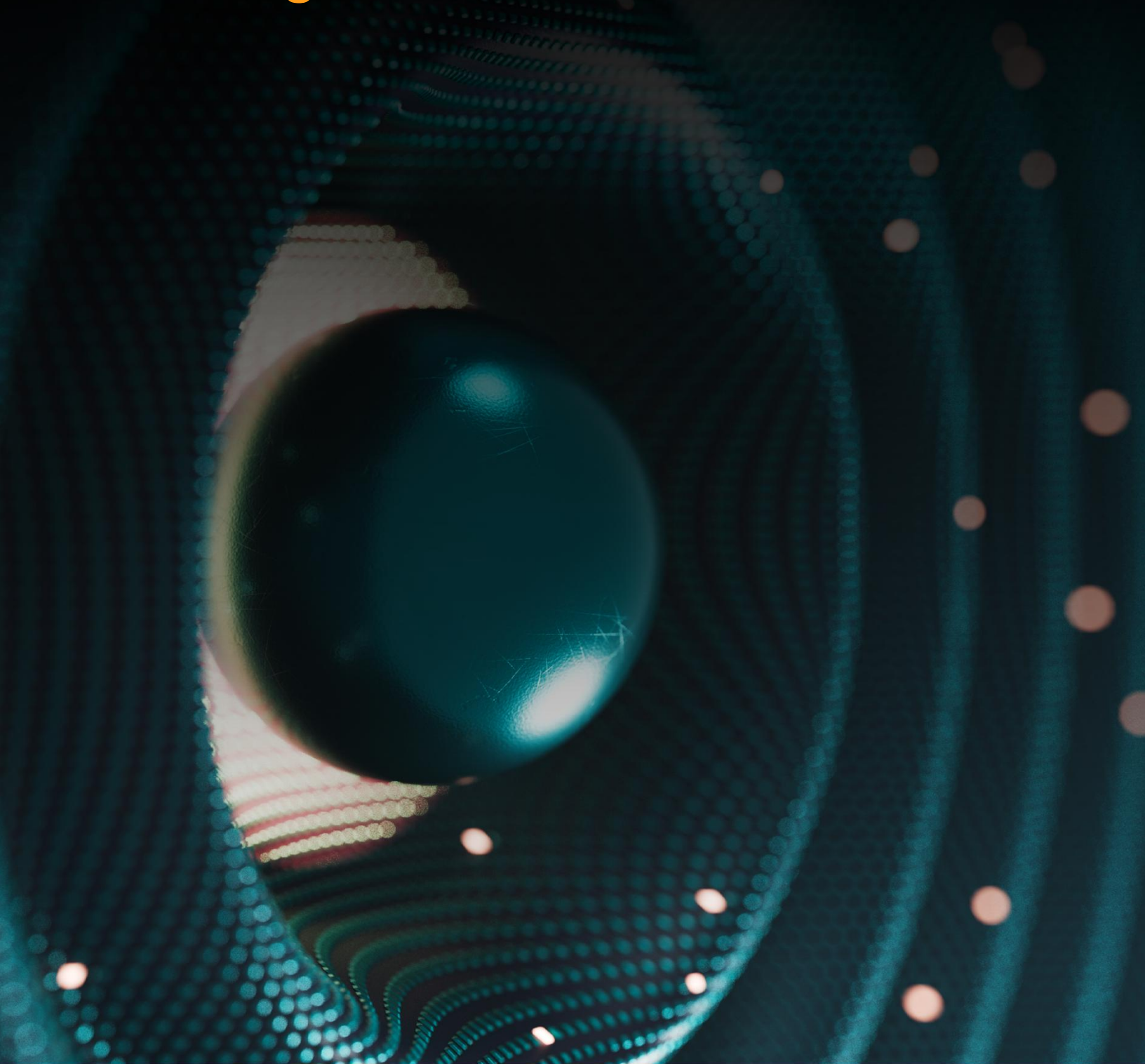




Science and  
Technology  
Facilities Council

# Gravitational Waves

Strategic Review 2025



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# 1 Summary and Key Recommendations

This report was commissioned by UKRI-STFC to review UK support for Gravitational Wave (GW) science, considering the timeline to the start of operations of the next generation GW facilities in the mid 2030s.

