In 1916 Einstein first predicted gravitational waves (GWs)[1], and extended the theory in 1918[2]. Their physical reality remained controversial[3] until Felix Pirani showed in 1957[4] that a passing wave would produce measurable changes in the separation of freely falling test masses, establishing the operating principle of all modern GW detectors[5]. Joseph Weber proposed the first practical detector in 1955[6], while Rainer Weiss showed in 1972 that laser interferometry offered the required sensitivity[7]. The first direct detection followed in 2015 with Advanced LIGO[8], recognised by the 2017 Nobel Prize[9]. Working with Virgo and KAGRA[10], the global network has reported 671 GW events by July 2026[11].

In 2008, before any direct detection of a GW and while Advanced LIGO and Advanced Virgo were still under construction, the Einstein Telescope (ET) was proposed as a third-generation GW observatory[12]. Together with the proposed Cosmic Explorer (CE)[13], ET aims to increase strain sensitivity by roughly an order of magnitude across much of the observing band while extending the low-frequency limit from about 10 Hz to approximately 2–3 Hz. The

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1 https://articles.adsabs.harvard.edu/pdf/1916SPAW.......688E

2 Über Gravitationswellen, https://adsabs.harvard.edu/pdf/1918SPAW.......154E

3 https://arxiv.org/abs/1602.04040

4 Albert Einstein, who predicted GWs, was nevertheless skeptical of their existence and detectability.

5 https://www.nature.com/articles/s41586-019-1129-z

6 https://www.aps.org/apsnews/2020/02/joseph-weber-first-gravitational-wave

7 https://link.springer.com/article/10.1007/s10714-022-03021-3

8 https://arxiv.org/pdf/1610.08803

9 https://www.ligo.caltech.edu/page/press-release-2017-nobel-prize

10 The uncertainty region (or localisation region) is the area of the celestial sphere within which the true position of the GW source is expected to lie with a specified statistical confidence, typically 90%. It is determined from the relative arrival times, amplitudes and phases of the signal measured at each detector. Additional detectors improve triangulation, substantially reducing this region and enabling rapid follow-up observations by optical, radio, X-ray and gamma-ray telescopes.

11 https://gwosc.org/eventapi/

12 The first-generation interferometers were primarily proof-of-principle instruments. They were followed by a second generation designed to detect GWs routinely.

13 Cosmic Explorer (CE), as an above-ground extension of LIGO, is funded for the major design work, site evaluation, and conceptual engineering, but construction has not yet been approved.

complementary Laser Interferometer Space Antenna (LISA)[14] will observe GWs in the 0.1 mHz–1 Hz frequency range, inaccessible to terrestrial detectors because of seismic and gravity-gradient noise[15].

The objective of ET is not simply to increase the rate of GW detections, but to establish GW astronomy as a precision observational science. Its scientific goals include observing binary black-hole (BBH)[16] and binary neutron-star (BNS) coalescences throughout much of cosmic history, detecting continuous GW emission from rapidly rotating neutron stars, measuring stochastic GW backgrounds, and potentially detecting relic GWs originating in the very early Universe[17].

Although ET depends critically on quantum-limited measurement techniques, quantum mechanics itself is not one of its principal scientific objectives. Instead, quantum fluctuations of the optical field[18] define several of the fundamental limits to the detector's achievable strain sensitivity[19]. Achieving the required sensitivity therefore requires advances in both classical precision engineering and quantum-optical measurement techniques.

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[14] Laser Interferometer Space Antenna (LISA) is an approved ESA-led mission currently in the implementation and construction phase, with launch planned for 2035.

[15] Gravity-gradient noise arises from tiny changes in the Earth's local gravitational field caused by moving masses, including seismic waves, atmospheric density fluctuations and groundwater motion. These changing gravitational forces act directly on the interferometer's test masses and therefore cannot be isolated by mechanical suspension systems.

[16] Binary Black Hole coalescences is when two black holes orbiting each other, lose orbital energy by emitting Gas, spiral inward (inspiral), merge into a single black hole, and the newly formed black hole settles into its final stable state (ringdown).

[17] The case for ET is much stronger because those scientific goals are now grounded in observational results rather than predictions. GWs will change astronomy because the Universe is essentially transparent to them. Intervening matter and gravitational fields do not absorb or deflect GWs to any significant degree. GWs will help answer some of the great questions in physics: Does general relativity correctly describe gravity and GWs? How do black holes form? How does matter behave under extreme temperature and pressure in neutron stars, during supernovae, and in the Big Bang?

[18] The electromagnetic field associated with the laser light circulating in the interferometer. In quantum optics, the optical field is treated as a quantised field whose quantum fluctuations give rise to photon shot noise, radiation-pressure noise and the effects exploited by squeezed-vacuum states.

[19] However, ET could also potentially discover different types of exotic compact objects or “blackhole mimickers", such as boson stars, gravastars, and stars composed of dark matter particles, etc. It's even been suggested that ET might see quantum gravity effects.

Classical precision engineering (to suppress non-quantum noise)

- Ultra-low-loss dielectric mirror coatings with optical absorption and scattering reduced beyond current capabilities while maintaining reflectivities exceeding 99.999%.
- Large monocrystalline silicon test masses operating near 10 K with exceptionally low optical absorption and mechanical dissipation for the low-frequency interferometers.
- Ultra-stable single-frequency lasers delivering several hundred watts of optical power with exceptionally low frequency, amplitude and pointing noise[20].

Quantum-optical techniques (to reduce quantum measurement limits)

- Frequency-dependent squeezed-vacuum[21] injection providing approximately 10 dB broadband reduction of quantum noise using ultra-low-loss filter cavities.
- Optimisation of laser power, mirror mass and quantum-optical readout to balance photon shot noise[22] against quantum radiation-pressure (back-action) noise[23].

