

SPG Mitteilungen Communications de la SSP

Auszug - Extrait

Progress in Physics (103)

Einstein Telescope: the exploration of the Universe with Gravitational Waves

Michele Maggiore, Université de Genève

This article has been downloaded from:
https://www.sps.ch/articles/progress_in_physics/

DOI: [10.5281/zenodo.13208963](https://doi.org/10.5281/zenodo.13208963)

Progress in Physics (103)

Einstein Telescope: the exploration of the Universe with Gravitational Waves

Michele Maggiore, Université de Genève

Gravitational waves (GWs) were predicted by Einstein in 1916, as a consequence of his theory of General Relativity. In General Relativity space-time becomes dynamical, and GWs can be visualized as tiny ripples on the space-time structure, that propagate as waves, at the speed of light. About one century after Einstein's prediction, the LIGO-Virgo Collaboration (LVC) observed for the first time the GWs emitted by the coalescence of a binary black hole (BBH) system. This first detection took place on Sept. 14th, 2015 [1], and represented a milestone in science. In this first detection, two black holes with masses about 36 and 29 solar masses, that since millions of years were orbiting around each other, losing energy by GW emission, finally coalesced and formed a single black hole of about 62 solar masses. To give an idea of how extraordinary this event was, one can mention that, in the last 10 millisecond of the merger, a mass m of about 3 solar masses was transformed into energy, according to $E = mc^2$, and carried away by the GWs. During these 10 ms, the luminosity (energy radiated per unit time) of this single stellar event was 10 times larger than the estimated electromagnetic luminosity of all stars and galaxies of the Universe. Despite that, when the GW reached our observatories on Earth, after having traveled for about 410 Mpc (by comparison, the typical distance among galaxies is of the order of the Mpc), it induced perturbations on the structure of space-time of just about a part in 10^{21} . Still, after decades of developments, the LIGO detectors were able to observe it, by monitoring, with interferometric techniques,

the change in the distance between the mirrors of an interferometer, induced by the passage of the GW. To get an idea, the change in the distance between the two mirrors in each arm of the interferometer, placed 4 km apart, was about 1000 smaller than the size of an atomic nucleus! The discovery, announced in Feb. 2026, had a huge resonance in the media worldwide, and was awarded with the Nobel Prize already the year after the announcement, in 2017.

Another extraordinary milestone was the detection, on Aug. 17, 2017, of the first binary neutron star (BNS) coalescence [2]. The event was observed in coincidence with a gamma-ray burst detected by Fermi-GBM [3] and by INTEGRAL [4]. The electromagnetic counterpart was subsequently identified and followed by dozens of telescopes in all bands of the electromagnetic spectrum [5]. This event was an extraordinary example of multi-messenger astronomy, i.e., astronomy where a source is observed and studied with different messengers, such as electromagnetic signals and GWs, and had important implications in many fields, from relativistic astrophysics to nuclear physics, nucleosynthesis in the Universe, and cosmology.

Nowadays, after improvements in the detectors, BBH coalescences are routinely detected, with events observed at a rate of about one every few days during the latest observing run. The current catalog of GW detections now contains about 90 BBH coalescences, two BNS coalescences