The current state of the art is summarised, noting the key contributions that UK based researchers have made in this rapidly emerging new window onto the cosmos. Since the first discovery of a GW source (through high precision measurements of perturbations in spacetime itself) in 2015, and the first identification of an electromagnetic counterpart to a GW source in 2017 (which thereby also heralded the start of the new field of multi-messenger science) there has been a rapid increase in scientific discovery, for example with new insights into star and galaxy formation through an increased understanding of the physics of black holes of various masses.

The report assesses the potential for a paradigm shift in science with the arrival of proposed future instrumentation, for instance new ground-based high-frequency GW facilities such as Einstein Telescope (ET) and Cosmic Explorer (CE).

The report identifies the importance of this rapidly expanding science field, supported by returns to the community consultation held as part of the panel's evidence gathering process, and notes opportunities for the UK to build on its current strengths. This will not only reap significant science gains but also returns in terms of improving the UK science base and human potential and returns through industrial spin-offs.

The report gives a set of recommendations (and estimates of the likely financial cost implications) that should be implemented to ensure that the UK is able to leverage its current expertise in the next phase of GW development.

In summary, the ten recommendations, along with the implied funding requirements for each requirement (in 2024 e.c.), are:

**1: Key:** Recognising the vital role that researchers in the UK have played in the rapid advances in GW research, it is essential that GW research and development is funded at a level necessary to maintain UK leadership in current and next generation GW observatories, both ground- and space-based.

**2: Ground-based A:** In order to ensure the maximum scientific return to the UK, funding is required to underpin UK participation in the Advanced LIGO upgrades (post A+, A#) programme, as an essential pre-requisite in preparation for the next leap in GW facilities with the Einstein Telescope (ET) and Cosmic Explorer (CE). This is through consolidated group funding and capital contributions to specific developments.

[Investment at the ~£12.5M /year is envisaged.]

**3: Ground-based B:** Funding commitments will be required in the near future to support the UK community through until a major investment decision. This will help secure UK leadership in one, or both, of the next generation GW ground facilities: either Einstein Telescope (ET) or Cosmic Explorer (CE).

[Investment at the ~£4M /year is envisaged for initial investment in ET and/or CE.]

**4: Ground-based C:** A major funding investment in infrastructure and people at the ~£200M level will be required to secure a significant leadership role in CE and/or ET. This will require support through a specific UK Gov funding line, e.g. the UKRI Infrastructure Fund (IF). Preparatory funding should be provided to enable the generation of the IF proposal (assuming that STFC 'have' prioritised a GW IF bid for submission).

[Investment at the ~£200M level is envisaged for the UK contribution to the next generation facility, this over the construction phase. Preparatory funding at the £100K/yr level in advance of construction for IF bid generation activities such as community workshops and a proposal writing team retreat.]

**5: Ground-based D:** STFC should change the scope and process of its current consolidated grant funding mechanism for GW research such that it supports all aspects of ground-based GW observations, including instrumentation, detector characterisation, data analysis and relevant theoretical modelling, for current and future generations of instruments.

[No additional financial commitment.]

**6: Space-based A:** LISA science exploitation investment will be required from UKRI in order to ensure full UK science exploitation of the UKSA/ESA investment in the construction and operation of LISA.

[UKRI funding, to supplement that from UKSA, required at the ~£2.5M/ year level pre-launch of LISA.]

**7: Space-based B:** Improve cross council coordination by convening a UKRI-STFC/UKSA GW advisory panel.

[No additional financial commitment.]

**8: Community A:** It is essential that membership of STFC grant review panels (e.g. AGP) includes expertise in the GW data/theory area for both ground and space-based applications.

[No additional financial commitment.]

**9: Community B:** Support for other GW technologies should be kept under review (e.g. IPTA participation, quantum techniques, atom interferometry), with initial involvement that can expand in response to demonstrated advancements in the field.

[Funding required at the ~£1M/ year level to support translational activity.]

**10: Community C:** Strengthen the coherence of the UK GW science community through the formation of a GW:UK interest group.

[Funding at the £100K/ year level.]

