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Einstein Telescope: Science and technology(*)

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Summary. — The document provides a concise overview of the key aspects defining the Einstein Telescope, including its configuration, the types of noise that affect it, and the innovative technologies being developed to mitigate them. A brief summary of its scientific potential is also incorporated.

1. – Introduction

Gravitational-wave (GW) observations have emerged as a novel and significant method for exploring the cosmos. The global network of gravitational-wave detectors currently includes two Advanced LIGO detectors [2] in the U.S. located in Hanford (Washington) and Livingston (Louisiana), the Advanced Virgo detector [4] near Pisa (Italy), and KAGRA [7] in Gifu prefecture(Japan). This network is set to expand with the addition of a third Advanced LIGO detector in India [31] in the near future.

To usher in the era of precision gravitational wave astronomy, a significant enhancement in sensitivity is necessary. Future space-based initiatives like the Laser Interferometer Space Antenna [29] and third-generation (3G) ground-based observatories such as the Einstein Telescope (ET) [14] and Cosmic Explorer [15] are anticipated to offer a significant increase in sensitivity and a broader accessible frequency band compared to second-generation detectors.

This paper will focus on the Einstein Telescope (ET), which will fully actualize the GW astronomy revolution, enabling us to address key issues concerning fundamental physics, relativistic astrophysics, and cosmology. Furthermore, multi-messenger astrophysics will significantly benefit from GW detectors, as they offer complementary information to electromagnetic radiation and other messengers, such as neutrinos and cosmic rays.

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2. – Design

ET will be an underground observatory. Its concept design foresees three GW detectors nested in a triangular shape of sides 10 km long (see fig. 1). However, an alternative ET design is under consideration: it would consist of two separated L-shaped detectors, each with arms 15 km long.

Extending the length of the interferometer's arms is crucial for enhancing the sensitivity to GWs. Yet, to achieve the sensitivity required for ET, additional technological advancements are necessary, as detailed in sect. **3**. Despite these advancements, achieving the desired sensitivity in the low frequency band (below 20 Hz) remains a challenge due to seismic and Newtonian noise. These factors constitute the final barriers to the sensitivity of ground-based GW detectors [30]. Therefore, ET will be built underground: this can mitigate the effects of seismic and Newtonian noise (see sect. **3**). An added benefit of reduced noise in the low-frequency band is a more stable instrument, leading to increased observation time.

Each detector will consist of two interferometers optimized in two complementary frequency bands (this configuration is often referred to as "xylophone"). This is a novel approach compared to current GW detectors, which often have to compromise between improving sensitivity at high frequencies and worsening it at low frequencies (and vice versa). As a result, the triangular ET will comprise six interferometers [19].

The triangular design has severl advantages. Firstly, it enables the determination of the GW's polarization content and optimizes the use of the tunnels (*i.e.*, excavated volume). Secondly, having three co-located detectors allows for the creation of a null-stream, a linear combination of detector signals that cancels out the gravitational-wave contribution, enabling noise events to be easily identified and rejected. Its effectiveness is under study. Lastly, three co-located detectors provide redundancy, ensuring that at least two detectors are always in observation mode, even during maintenance periods. This would make of ET a constant observer of the Universe. Even if one instrument is not operational, we can still fully detect both gravitational-wave polarizations, with the only limitation being the inability to construct a null-stream [16].

The 2L design on the other hand, would allow to remove correlated noise that would instead heavily affect the triangle [21]. However, in the 2L design the null-stream construction would be less effective, due to the distance of the detectors. Branchesi et al. studied the science potential of ET considering different geometries. A substantial improvement in the science reaches can be obtained by adopting the 2L-15 km geometrical configuration [10]. Currently, the optimal configuration is still under evaluation, considering other parameters like technical risks and costs.

3. – Main noises and new solutions

Gravitational wave detectors measure the relative movement between two test masses, which are typically highly reflective mirrors. Any mechanism that causes a displacement of these test masses, other than gravitational waves, is considered noise. The primary sources of noise in these detectors include seismic noise, thermal noise, Newtonian noise, and quantum noise. Each type of noise, along with the technologies used to mitigate them, will be briefly discussed below.