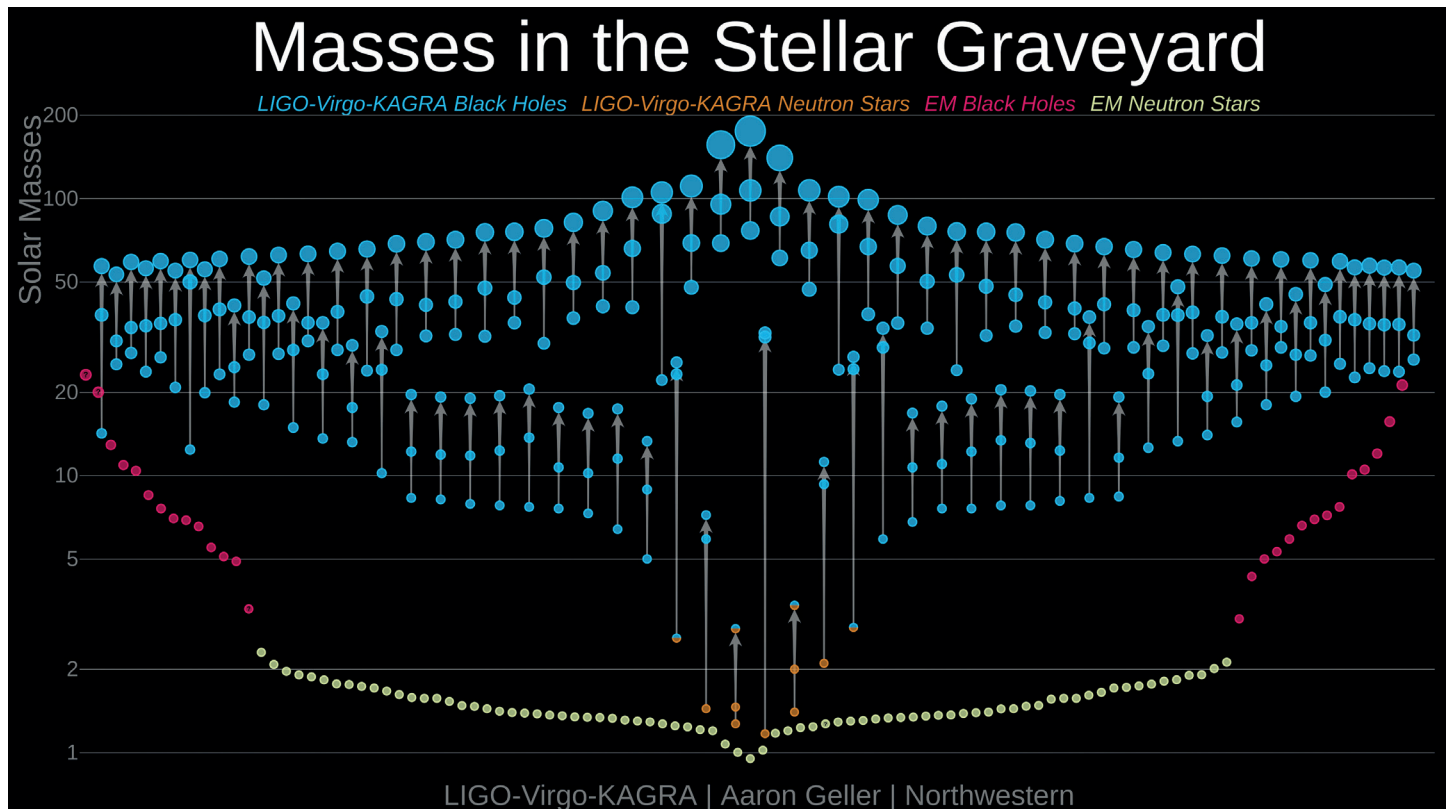


Figure 1: Masses of the BHs (blue) and NSs (orange) detected during the O1, O2 and O3 runs. Also shown the BHs that were known from electromagnetic observations of X-ray binaries (red), and the NSs observed electromagnetically (yellow); from <https://www.ligo.caltech.edu/MIT/image/ligo20211107a>, credit: LIGO-Virgo/Aaron Geller/Northwestern University.

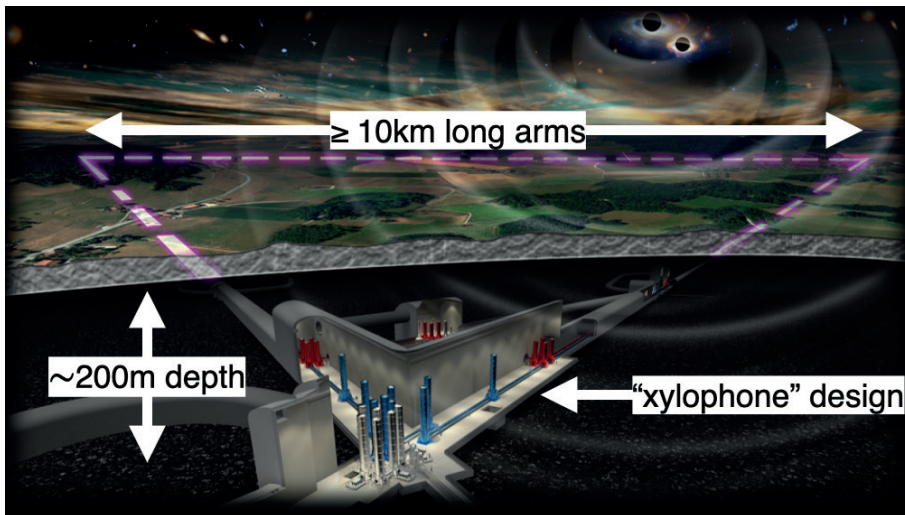


Figure 2: An artist rendering of the Einstein Telescope. Credit: ET Collaboration.

and two neutron star–black hole coalescences [6,7]. Fig. 1 shows the catalog of current observed events.