## 2 Introduction and Scope

### 2.1 Background

Gravitational waves (GWs) were first postulated<sup>1</sup> over 100 years ago in the context of Einstein’s general theory of relativity. The first direct detection of GWs<sup>2</sup>, resulting from a binary black hole merger, was made by the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO)<sup>3</sup>, some 10 years ago in 2015. Shortly thereafter, in 2017, the first electromagnetic (EM) counterpart to a GW source was confirmed: GW170817<sup>4</sup>, emitted from the merger of a binary neutron star (BNS) system, which was associated with a short gamma-ray burst and optical emission from a kilonova<sup>5</sup>. These detections heralded the dawn of both GW and GW-EM multi-messenger discovery<sup>6</sup>.

Gravitational waves can be detected across a range of frequencies as shown diagrammatically in Figure 1. Differing detection techniques are employed depending on frequency range. Likewise, the relevant astrophysical sources vary with frequency of the GWs.

### 2.2 The UKRI-STFC Gravitational Review 2025

This report was commissioned by UKRI-STFC in May 2024 with the main objective being to review the current Gravitational Wave landscape, from a UK perspective, and recommend priorities for UK public research investment in the coming ten-year period, 2025–2035.

## 3 Gravitational Wave Science: Current State of the Art

### 3.1 GW Science and Relevance to UK STFC Priorities

Gravitational waves – oscillations in spacetime itself – offer a completely new way to observe the Universe. UK groups have long-standing international collaborations

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<sup>1</sup> Einstein, A. Approximative integration of the field equations of gravitation. *Sitzungsber. Preuss. Akad. Wiss.* 1, 688–696 (1916)

<sup>2</sup> Abbott, B. P. et al. Observation of gravitational waves from a binary black hole merger. *Phys. Rev. Lett.* 116, 061102 (2016).

<sup>3</sup> J. Aasi et al., Advanced LIGO, *Class. Quantum Grav.* 32 074001 (2015)  
<http://iopscience.iop.org/0264-9381/32/7/074001/>

<sup>4</sup> Abbott, B. P. et al. GW170817: observation of gravitational waves from a binary neutron star inspiral. *Phys. Rev. Lett.* 119, 161101 (2017)

<sup>5</sup> Abbott, B. P. et al. Multi-messenger observations of a binary neutron star merger. *Astrophys. J. Lett.* 848, L12 (2017).

<sup>6</sup> See for a recent review: Bailes, M., et al. “Gravitational wave physics and astronomy in the 2020s and 2030s”, *Nat. Astron.* 3, 364 (2021), <https://doi.org/10.1038/s42254-021-00303-8>

pioneering GW science, including as founding members of the LIGO Scientific Collaboration almost 30 years ago. UK scientists made critical contributions to the first direct observation of gravitational waves by LIGO in 2015, such as providing the detector's mirror suspensions, analysis routines used to detect the signal of the two merging black holes, and the theoretical models used for astrophysical interpretation of the data. UK scientists have also made significant contributions to space-based GW detection, including providing the optical benches for LISA Pathfinder, leading the design and build of the optical benches, as well as contributing to the development of the ground segment, for ESA's Laser Interferometer Space antenna (LISA). Since the first Advanced LIGO observing run (O1) in 2015-16, LIGO and Virgo<sup>7</sup> (a joint French-Italian interferometer project) have detected approximately 100 confirmed signals and released public alerts for approximately 200 more candidate signals. All events observed to date were most likely due to the merger of compact-object binaries composed of two black holes, two neutron stars, or a black hole – neutron star pair. Scientific highlights include the first observation of a binary neutron star merger, GW170817, which triggered a worldwide follow-up campaign across the electromagnetic spectrum. Multi-messenger observations of GW170817 yielded insights into the origin of heavy elements and the astrophysics of gamma-ray bursts, the most stringent test to date of the speed of gravity, and a novel measurement of the Hubble constant. The source GW190521 was determined to be the gravitational signal from the merger of two massive black holes, with masses of  $85 M_{\odot}$  and  $66 M_{\odot}$ , this being the first clear discovery of an intermediate-mass black hole<sup>8</sup>.