The Annex describes the overall design of the Einstein Telescope. However, among all its advanced technologies, the macroscopic test masses are arguably the most conceptually interesting, because they are engineered so that quantum fluctuations in the

[20] Unwanted fluctuations in the direction or position of the laser beam. Even extremely small beam motions can couple into the interferometer through mirror imperfections or misalignments, producing false length signals that reduce strain sensitivity.

[21] A squeezed vacuum is a non-classical quantum state of the electromagnetic field in which Heisenberg uncertainty is redistributed between the amplitude and phase quadratures of the light. A filter cavity rotates the squeezed state with frequency, reducing shot noise at high frequencies and radiation-pressure noise at low frequencies.

[22] Random fluctuations in the number of photons arriving at the photodetector due to the discrete, particle-like nature of light. It limits the precision with which changes in the interferometer arm lengths can be measured and becomes the dominant noise source at high frequencies.

[23] A quantum noise arising because each reflected photon transfers momentum to a mirror. Random fluctuations in photon number produce fluctuating forces on the mirrors, so that the act of measuring their position also perturbs their motion.

optical field measurably influence the motion of mirrors weighing hundreds of kilograms.

Overcoming Quantum Limits

In 1957, Felix Pirani showed that a passing GW would produce a changing separation between freely falling test masses[24]. His proposal transformed Einstein's mathematical prediction into a measurable physical effect. For the next seventy years, the development of GW detectors focused on reducing every identifiable source of classical noise[25].

The strongest GWs expected to reach the Earth produce strains of only about 10^{-21}. For an interferometer with 10 km arms, this corresponds to a differential change in length of approximately 10^{-17} m, or around one hundredth of the diameter of a proton[26]. However, ET is designed to measure strain amplitudes approaching 10^{-23} over much of its observing band, equivalent to differential arm-length changes of approximately 10^{-19} m.

The measurement is performed using laser interferometry. A highly stabilised laser[27] located at the central station is divided by a beam splitter into two separate beams, each travelling through its own evacuated 10 km vacuum tube approximately 1 m in diameter. The beams are reflected many hundreds of times between mirrors forming Fabry–Pérot cavities before returning to the beam splitter, where they recombine at the photodetector. A passing gravitational wave changes the relative optical path lengths of the two arms,

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[24] The test masses are the interferometer mirrors. Each is suspended as the final stage of a multi-stage pendulum isolation system that provides mechanical support while attenuating seismic motion by many orders of magnitude. Above the pendulum resonance frequencies, the mirrors behave to an excellent approximation as freely falling inertial test masses along the interferometer arms, allowing them to respond to gravitational waves rather than to ground vibrations.

[25] Seismic vibrations, thermal motion, residual gas, optical imperfections and electronic noise were progressively suppressed until the detector approached the point where the remaining uncertainty no longer originated in its mechanical or electrical components.

[26] Equivalent to measuring the Earth-Sun distance to within about the diameter of an atom.

[27] ET consists of two complementary interferometers. The high-frequency interferometer uses room-temperature fused-silica mirrors and a 1064 nm Nd:YAG laser. The low-frequency interferometer uses monocrystalline silicon mirrors operated at approximately 10 K and therefore requires a 1550 nm laser, since silicon strongly absorbs 1064 nm light but is highly transparent at 1550 nm. The circulating optical power is approximately 3 MW in the high-frequency interferometer and 18 kW in the low-frequency interferometer, reflecting the different quantum-noise limits in the two frequency bands.

producing an interference signal from which the strain is determined. The vacuum system extends for approximately 130 km and is maintained at a pressure of about 10^{-10} millibar[28] to minimise scattering and refractive-index fluctuations caused by residual gas molecules.

Each arm cavity terminates in mirrors with proposed masses of approximately 200 kg[29]. The low-frequency interferometer uses monocrystalline silicon mirrors operating at about 10 K, while the high-frequency interferometer uses fused-silica mirrors at room temperature. The mirrors are suspended as the final stage of multi-stage pendulum isolation systems and polished to nanometre accuracy. After the classical sources of disturbance have been reduced, the measurement uncertainty is dominated by the quantum properties of the light itself.

Laser light is composed of individual photons. Their random arrival at the photodetector produces photon shot noise, while every reflected photon transfers momentum to a mirror, producing radiation-pressure noise. Increasing the laser power reduces shot noise but simultaneously increases the random forces acting on the mirrors. The measurement precision is therefore determined by two competing quantum processes whose relative importance depends upon both the circulating optical power and the observation frequency.

There is another contribution. Quantum field theory predicts that the electromagnetic vacuum is not completely empty. Vacuum fluctuations enter the interferometer through its unused output port and contribute directly to both photon shot noise and radiation-pressure noise. Above approximately 100 Hz, shot noise becomes the dominant limitation to sensitivity, while at lower frequencies radiation-pressure noise becomes increasingly important.

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[28] About 10 trillion times lower than atmospheric pressure, and comparable to the vacuum inside the beam pipes of CERN's Large Hadron Collider, although still several orders of magnitude denser than interplanetary or interstellar space.

[29] Based upon the 2026 prototype, each arm will terminate in a silicon mirror approximately 45–50 cm in diameter, up to 60 cm thick and weighing about 200 kg. The mirrors are polished to within ±2 nm of their ideal optical figure, have a surface roughness below 0.1 nm RMS, and are cooled to around 10 K in the low-frequency interferometer. They will be housed in vacuum towers up to 20 m high and suspended as the final stage of multi-stage pendulum systems.