These discoveries are allowing us to observe the Universe through a new and, from many points of view, unique window, and have already started to provide important results in fundamental physics, astrophysics, and cosmology. However, second-generation (2G) GW detectors, as the current LIGO and Virgo detectors are called (to distinguish them from initial LIGO/Virgo) have intrinsic limitations, and the scientific community has long been aware of the need for a new generation of ground-based detectors. In a sense, current detectors have shown the existence of an unknown territory, and the next generation of experiments has been designed so to deeply explore it. The main projects that have emerged, for ground-based GW detectors, are Einstein Telescope (ET) [8,9] in Europe and Cosmic Explorer (CE) [10,11] in the US, and could become operative by the late 2030s. At the same time, after decades of preparation, the LISA space interferometer [12] is scheduled to launch in 2034. Third-generation (3G) ground-based detectors such as ET and CE operate in a frequency band very different from LISA; so ET/CE and LISA will be complementary, similarly to electromagnetic telescopes operating in different bands of the electromagnetic spectrum.

Fig. 2 gives an artist rendering of the Einstein Telescope.

Its design involves several innovative elements that allows it to make a jump in sensitivity, compared to current detectors. While several aspects of the design, including the detector geometry, are still under definition, the current baseline configuration involves a facility about 200 m underground; this is because one of the main source of noise that ground-based detectors must fight is seismic noise, which is significantly reduced going underground. The arm-length of the interferometers will be increased to 10 km (compared to 3 km for Virgo and 4 for LIGO). In one option for the geometry of the detector, three nested interferometer will form a triangle, in a single underground facilities, but other designs are currently under study, including the possibility of two L-shaped interferometers in two widely separated sites, still in Europe, and possibly reaching an arm-length of 15 km. Each interferometer will actually be in a so-called “xylophone” configuration made of two instruments, one optimized for GWs of high frequencies and one, working at cryogenic temperatures, optimized for low frequencies. Two official candidate sites have been proposed, one in Italy, in Sardinia and one in the Netherlands, in the Meuse-Rhine region, and are strongly supported by the respective governments. The final site(s) and geometry selection depends on many aspects, including on-going geological studies, studies of the scientific potentials of different configurations, analysis of the risks involved, as well as financial and political aspects, and will possibly finalized by 2026. The current schedule is that ET might enter into operation by the late 2030s.

The ET Collaboration now counts over 1600 members, organized in Research Units all over the world. Switzerland is significantly involved in ET, through the University of Geneva and its Research Unit, as well as its Gravitational Wave Science Centre (GWSC, <https://gwsc.unige.ch/>), that brings together research groups from the Department of Theoretical Physics, the Department of Nuclear and Particle Physics, and the Department of Astronomy of UniGe; several members of the UniGe Research Unit have significant re-