Observing campaigns continue, with the fourth observing run (O4) currently underway with a projected end date of November 2025<sup>9</sup>. Targets include other anticipated GW sources such as core-collapse supernovae, spinning neutron stars (GW pulsars), and cosmological and astrophysical stochastic backgrounds. GW data are also used for non-GW science such as searches for ultralight dark matter and for fundamental physics measurements including quantum effects at the kilogram-mass scale.

Gravitational-wave science has long been a top priority of the UK particle astrophysics community. It addresses a range of [STFC science priorities](#), probing violent events occurring in the universe and cosmological properties (A.8). GWs provide a unique capability to study the endpoints of stellar evolution: neutron stars, black holes (from stellar mass to supermassive), and white-dwarf binaries, providing information about the underlying populations (A.5) and, in the future, providing information about the formation of the first stars, black holes and galaxies (A.4). Joint gravitational-wave and electromagnetic observations can probe the nuclear processes involved in neutron star mergers and supernovae (A.6). Observations of neutron stars, both individually and in binaries, enable measurements of nuclear matter at extreme densities (C.6) and may

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<sup>7</sup> See <https://www.virgo-gw.eu>

<sup>8</sup> Abbott, R, et al, GW190521: A Binary Black Hole Merger with a Total Mass of  $150 M_{\odot}$ , Phys. Rev. Lett. 125, 101102 – Published 2 September, 2020 DOI: <https://doi.org/10.1103/PhysRevLett.125.101102>

<sup>9</sup> See LIGO, Virgo and KAGRA observing run plans at <https://observing.docs.ligo.org/plan/>

potentially identify new states of matter such as quark or boson stars (C.7). GW observations provide a direct probe of gravity (A.7) both through the generation of gravitational waves in extreme environments and their propagation to the Earth (C.3). Observations of primordial gravitational waves will provide a glimpse of the very early universe (A.1), while using gravitational waves as standard sirens provides an independent probe of the cosmological evolution of the universe (A.3). Finally, gravitational-wave observatories have already been used to test theories of dark matter (C.4).

Whilst the following sections focus on UK involvement in the GW facilities, it is important to note that there has been considerable UK involvement in the science exploitation from the GW facility consortia. For instance, UK teams in the LIGO Science Collaboration and the LIGO-Virgo-KAGRA (LVK) Collaboration have a significant track record. The most recent ‘Discovery Paper’ from the current O4 run<sup>10</sup> for instance, involves UK researchers from 15 institutes spread across the UK.

## **3.2 Current GW Observational Facilities and Supporting Programmes**

In this section we give a brief overview of existing GW observational facilities and related capacities. We focus on the  $10^{-9}$  Hz –  $10^3$  Hz frequency range and supporting technologies and techniques such as computation and theory, where the bulk of the UK GW research funding has been focused. Lower frequency capabilities, e.g. associated with pulsar timing arrays and cosmic microwave background experiments, are included in Section 8 on future facilities, for which GW search requirements are part of the development plans.

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<sup>10</sup> A. G. Abac *et al*, “Observation of Gravitational Waves from the Coalescence of a 2.5–4.5  $M_{\odot}$  Compact Object and a Neutron Star”, 2024 *ApJL* **970** L34 DOI 10.3847/2041-8213/ad5beb

