network of three 3G detectors, a BBH coalescence with total mass $(50 - 100)$ $M_{\odot}$ at redshift 10 could be seen with SNR of order 50, and the SNR of some events, at high redshift, will even be of order 100-200, allowing to study compact binary population [11] and determine the GW sources parameters with high precision [12]. Great interest comes from the ET capability to study the structure of neutron stars through the GW emitted during the coalescence phase [13] allowing to reconstruct the NS equation of state.

It is expected that ET will play in the future a decisive role in the cosmological parameters estimation [14, 15]. The ET detection of GW from binary compact-object systems could greatly improve the constraints on dark energy cosmological models and on breaking the cosmological parameters degeneracy arising from the current cosmological electromagnetic observational data.

A not exhaustive schematic list of the ET science goals is reported in table 1. In the next section we will discuss some of the proposed technical solutions that will be adopted to meet the ET sensitivity requirements.

3. ET detector

The European GW scientific community has developed the conceptual design of the Einstein Telescope, a 3^{rd} generation GW observatory, which will revolutionize our knowledge of the Universe [16]. The main characteristics of ET will be: 1) increased sensitivity of at least one order of magnitude with respect to the nominal sensitivity of 2^{nd} generation detectors; b) widening the frequency band of observation; c) focus on massive (or intermediate mass) black holes by achieving an extraordinary sensitivity at low frequency (few Hz); d) having the possibility to make science in a standalone configuration; e) having localisation and GW polarisation disentanglement capabilities and have a more uniform sky coverage; f) having a lifetime spanning several decades (at least 50 years); g) giving the possibility to host the evolution of the detectors, without limiting their sensitivity.

The achievement of such challenging requirements call for the introduction of a series of innovative solutions compared to the 2^{nd} generation detectors. These include an underground infrastructure to minimize the atmospheric, seismic and the so-called Newtonian noise [17, 18],

Astrophysics			
Black hole	Origin	Evolution	Demography
Neutron star	Interior structure	Demography	
Multi-messenger	Nucleosynthesis	Physiscs of jets	Role of neutrinos
New GW sources	Core collapse supernovae	Isolated neutron stars	Stochastic background of astrophysical origin
Fundamental physics and Cosmology			
Compact objects	Near-horizon physics	No-hair theorem	Exotic compact objects
Dark matter	Primordial BH	Axion clouds	Dark matter accreting on compact objects
Dark energy	Dark energy equation of state	Modified GW propagation	
General relativity	Post-Newtonian expansion	Strong field regime	
Stochastic backgrounds of cosmological origin	Inflation	Phase transition	Cosmic strings

Table 1. Main ET science goals

all sources limiting the low frequency sensitivity. To widen the frequency band, each detector will be made of two interferometers, one optimized for the low frequency band between 3 Hz and 40 Hz (ET-LF) and one optimized for the high frequency (ET-HF) working in the band 40 Hz to 10 kHz. To reduce thermal noises [19], the main optics of ET-LF will operate at cryogenic temperature, and to optimize their performance the optics substrates will be made of silicon. The intra-cavity light power will be low, around 18 KW, to reduce the power dissipation in the optics. For what concern ET-HF, it will operate at room temperature with fused silica mirrors and to reduce the shot noise it will use high circulating light power of up to 3 MW.

ET will have a triangular geometry with a total of three nested detectors (it means a total of six interferometers) to allow better sky coverage, sources localization and polarization measurement capability. A straightforward increase of the SNR, compared to second generation detectors, will be attained by increasing the length of the arms to 10 km. Despite their size and the large mass of mirrors involved, GW detectors are quantum mechanics limited instruments. At high frequency they are limited by the light phase noise, also called shot noise, while at low frequency they are limited by the light amplitude noise that produces a radiation pressure noise on the suspended mirrors. For a review on the subject see [20]. To reduce the quantum noise in ET it will be adopted a frequency dependent squeezed vacuum injected into the output port. The overall optical configuration for the Einstein Telescope will be a dual recycled arm cavity Michelson interferometer with frequency-dependent squeezing.

If we look at the noise budget of ET we can identify a certain number of fundamental noises limiting the sensitivity depending on the frequency range considered. At low frequency, around a few Hz, the limitation comes from the seismic and gravity gradient noises. Below ~ 300 Hz, the thermal noise from the mirrors coating, the mirrors suspensions, the radiation pressure quantum noise and the residual gas pressure in the towers give the main contribution. Above 300 Hz the limitation comes from the light shot noise. The figures 1 and 2 show the various contributions to the ET noise budget for the interferometer working at low and high frequency respectively.