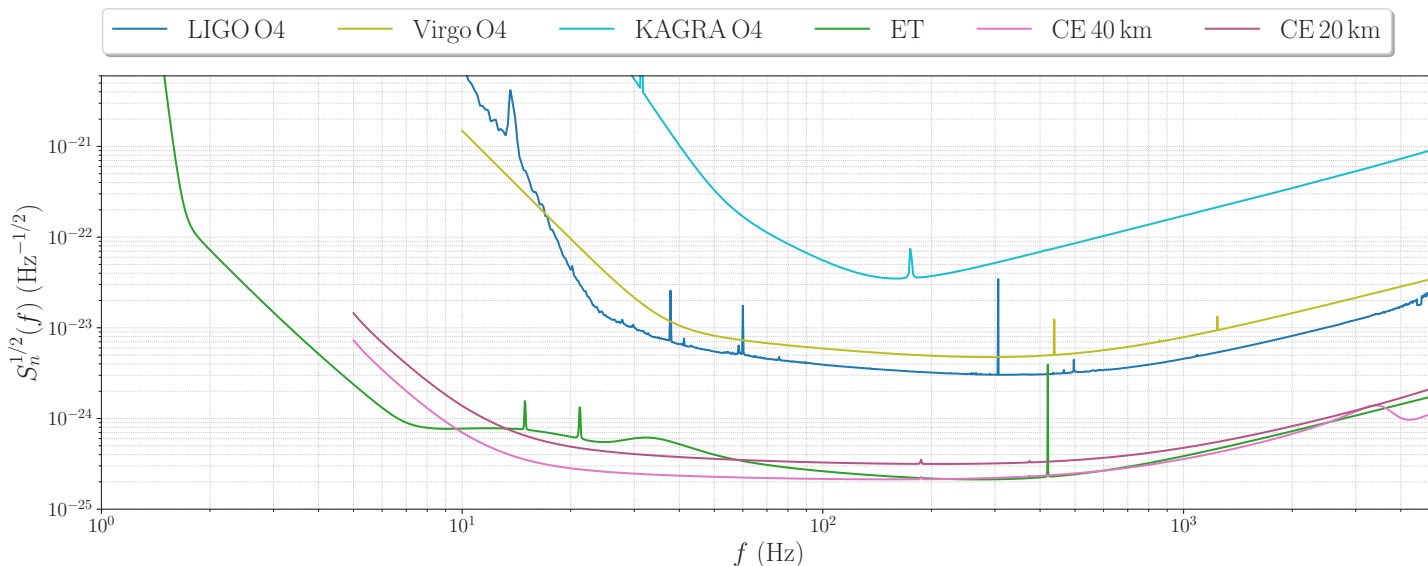


Figure 3: Sensitivities of ET, CE-40 km and CE-20 km, compared to the sensitivities expected for LIGO, Virgo, and KAGRA at the end of the O4 run. From [14].

sponsibility roles in the Collaboration, including the role of co-Chair of the Observational Science Board (<https://www.et-gw.eu/index.php/the-et-collaboration/observational-science-board>), that includes over 450 scientists, organized in 10 thematic divisions, and coordinates all the work on the Science Case for ET.

at the center of galaxies, and whose merger is one of the main target of LISA.

GWs also allow us to penetrate into regions that are opaque to electromagnetic radiation. For instance, they will give us access to the interior of neutron stars, carrying the imprint of the equation of state of nuclear matter at densities inaccessible with any other experiment, and providing us unique information on the fundamental theory of strong interaction, quantum chromodynamics, in this regime. Also, if a sufficiently strong stochastic background of GWs is produced close to the Big Bang, it will arrive to us unaltered, carrying pristine information on the first instants of the Universe (by comparison, the Cosmic Microwave Background carries a picture of the Universe about 100'000 yr after the Big Bang, since the earlier epoch is not transparent to electromagnetic radiation).

The combination of large distances explored (up to the depth of the Universe, with redshifts $z \sim 10-100$), extended range of masses (from subsolar to 10^4 solar masses), sheer number of detections (of order $10^4 - 10^5$ BNSs and BBHs, per year), detections with very high signal-to-noise ratio, and the fact that GWs can carry messages from regions inaccessible to electromagnetic radiation, will provide a wealth of high-quality data that have the potential of triggering revolutions in astrophysics, cosmology and fundamental physics.

References

- [1] LIGO Scientific, Virgo Collaboration, B. P. Abbott *et al.*, "Observation of Gravitational Waves from a Binary Black Hole Merger," *Phys. Rev. Lett.* **116** no. 6, (2016) 061102, arXiv:1602.03837 [gr-qc].
- [2] LIGO Scientific, Virgo Collaboration, B. P. Abbott *et al.*, "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral," *Phys. Rev. Lett.* **119** no. 16, (2017) 161101, arXiv:1710.05832 [gr-qc].
- [3] A. Goldstein *et al.*, "An Ordinary Short Gamma-Ray Burst with Extraordinary Implications: Fermi-GBM Detection of GRB 170817A," *Astrophys. J. Lett.* **848** no. 2, (2017) L14, arXiv:1710.05446 [astro-ph.HE].
- [4] V. Savchenko *et al.*, "INTEGRAL Detection of the First Prompt Gamma-Ray Signal Coincident with the Gravitational-wave Event GW170817," *Astrophys. J. Lett.* **848** no. 2, (2017) L15, arXiv:1710.05449 [astro-ph.HE].
- [5] B. P. Abbott *et al.*, "Multi-messenger Observations of a Binary Neutron Star Merger," *Astrophys. J. Lett.* **848** no. 2, (2017) L12, arXiv:1710.05833 [astro-ph.HE].
- [6] LIGO Scientific, Virgo Collaboration, R. Abbott *et al.*, "GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run," *Phys. Rev. X* **11** (2021) 021053, arXiv:2010.14527 [gr-qc].
- [7] LIGO Scientific, VIRGO, KAGRA Collaboration, R. Abbott *et al.*, "GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run," arXiv:2111.03606 [gr-qc].
- [8] M. Punturo *et al.*, "The Einstein Telescope: A third-generation gravitational wave observatory," *Class. Quant. Grav.* **27** (2010) 194002.
- [9] M. Maggiore *et al.*, "Science Case for the Einstein Telescope," *JCAP* **2003** (2020) 050, arXiv:1912.02622 [astro-ph.CO].
- [10] D. Reitze *et al.*, "Cosmic Explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO," *Bull. Am. Astron. Soc.* **51** no. 7, (2019) 035, arXiv:1907.04833 [astro-ph.IM].
- [11] M. Evans *et al.*, "A Horizon Study for Cosmic Explorer: Science, Observatories, and Community," arXiv:2109.09882 [astro-ph.IM].
- [12] LISA Collaboration, P. Amaro-Seoane *et al.*, "Laser Interferometer Space Antenna," arXiv:1702.00786 [astro-ph.IM].
- [13] M. Branchesi, M. Maggiore, *et al.*, "Science with the Einstein Telescope: a comparison of different designs," *JCAP* **07** (2023) 068, arXiv:2303.15923 [gr-qc].
- [14] F. Iacovelli, M. Mancarella, S. Foffa, and M. Maggiore, "Forecasting the detection capabilities of third-generation gravitational-wave detectors using GWFAST," *Astrophys. J.* **941** no. 2, (2022) 208, arXiv:2207.02771 [gr-qc].