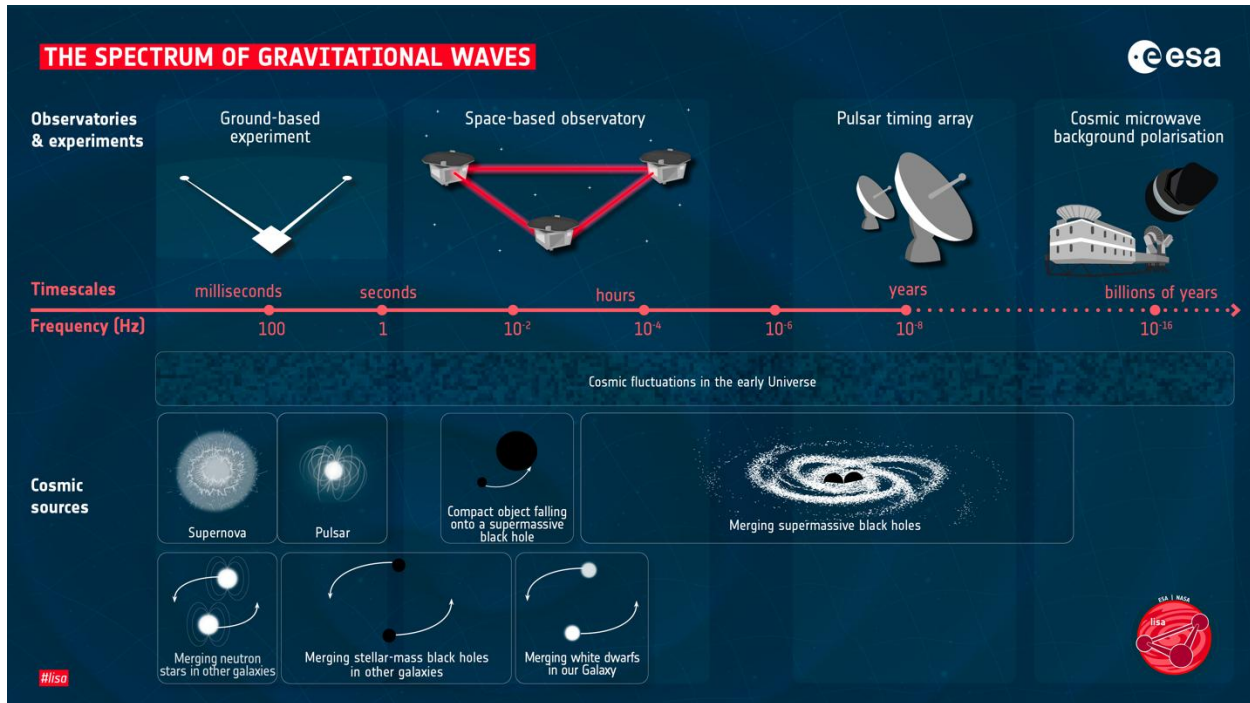


Figure 1: Diagrammatic representation of main astrophysical sources and observational techniques probing across the GW spectrum from high to low frequency. Credit: LISA Definition Study Report, ESA.

### 3.2.1 LIGO

The LIGO detectors comprise two instruments 3,000 km apart in the USA. LIGO Livingston is located near Baton Rouge, Louisiana and LIGO Hanford is located on the Department of Energy reservation just outside Hanford, Washington. The two detectors see almost the same combination of the two GW polarisations, meaning the signals in the two detectors tend to be very highly correlated. This gives confidence that the detected event is a real GW and not due to coincidental background fluctuations. The LIGO Lab (Caltech/MIT and the detector sites) have responsibility of the LIGO Laboratory including operating the detectors and R&D aimed at further improving the capabilities of the detectors. The LIGO Scientific Collaboration (LSC)<sup>11</sup>, formed in 1997, and of which UK researchers from, currently, 15 institutions are members, brings together researchers from institutions other than the LIGO Lab who are dedicated to furthering the scientific goals of LIGO. The LSC and LVK collaborations work toward these goals through research on, and development of techniques for, GW detection, and the development, commissioning and exploitation of GW detectors.

In 2010, after its 6th science run, the LIGO detectors commenced a five-year period of major upgrades, to the aLIGO configuration. Key features of the aLIGO instrument<sup>12</sup> were the inclusion of signal recycling mirrors, in addition to the power recycling mirror,

<sup>11</sup> LSC: see <https://ligo.org>

<sup>12</sup> The LIGO Scientific Collaboration et al., "Advanced LIGO", *Class. Quantum Grav.* 32 074001 (2015) <https://doi.org/10.1088/0264-9381/32/7/074001>

increased laser power at 1064 nm and, a key UK contribution, the monolithic fused silica suspensions for the core optics<sup>13</sup>. These upgrades provided a sensitivity improvement of approximately a factor of 10 (increasing the expected event rate by a factor of 1000) compared to the initial configuration.

A third LIGO detector, identical to those at Hanford and Livingston, is under construction in India. LIGO-India is expected to be operation in the next few years and will greatly improve the network's sky localisation capabilities<sup>14</sup>. UK groups contribute to LIGO India activities, for instance providing expertise in data analysis and instrumentation.