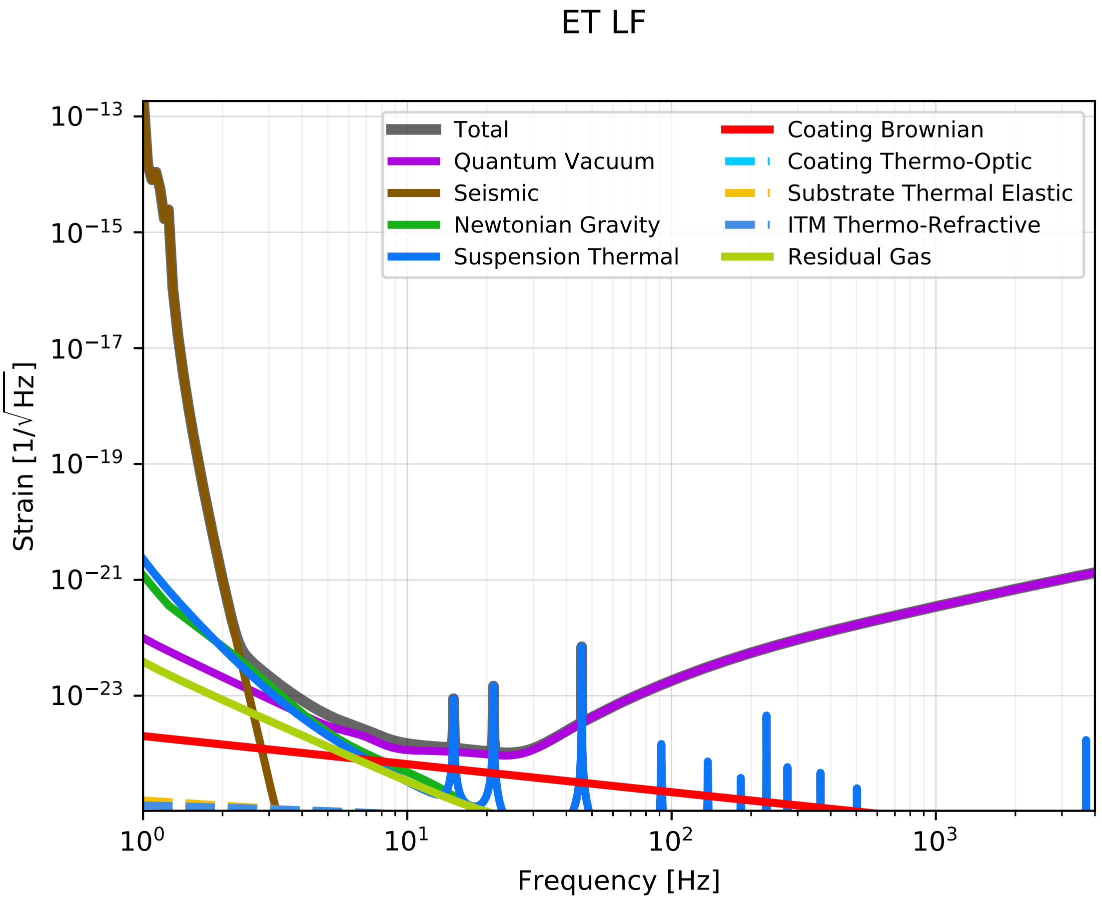

Figure 1. Noise budget for ET-LF assuming 18KW power in the cavities, silicon mirrors of 211 Kg weight working at 10k and a laser wavelength of 1550 nm

The curves, obtained using the Pygwinc code [21], show clearly which noise in which frequency range limits the detector sensitivity.

The cost of the whole ET project is around 2 billions euro, of these almost half are required to build the underground infrastructure. The second subsystem is the beam pipe vacuum system that consists of a 1 m diameter, 120 km long tube operating in Ultra High Vacuum (UHV). There are several motivations to have the laser beam propagating in ultra high vacuum (UHV): keeping low enough the fluctuations in the refractive index of residual gases, which would change the laser optical path and in this way mimic GW signals; avoiding mirrors contamination; reducing gas damping of the suspended optics and allows thermal and acoustic isolation of the mirrors. The ET vacuum vessel will be the largest UHV system ever made with a total volume of $9.4 \times 10^4\ m^3$. The requirements on the partial pressure foresee 10^{-10} mbar for H_2, 5×10^{-11} mbar for water and less than 10^{-14} mbar for hydrocarbons. These specifications should guarantee a noise floor due to residual gas fluctuations in the beam pipes below 10^{-25} $(1/\sqrt(Hz))$. The estimated cost is around 560 Meuro assuming a construction approach similar to the one adopted in Virgo. There is an ongoing huge effort in finding solutions to reduce such costs. In particular, the attempt is to find new cheaper materials for the beam pipe, as a substitute of the usual austenitic stainless steel, with high resistance to corrosion to ensure the required detector lifetime and that requires mild or no thermal treatments to remove the hydrogen from the bulk steel [22].