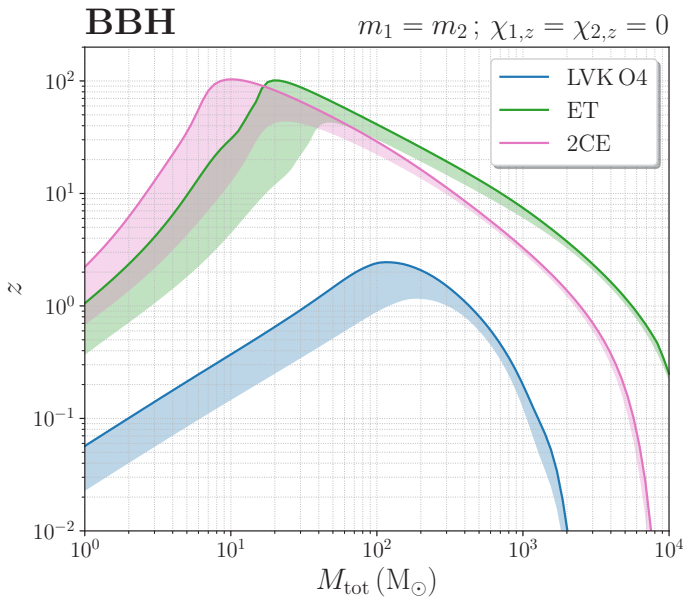


Figure 4: Detection horizons for the LVK detector network during O4, for ET, and for a network of two CE detectors (with 20 and 40 km arms). The shaded bands represent the maximum z out to which 50 % of the population with given masses and spins could be detected. From [14].

The Science Case of ET is very rich and covers many areas of fundamental physics, astrophysics, and cosmology (see [9, 13] for detailed discussion). To have a first glimpse of the scientific potential of 3G detectors, we show in Fig. 3 the detector sensitivities and in Fig. 4 the corresponding detection horizons (i.e., the maximum redshift to which a source with a given total mass can be detected) for ET and CE, and compare it with the result expected for the 2G detector by the end of the O4 observing run, which is currently ongoing. We see from Fig. 4 that, for optimal values of the masses and source orientation, ET and CE can reach redshifts higher than 10, and in fact in some cases up to 100, thereby exploring all the observable Universe up to the so-called dark ages, before star formation begun. Current models of stellar evolution, together with the LIGO-Virgo observations at low redshift, predict about 10^5 BBH coalescences/yr and $10^4 - 10^5$ BNS/yr, and ET and CE will then detect basically them all. This means that these detectors will detect a compact-binary merger every about 5 minutes! Some of these events will have a very large signal-to-noise ratio (SNR): we forecast that there will be more than 10^3 events/yr with SNR larger than 100, and in fact many of them with SNR up to several hundreds; their waveform will then be reconstructed with great accuracy, allowing us to perform accurate test of General Relativity, fundamental physics, and cosmology. ET will also significantly extend the range of masses for which black hole binaries are detectable, from sub-solar masses (a smoking-gun signature of primordial black holes, produced in the early Universe by the collapse of primordial density fluctuations) up to masses of $(10^3 - 10^4)$ solar masses, that would be the bridge to the supermassive BHs known to exist