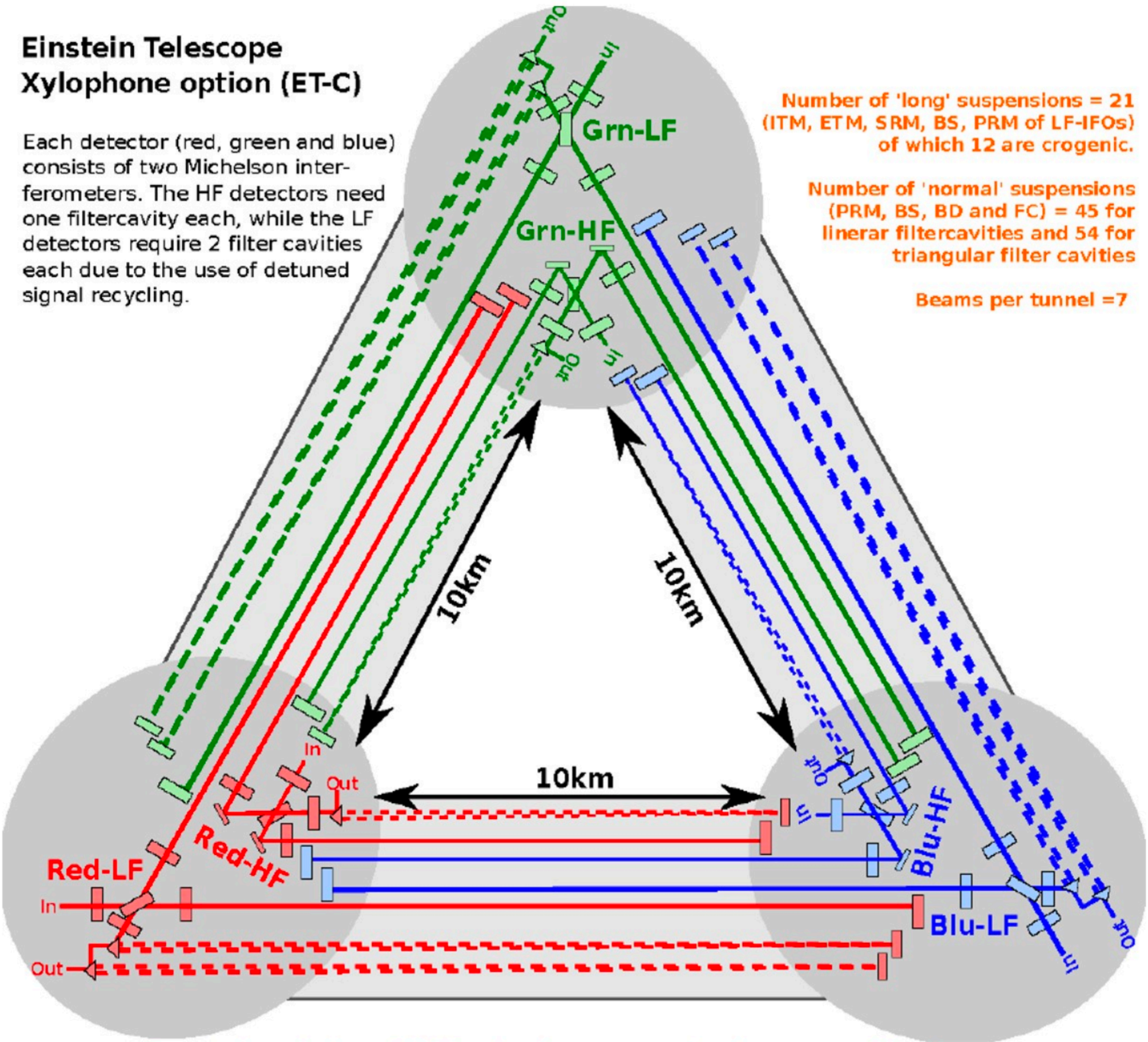
Rather than accepting these fluctuations as unavoidable, ET modifies them before they enter the interferometer. A squeezed-vacuum source, together with a filter cavity approximately 300 m long, prepares a frequency-dependent quantum state that reduces radiation-pressure noise at low frequencies and shot noise at high frequencies. The mirrors, suspensions, lasers and vacuum system are all engineered components of the observatory. So too is the prepared quantum state entering the interferometer.

These technologies are not scientific objectives in themselves. Their purpose is to reduce the measurement uncertainty sufficiently for ET to observe GW sources that are either too distant or too weak to be detected by existing observatories, thereby extending gravitational-wave astronomy across much more of the observable Universe.

Annex — Technical Description of the Einstein Telescope

Observatory architecture

The Einstein Telescope (ET) is a proposed third-generation underground gravitational-wave (GW) observatory designed to improve strain sensitivity[30] by approximately one order of magnitude over current detectors while extending the observable frequency



[30] Gravitational-wave strain (h) is the dimensionless fractional change in the proper distance between two freely falling test masses caused by the passage of a gravitational wave. It is defined as $h=\Delta L/L$, where L is the original separation and ΔL is the change in that separation. Because strain is the ratio of two lengths it has no units. Unlike the measured displacement ΔL, which depends on the length of the detector arms, the strain h is an intrinsic property of the gravitational wave itself.

range from the present lower limit of about 10 Hz down to 2–3 Hz[31]. The baseline design consists of three 10 km long V-shaped interferometers arranged as an equilateral triangle with 60° opening angles.