Seismic noise is caused by the mechanical transmission of ground vibrations to the

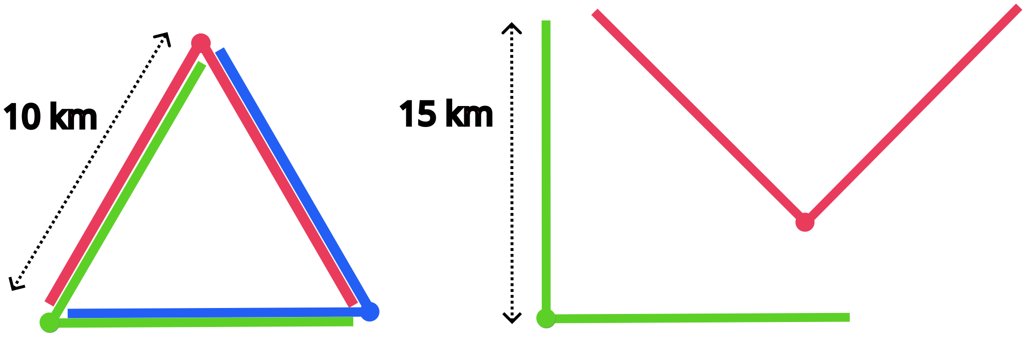

Fig. 1. – In the reference design (*left*) the ET observatory consists of three colocated detectors, each composed by two interferometers (Xylophone design), nested to form a triangle. An alternative design (*right*) is under study. It consists of a network of two distributed detectors, L shaped, implementing the Xylophone design. The 2L are expected to be rotated by about 45 degrees.

test masses. This can be mitigated by selecting a seismically quiet location, going underground [6], and especially by suspending the test masses from a chain of pendulums attached to an inverted pendulum, as is done in Virgo [3]. Active seismic isolation methods can also be used, as is done for LIGO [26]. The taller the suspensions, the greater the seismic suppression. The current design anticipates suspensions that are 17 m tall [19]. However, one could take advantage of the presence of the rock to drill space for the pendulum and then hang the test mass from higher places. This would, however, make the suspensions difficult to move for future upgrades of the instrument [5].

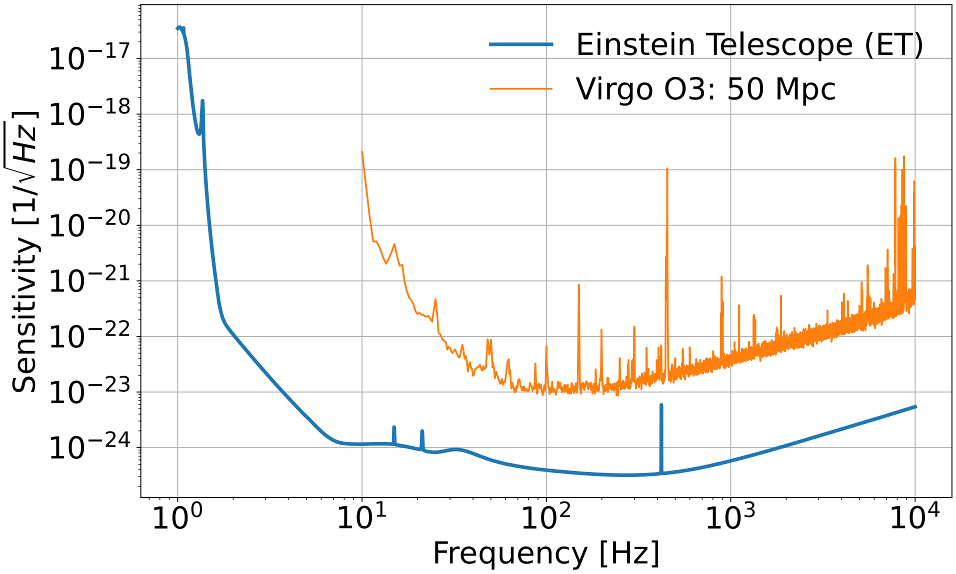

Fig. 2. – Sensitivity curve of ET compared to the best sensitivity curve measured in Virgo during O3.

Newtonian noise is generated by changes in the density of the surrounding materials, which in turn produce fluctuations in gravity. Atmospheric Newtonian noise occurs when there are air temperature or air pressure fluctuations [18]. Going underground greatly helps to reduce it, even though the noise produced by temperature fluctuations could still be a problem under certain conditions [12]. Seismic Newtonian noise is closely related to seismic noise, so being underground greatly reduces it, but a noise cancellation system will still be needed [8, 9]. An effective way to reduce Newtonian noise is to place an array of seismic sensors to monitor the seismic field with the aim of estimating the Newtonian noise affecting the test masses. This approach will be applied and tested for the first time in Virgo [23]. A similar approach needs to be investigated for atmospheric Newtonian noise.

Thermal noise primarily affects the lower frequency band and is produced by the normal modes of vibrations of the test masses and the fibers used to suspend them. Thermal noise is proportional to $\sqrt{T/(Qm)}$, where T is the temperature, Q the material quality factor of the test mass and and m its mass [17, 28]. Therefore, materials with excellent Quality-factors and low temperatures will be necessary to reach the design sensitivity. Cryogenic technologies will be required to cool down the test masses. This implies that specific materials for the main optics will be needed to ensure good mechanical properties (*i.e.*, quality factor) at such low temperatures. The laser wavelength will have to adapt to the new material properties. Moreover, a wider beam size will be required to reduce the thermal load on the test mass, which will also have to be heavier [24].