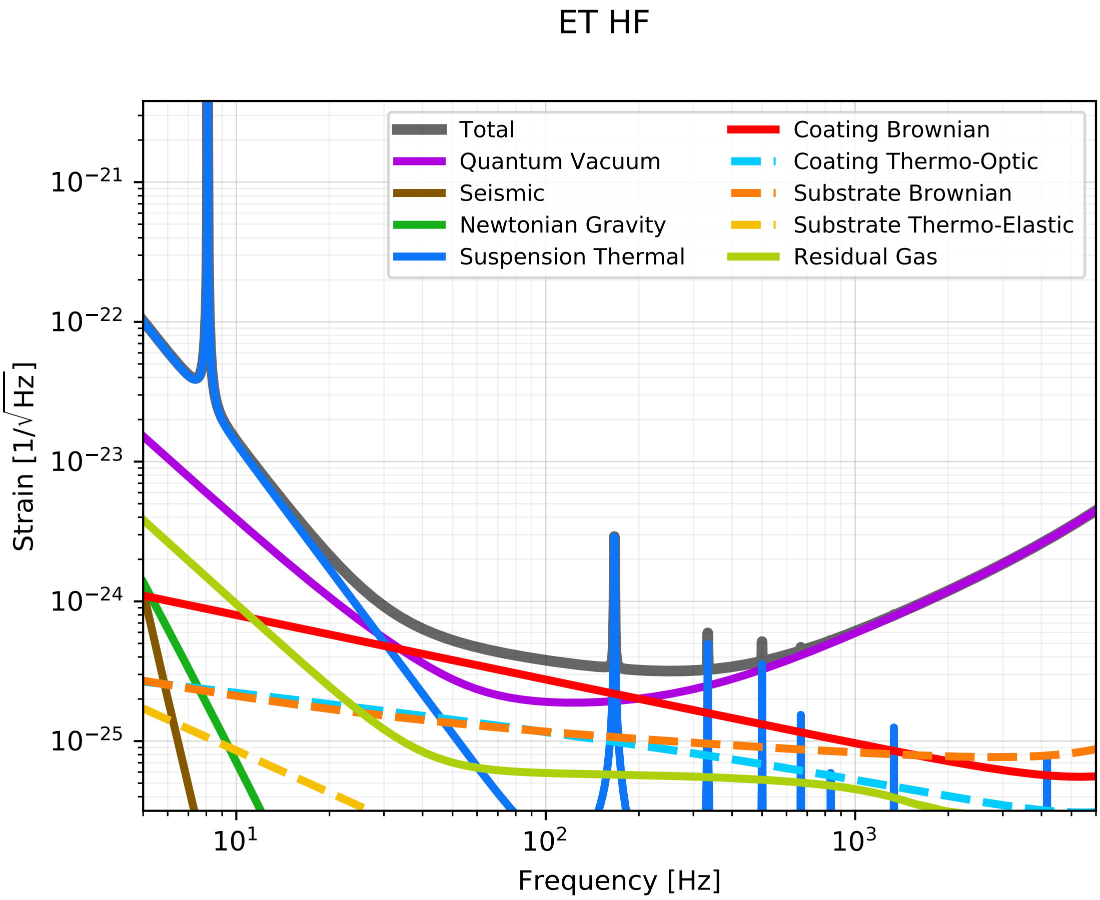

Figure 2. Noise budget for ET-HF assuming 3MW power in the cavities, fused silica mirrors of 200 Kg weight working at room temperature and a laser wavelength of 1064 nm

4. Conclusions

The Einstein Telescope is a 2 billion euro project, entered in the ESFRI road map in 2021, that is expected to be in operation in 2035. ET promise to revolutionise our understanding of the Universe up to the dark age. To meet the requirement of a factor 10 increase in the detector sensitivity with an optimized detection capability at low frequency, a suite of solutions have been proposed. These includes splitting each detector in two interferometers one optimized for the low frequency and operating at cryogenic temperature and low laser power and one operating at high frequency with high power circulating light. ET will have a triangular shape and will be made of a total of six nested interferometers allowing for a better GW sources localization and stand alone operation capability. The reduction of seismic, atmospheric and gravity gradient noise will be secured by installing the detector 200 – 300 meters underground.

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