Each V contains two independent Michelson interferometers sharing the same underground infrastructure, namely a low-frequency (LF) interferometer operating at cryogenic temperature and a high-frequency (HF) interferometer operating at room temperature. The complete observatory therefore comprises six interferometers in the so-called *xylophone* configuration[32], allowing the conflicting requirements of low- and high-frequency operation to be optimised independently.

Xylophone configuration

A conventional gravitational-wave observatory uses a single broadband interferometer that attempts to achieve the highest possible sensitivity across the entire observing band. However, ET is designed to operate from approximately 2 Hz to 5 kHz, a frequency range over which the dominant sources of detector noise change dramatically. The engineering requirements needed to minimise these different noise sources are fundamentally incompatible, making it impossible for a single interferometer to achieve optimum performance over the full observing band.

At frequencies above approximately 30 Hz, detector sensitivity is limited primarily by quantum photon shot noise[33]. This noise is reduced by increasing the circulating laser power, thereby

[31] Current detectors (Advanced LIGO and Advanced Virgo) become effectively blind below about 10 Hz because of seismic noise, gravity-gradient (Newtonian) noise, suspension noise and radiation-pressure noise. Below this frequency, the detector noise rises so rapidly that gravitational-wave signals disappear into it. Inspiralling binaries emit gravitational waves whose frequency increases as they spiral together. Lowering the limit from 10 Hz to 2–3 Hz means increasing a binary neutron-star system's visibility from about 15–20 minutes to several hours before the merger. Similarly, stellar-mass binary black holes remain observable for much longer. In simple terms, the detector should records many more wave cycles per event.

[32] The name "xylophone" is informal, and plays on a xylophone's wooden bars, each tuned to produce a different range of frequencies, the same as the two differently "tuned" interferometers.

[33] Quantum photon shot noise is the fundamental uncertainty in an optical measurement arising from the Poissonian fluctuations in the number of photons detected from a coherent laser beam. Because the interferometer determines the gravitational-wave signal by measuring extremely small changes in the optical phase, these unavoidable quantum fluctuations limit the precision with which mirror displacements can be measured.

increasing the number of photons available to measure the mirror positions. However, the resulting optical absorption heats the mirrors and their reflective coatings, increasing thermal noise[34]. At lower frequencies, sensitivity is instead limited principally by thermal noise, seismic noise, gravity-gradient (Newtonian) noise and quantum radiation-pressure noise. Suppressing these sources requires cryogenic operation, lower optical power, and suspension systems optimised for very low-frequency isolation. These requirements conflict directly with those needed for optimum high-frequency performance.

Rather than accepting this unavoidable engineering compromise, ET adopts a *xylophone* configuration, in which each of the three 60° V-shaped detectors contains two independent Michelson interferometers, giving a total of six interferometers. Each interferometer is designed to operate over a different part of the GW spectrum[35].

The low-frequency interferometer (LF) is optimised for frequencies between approximately 2 and 30 Hz. It uses monocrystalline silicon test masses cooled to approximately 10 K, 1550 nm laser light, and optical parameters chosen to minimise thermal and radiation-pressure noise[36]. The high-frequency interferometer (HF) is optimised for frequencies above approximately 30 Hz. It operates at room temperature using fused-silica mirrors[37], 1064 nm laser light, and very high circulating optical power to reduce photon shot noise.

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[34] Thermal noise is the random vibration of atoms in the mirrors, coatings and suspensions caused by their finite temperature. These microscopic motions produce position fluctuations that limit the detector's sensitivity.

[35] The gravitational-wave (GW) spectrum is the range of gravitational-wave frequencies that a detector can observe. Different astrophysical sources emit gravitational waves over different frequency ranges, and detector sensitivity varies across this spectrum.

[36] Unlike photon shot noise, which produces uncertainty in the optical measurement, radiation-pressure noise is caused by random fluctuations in the force exerted by laser photons on the mirrors. These quantum fluctuations in photon momentum produce tiny mirror displacements that become the dominant quantum noise at low frequencies.

[37] Fused silica is an ultra-pure, amorphous (non-crystalline) form of silicon dioxide (SiO_2) used for the mirrors in Advanced LIGO and Advanced Virgo because of its exceptionally low optical absorption and mechanical stability at room temperature. However, its mechanical dissipation increases at cryogenic temperatures, making it unsuitable for the ET's low-frequency interferometers. Monocrystalline silicon has much lower mechanical loss and much higher thermal conductivity at approximately 10 K, greatly reducing thermal noise. Consequently, ET uses cryogenic silicon mirrors for its low-frequency interferometers and room-temperature fused-silica mirrors for its high-frequency interferometers, where higher laser power and shorter laser wavelength (1064 nm) remain advantageous.

The outputs from the low- and high-frequency interferometers are combined during data analysis to produce a single broadband detector response. This approach eliminates the need for a single interferometer and a compromise between conflicting design requirements. This is one of the principal reasons why ET is expected to achieve approximately an order-of-magnitude improvement in strain sensitivity while extending its observable frequency range down to about 2–3 Hz.

The observatory also requires major advances in classical precision engineering. These include the construction of a deep underground facility to minimise seismic and gravity-gradient disturbances, 10 km ultra-high-vacuum beam tubes, multi-stage seismic isolation and suspension systems, cryogenic infrastructure for the low-frequency interferometers, ultra-stable laser systems and large-scale precision optics. These technologies suppress environmental and thermal disturbances sufficiently for the instrument to approach its fundamental quantum limits[38].