Quantum noise: is related to the quantum nature of light. It manifests in two components: quantum shot noise, which dominates at high frequencies of the detector spectrum, and quantum radiation pressure noise, which dominates at low frequencies. Radiation pressure can be suppressed by reducing the laser power impinging on the mirror and increasing the test mass weight. Conversely, shot noise can be reduced with increased laser power and by using squeezing, which if it is frequency-dependent can also be beneficial to the radiation pressure noise. Squeezing is a technique aimed at reducing the fluctuations in phase (*i.e.*, reducing the shot noise) or amplitude (*i.e.*, reducing the radiation pressure noise) of the light. Frequency dependent squeezing and the separation of the detector into a high- and a low-frequency bands are therefore fundamental to reduce quantum noise over all the frequency band of ET [20, 22].

In addition to the fundamental noises, there are also technical noises. These originate from the electronics, controls, and other auxiliary components of the detector that can contribute to noise generation. As such, these elements need to be closely monitored, and strategies must be developed to minimize their impact.

4. – Science case

While second-generation GW detector's results are indeed remarkable, they represent just the beginning of our journey to explore the Universe with GWs. 3G GW detectors, such as ET, will fully realize the revolution of gravitational wave astronomy. With an order of magnitude better sensitivity and a broader accessible frequency band compared to second-generation detectors (fig. 2), ET will enable us to tackle a wide range of key issues in astrophysics, fundamental physics, and cosmology.

The detection rates of merging binaries events will be staggering, with estimates of $10^5 - 10^6$ black hole-black hole and $7 \cdot 10^4$ neutron star-neutron star coalescences per year [25]. For neutron star binaries, with total mass around 3 solar masses, ET will reach distances of the order of $z \sim 2-3$; by comparison, the binary neutron star GW170817 was at $z \sim 0.01$ and the final target sensitivity of second-generation detectors should reach $z \sim 0.2$ [25]. Thus, depending on the network of electromagnetic facilities operating at the time of ET, over a few years, one might collect on the order of $10^2 - 10^3$ binary neutron star mergers with observed electromagnetic counterparts. Provided that GWs allows for an absolute measurement of the luminosity distance to the source, this will shed light on the Hubble tension [1].

Moreover, ET will reveal the full population of coalescing stellar and intermediate mass black holes in the Universe, over the entire epoch since the end of the cosmological dark ages. Thanks to the fact that the reach of ET for binary black hole systems is well beyond the peak of star formation at $z \sim 2$, by comparing the redshift dependence of the binary black hole merger rate with the cosmic star formation rate, it will be possible to distinguish the contribution of black holes of stellar origin from that of possible black holes of primordial origin (whose merger rate is not expected to be correlated with the star formation density) [25].

Many of these GW events will have a high signal-to-noise ratio (up to 200), allowing us to determine the shape of the gravitational wave with exceptional precision. This will allow ET to use the Universe as a laboratory to prove particle physics at high energies and densities by exploiting neutron star mergers. Indeed, a better understanding of the entire QCD phase diagram can be reached studying the signal shape of the neutron mergers during coalescence. This will provide a strong synergy with terrestrial heavy-ion collision experiments [25].

A stochastic background of gravitational waves will provide us with the opportunity to test particle physics models of the early Universe, at energy scales significantly higher than those achievable at the Large Hadron Collider [13].

The origin of dark matter can also be examined from various perspectives, as it could be anything from primordial black holes to particles beyond the Standard Model, which could influence GW emissions or leave a marks on the detector signal through direct interaction with it [11, 32].

ET will play a crucial role in probing both the nature of gravity in the strong field regime and the structure of compact objects, and could even pave the way for exploring the realm of quantum gravity [27].

Lastly, ET can be seen as a "discovery machine" in that it could also reveal unexpected signals, opening up new areas of research.

5. – Conclusion

ET will revolutionize astrophysics with a tenfold sensitivity improvement compared to current GW detectors. To reach its sensitivity goal, current technologies must be pushed to their limits and new technologies must be developed. Its sensitivity will allow to detect a plethora of GW signals, which will need to be processed by employing new techniques and developing new and faster computational infrastructures.

The ET collaboration was officially established in June 2022 and has since grown to include over 1400 members from more than 200 institutions. In 2021, ET was added to the European Strategy Forum on Research Infrastructures (ESFRI) roadmap. The location for the construction of ET is set to be decided by 2025, with potential sites including Sardinia in Italy and Terziet in Belgium-Netherlands.

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