Progress Towards Full-Scale Monocrystalline Silicon Test Masses

One of the most significant recent milestones in the development of ET occurred on 17 June 2026, when researchers announced the successful manufacture of the largest monocrystalline silicon mirror ever produced. Measuring 45 cm in diameter, weighing approximately 80 kg, and polished to a residual surface roughness of about one nanometre, the mirror represents the present state of the art in large cryogenic optical components for gravitational-wave detectors. Although it does not yet satisfy all the specifications required for the ET, it demonstrates that many of the critical manufacturing technologies have now reached an unprecedented level of maturity.

The project originated more than five years earlier as part of the ERC SILENT (Silicon Mirrors for the Einstein Telescope) project[39]

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[38] Description based upon a 2011 design study https://zenodo.org/records/3911261, the 2020 Design Report Update https://www.einsteintelescope-emr.eu/wp-content/uploads/2024/05/ET-0007B-20_ETDesignReportUpdate2020.pdf, and a 2022 Prototype Design Report https://arxiv.org/abs/2212.10083.

[39] https://www.einsteintelescope-emr.eu/en/2026/06/17/worlds-largest-mono-crystalline-silicon-mirror-produced-for-the-einstein-telescope/

led by Professor Christophe Collette, Director of the Precision Mechatronics Laboratory at the University of Liège. The objective was to determine whether optical components approaching the dimensions required for ET could be manufactured while preserving the exceptional crystal quality and optical finish needed for quantum-limited interferometry.

The manufacturing process itself required expertise from several organisations. The raw material began as an exceptionally large monocrystalline silicon ingot, grown by a specialist American manufacturer using crystal-growth technology capable of producing a single crystal almost half a metre in diameter. Producing a crystal of this size without dislocations, grain boundaries or internal defects lies at the practical limit of present-day crystal-growth techniques, and only a very small number of companies worldwide currently possess this capability. After growth, the ingot was transported to Belgium, where the precision optics company AMOS, a spin-off from the University of Liège, undertook the machining and polishing.

Transforming the raw silicon ingot into a precision optical mirror required approximately six months of manufacturing. Because silicon is simultaneously extremely hard and extremely brittle, conventional machining techniques cannot be used. Diamond cutting tools first produced the basic geometry, followed by successive stages of grinding, lapping and polishing. After every polishing cycle the surface was measured using high-precision optical metrology, progressively removing microscopic subsurface damage until a residual surface roughness of approximately 1 nm was achieved. At this level the remaining surface irregularities are approximately one million times smaller than a millimetre.

The completed mirror will become the principal optical component of the ET-CRISTAL (CRyogenic and Inertial STAbility Laboratory) at the Centre Spatial de Liège, where it will be installed within the E-TEST prototype interferometer[40]. Rather than serving as a detector itself, the mirror provides an experimental platform for validating the technologies required for ET, including cryogenic operation, ultra-

[40] https://www.einsteintelescope-emr.eu/wp-content/uploads/2024/05/E-TEST_Conceptual-Design-Report_June_2022-reduced_size.pdf

low-noise suspensions, vibration isolation, optical coatings and quantum-limited interferometry.

Despite this achievement, significant engineering challenges remain before full ET mirrors can be produced. The current prototype mirror weighs approximately 80 kg, whereas the planned low-frequency ET interferometers are expected to employ silicon test masses of approximately 200 kg, together with even more demanding requirements on optical figure[41], coating performance, cryogenic operation and suspension. Nevertheless, the successful manufacture of the 45 cm monocrystalline silicon mirror demonstrates that the most difficult aspect of the problem, i.e. producing and finishing an exceptionally large, defect-free single crystal with nanometre-scale optical quality, is now technically feasible. It therefore represents one of the most important technology milestones yet achieved in preparation for the construction of the ET.

Optical configuration

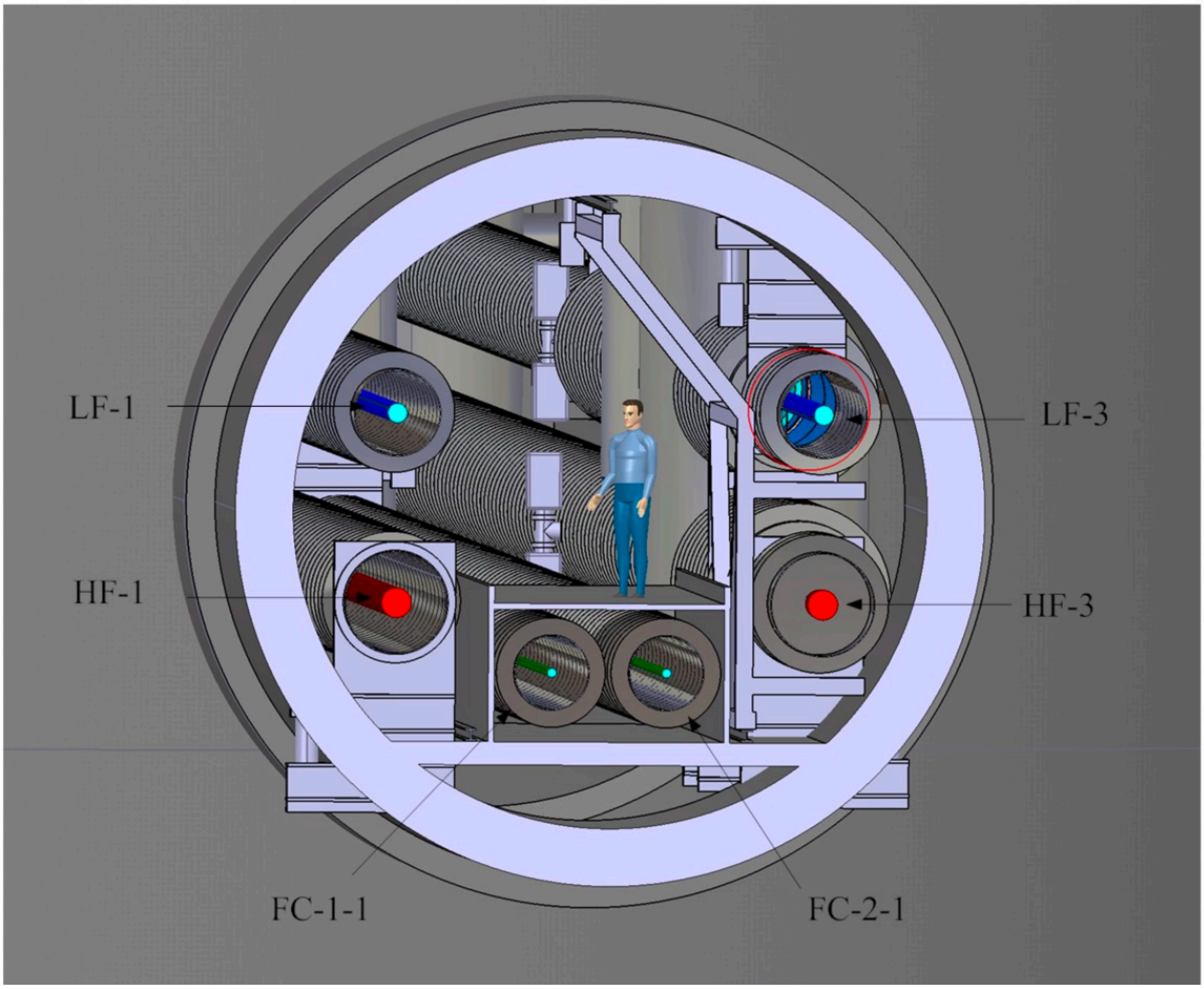
Each Michelson interferometer employs a highly stable, single-frequency laser whose output is spatially and temporally filtered before entering the interferometer. A beam splitter divides the optical field into two beams that propagate along perpendicular 10 km arms. Each arm contains a Fabry-Pérot resonant cavity[42] formed by an input test mass and an end test mass with extremely high reflectivity. The resonant cavities store the light for many hundreds of round trips, increasing the effective optical path length and amplifying the phase shift produced by a passing gravitational wave.

Additional power-recycling and signal-recycling optics increase the circulating optical power and optimise the detector response across the required frequency band. The complete optical system therefore

[41] Optical figure is the accuracy with which the polished mirror surface conforms to its intended shape. For the Einstein Telescope, deviations from the ideal surface must be no more than a few nanometres across the entire mirror, ensuring that the laser beam remains precisely focused and that optical losses are minimised.

[42] A Fabry–Pérot resonant cavity is the optical cavity that forms each 10 km arm of the Einstein Telescope. It consists of two highly reflective test-mass mirrors facing one another, between which the laser beam reflects hundreds of times. These multiple reflections greatly increase the effective optical path length, enabling the detector to measure the extremely small mirror displacements produced by passing gravitational waves.

converts an extremely small differential change in arm length into a measurable change in the optical phase at the interferometer output.



Schematic outline of the tunnel. The tunnel is occupied by the vacuum vessels that hold the low frequency (LF-1 and LF-2) and high frequency (HF-1 and HF-2) arms of two interferometers. In addition, the vacuum vessels for both filter (FC-1-1 and FC-2-1) cavities are housed. The inner diameter is 5.5 m and the tunnel wall has a thickness of 50 cm.

The Einstein Telescope employs two different laser systems because the observatory consists of two complementary interferometers optimised for different frequency ranges. The high-frequency interferometer (ET-HF) uses a continuous-wave, single-frequency Nd:YAG laser operating at a wavelength of 1064 nm, injecting approximately 500 W of optical power into the interferometer. Resonant Fabry–Pérot arm cavities increase the circulating optical power to approximately 3 MW, reducing photon shot noise and improving sensitivity above about 100 Hz. The mirrors are made from room-temperature fused silica, a material that is highly transparent and exhibits extremely low optical absorption at 1064 nm.

The low-frequency interferometer (ET-LF) uses a continuous-wave laser operating at 1550 nm, injecting approximately 3 W of optical power and producing a circulating arm-cavity power of about 18 kW. The much lower optical power reduces radiation-pressure fluctuations acting on the cryogenic mirrors, improving sensitivity below a few tens of hertz. At these frequencies thermal noise is reduced by cooling the mirrors to approximately 10–20 K.

The choice of laser wavelength is determined primarily by the mirror material rather than by the optical design. Silicon, selected for the cryogenic mirrors because of its exceptionally low mechanical loss and high thermal conductivity at low temperatures, strongly absorbs light at 1064 nm, which would produce unacceptable heating. At 1550 nm, however, silicon is highly transparent and optical absorption is reduced by several orders of magnitude, allowing the mirrors to operate at cryogenic temperatures. The room-temperature fused-silica mirrors of the high-frequency interferometer continue to use the mature and well-established 1064 nm laser technology developed for Advanced LIGO and Advanced Virgo. The two interferometers therefore employ different laser wavelengths, optical powers and mirror materials, each optimised for a different part of the gravitational-wave frequency spectrum.

Measurement principle

The observable measured by ET is the gravitational-wave strain,

$$h = \Delta L/L$$

where L is the interferometer arm length and ΔL is the differential change in length produced by the passing gravitational wave.

A gravitational wave passing through ET changes the lengths of its interferometer arms in opposite directions. As one arm becomes longer, the other becomes shorter, producing a differential change in the optical path lengths that is measured by the interferometer. The two laser beams therefore accumulate slightly different optical phases during their propagation through the Fabry-Pérot cavities. When the beams recombine at the beam splitter, this phase difference produces constructive or destructive interference at the output port. A high-speed photodetector continuously measures the resulting variations in optical power, from which the gravitational-wave strain is reconstructed.

The displacement to be measured is extraordinarily small. A strain of approximately 10^{-23} corresponds to a differential arm-length change of about 10^{-19} m over a 10 km baseline. Achieving this sensitivity requires every other source of optical, mechanical and environmental noise to be reduced below the expected gravitational-wave signal.

Classical noise suppression

The overall sensitivity of an interferometric gravitational-wave detector is determined by the combined contributions of numerous independent noise sources. At low frequencies the dominant disturbances arise from seismic motion, gravity-gradient (Newtonian) noise and suspension motion. At intermediate frequencies thermal noise within the mirror substrates, optical coatings and suspension fibres becomes important. At high frequencies the dominant limitation is the quantum nature of the optical measurement.

The underground location substantially reduces seismic and anthropogenic disturbances. Multi-stage seismic isolation systems and multi-stage pendulum suspensions minimise the transmission of ground motion to the test masses. Ultra-high-vacuum beam tubes eliminate fluctuations arising from the refractive index of air. Cryogenic operation of the low-frequency interferometers reduces thermal noise within the mirrors, coatings and suspensions. Collectively these engineering systems suppress classical noise sufficiently for quantum noise to become the principal limitation over much of the observing band.

Quantum-limited measurement

Once classical noise sources have been sufficiently reduced, the measurement precision is determined by quantum fluctuations of the optical field[43].

[43] The optical field is the laser light circulating within the interferometer, treated as an electromagnetic field. Quantum fluctuations of this field give rise to photon shot noise and radiation-pressure noise, which limit the precision of the interferometric measurement.

At high frequencies the dominant limitation is photon shot noise. The laser beam is a coherent quantum state consisting of discrete photons whose arrival at the photodetector follows Poisson statistics. These statistical fluctuations produce uncertainty in the measured optical phase and therefore limit the precision with which gravitational-wave strain can be determined. Increasing the circulating laser power increases the number of detected photons and reduces shot noise.

However, photons also carry momentum. Every reflection transfers momentum to the suspended test masses. Because the arrival of photons fluctuates statistically, the momentum transferred to the mirrors also fluctuates, producing random force fluctuations known as quantum radiation-pressure noise. Radiation-pressure noise increases with optical power and dominates the quantum noise budget at low frequencies.

Increasing laser power therefore produces two opposing effects, it reduces shot noise while simultaneously increasing radiation-pressure noise. The optimum sensitivity is obtained by balancing these two quantum noise mechanisms through the choice of laser power, mirror mass, optical configuration and quantum-optical readout. This trade-off defines the Standard Quantum Limit for interferometric position measurement.

Quantum engineering

Vacuum fluctuations[44] entering the normally dark output port[45] introduce additional quantum uncertainty into the interferometer.

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[44] Vacuum fluctuations and the unavoidable quantum fluctuations of the electromagnetic field that exist even in empty space. When vacuum fluctuations enter the interferometer through the dark output port, they contribute to photon shot noise and radiation-pressure noise, ultimately limiting measurement sensitivity.

[45] The dark output port is the interferometer output at which the laser beams returning from the two arms interfere destructively, so that, in the absence of a gravitational wave, almost no laser light reaches the photodetector. A passing gravitational wave disturbs this cancellation, allowing a small amount of light to emerge that carries the gravitational-wave signal.

The ET suppresses this uncertainty by injecting squeezed-vacuum states[46] into the output port.

Present-generation detectors, including Advanced LIGO and Advanced Virgo, already employ frequency-independent squeezing[47], providing routine sensitivity improvements of approximately 2–3 dB. The Einstein Telescope requires frequency-dependent squeezing approaching 10 dB across much of the observing band. This is achieved using ultra-low-loss optical filter cavities that rotate the squeezing angle as a function of frequency, reducing shot noise at high frequencies while simultaneously limiting radiation-pressure noise at low frequencies.

Together with high circulating optical power and optimised readout optics, frequency-dependent squeezing constitutes one of the principal quantum technologies enabling the target sensitivity of the Einstein Telescope.

Cryogenic interferometers

The low-frequency interferometers employ large monocrystalline silicon test masses operating at approximately 10 K. Silicon is selected because of its low optical absorption at the operating wavelength, low mechanical dissipation and favourable cryogenic properties. The mirrors are suspended using low-loss crystalline suspension elements and coated with ultra-low-loss dielectric multilayer coatings.

Cryogenic operation substantially reduces thermal noise within the mirror substrates, optical coatings and suspension system, allowing

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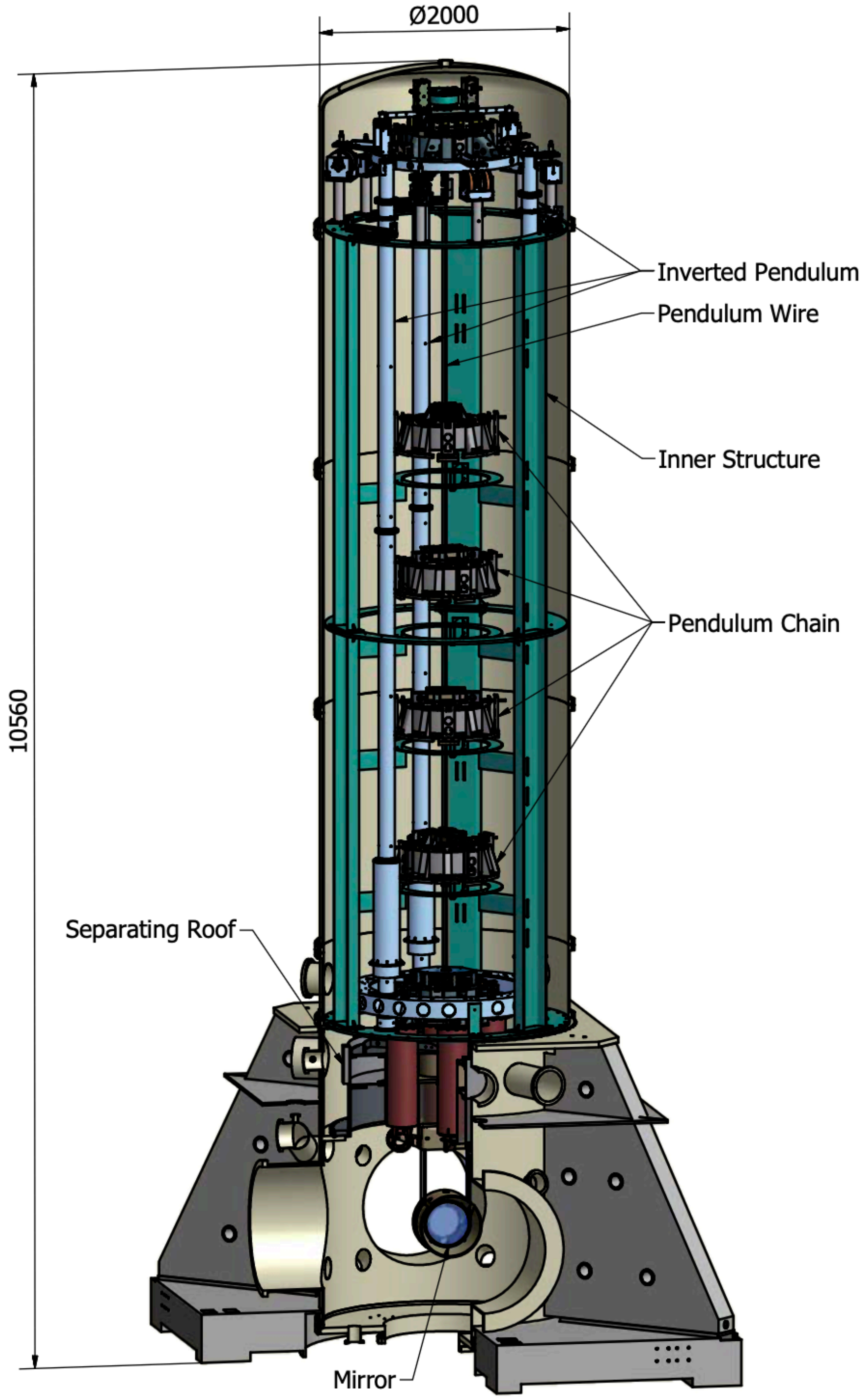
[46] A squeezed vacuum state is a specially prepared quantum state of the electromagnetic field in which the unavoidable quantum fluctuations are redistributed between two complementary quadratures of the laser light, namely between the amplitude quadrature and the phase quadrature. Reducing fluctuations in the phase quadrature decreases photon shot noise, whereas reducing fluctuations in the amplitude quadrature reduces radiation-pressure noise. Because the Heisenberg uncertainty principle requires the total uncertainty to remain constant, reducing one quadrature necessarily increases the other. The Einstein Telescope employs frequency-dependent squeezing, in which the squeezed quadrature is rotated as a function of frequency, so that the amplitude quadrature is squeezed at low frequencies and the phase quadrature at high frequencies, thereby reducing both forms of quantum noise across the observing band.

[47] Frequency-independent squeezing applies the same squeezed quadrature across the detector's entire observing frequency range. It can reduce either photon shot noise or radiation-pressure noise, but not both simultaneously. Frequency-dependent squeezing uses a filter cavity to rotate the squeezed quadrature as a function of frequency, reducing radiation-pressure noise at low frequencies and photon shot noise at high frequencies. This provides significantly better broadband sensitivity and is therefore the approach adopted for the Einstein Telescope.

the interferometer to approach the quantum-noise limit over much of the low-frequency observing band. The required technologies are currently being developed and validated in dedicated prototype facilities including ETpathfinder and E-TEST.

Test masses



Schematic view of a Virgo Superattenuator, similar to the ones proposed for ET.

The interferometer mirrors are simultaneously precision optical elements and freely suspended inertial reference masses. Optically they define the Fabry-Pérot arm cavities, determine the cavity finesse and optical storage time, and preserve the wavefront quality required for high-fidelity interferometry. Mechanically they provide the nearly free-falling reference masses whose differential motion constitutes the gravitational-wave signal.

The low-frequency test masses have masses of approximately 200 kg and operate at cryogenic temperature. Their optical quality, mechanical dissipation, thermal stability and susceptibility to radiation-pressure fluctuations directly determine the achievable strain sensitivity. The position of each mirror must be measured with a precision approaching 10^{-19} m while simultaneously limiting the disturbance produced by the measurement process itself.

Consequently, the Einstein Telescope represents one of the most demanding examples of quantum-limited precision measurement ever attempted. Rather than being limited by imperfections in conventional engineering, the ultimate sensitivity is determined by the interaction between a quantised optical field and kilogram-scale mechanical test masses. It is this transition from classical precision engineering to quantum-limited measurement that distinguishes the Einstein Telescope from previous generations of gravitational-wave detectors and motivates the discussion in the main text.