### 3.2.2 Virgo

The Virgo detector is a 3 km long laser interferometer located just outside of Cascina, Italy. Similarly to LIGO, the initial Virgo detector collected data from 2007 to 2011, until it was decommissioned for a major upgrade to its Advanced configuration. Upgrades included the use of heavier 40 kg test masses and higher laser power, with the aim to improve sensitivity<sup>15</sup> by a factor of 10. The Advanced Virgo detector joined the aLIGO detectors in 2017 to observe gravitational wave signals and to provide improved sky localisation, this due to the longer separations between the LIGO and Virgo detectors compared to between the two LIGO detectors only. Virgo played a key role in the localisation of the first multi-messenger event, GW170817.

### 3.2.3 KAGRA

KAGRA (Kamioka gravitational wave detector) is located in Japan near Toyama. The detector is unique in that it utilises technologies that will likely be implemented in 3rd generation detectors, including underground operation and cryogenic cooling to lower thermal noise<sup>16</sup>. The detector is co-located in the same mine as the Super Kamiokande neutrino detector, so potentially allows for coincident particle astrophysics observations.

The KAGRA project is split into two phases: initial KAGRA (iKAGRA) and baseline KAGRA (bKAGRA). The main purpose of the iKAGRA phase was to test all the basic systems, from the underground interferometer controls to the data analysis pipelines at room temperature operation. This was completed in 2017. The bKAGRA phase, which aims for full cryogenic operation, is now in progress. Although there have been delays from unexpected sources such as excess water in the tunnels and earthquakes, KAGRA is expected to rejoin the O4 observing run later in 2025 with a sensitivity of approximately 10 Mpc, as noted in the following section.

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<sup>13</sup> S M Aston *et al* 2012 *Class. Quantum Grav.* **29** 235004

<sup>14</sup> <https://dcc.ligo.org/ligo-p1200087/public>

<sup>15</sup> Acernese, F., *et al.*, “Advanced Virgo: a second-generation interferometric gravitational wave detector”, *Class. Quantum Grav.* 32 024001 (2015)  
<https://doi.org/10.1088/0264-9381/32/2/024001>

<sup>16</sup> Akutsu, T., *et al.*, “Overview of KAGRA: Detector design and construction history”, *Progress of Theoretical and Experimental Physics*, Volume 2021, Issue 5, May 2021, 05A101, (2021), <https://doi.org/10.1093/ptep/ptaa125>

### 3.2.4 GEO600

GEO600<sup>17</sup> is the German-British laser-interferometric gravitational wave detector that was built outside Hannover, Germany in the late 1990s and started operation in the early 2000s. GEO600 has an effective 1200 m arm length detector which uses a dual-recycled Michelson configuration with folded arms inside 600 m long beam tubes.

From the outset, GEO has focussed on R&D and developing technologies that could be demonstrated and ultimately implemented in the longer LIGO and Virgo detectors. Examples where GEO600 has pioneered technology include:

- the development of multi-chain suspensions with a monolithic fused silica final stage and a reaction mass chain, with electro-static actuators on the test mass;
- signal recycling at the output port of the interferometer, where GEO was the first detector to operate with shot-noise squeezed light. The injection of squeezed light states into the interferometer was part of the GEO-HF upgrade which began in 2010.

Such pioneering development has directly enabled the UK to play a leadership role in hardware development for aLIGO and its future upgrades.

Since 2007, GEO600 has served as the community's Astrowatch detector. Astrowatch mode is a science run from the standpoint of detector operations such that GEO600 is maintained at its highest possible sensitivity while the other detectors are being upgraded. GEO600 continues to actively pursue the goals of the GEO-HF upgrade program while dedicating significant time to collecting Astrowatch data.

### 3.2.5 Pulsar Timing Arrays

Pulsar timing arrays (PTAs) use highly stable millisecond pulsars as "clocks" to create a galactic-scale GW detector, sensitive to nanoHz-to-microHz GWs. PTAs such as the European Pulsar Timing Array (EPTA), North American NANOGrav, and the Parkes Pulsar Timing Array (PPTA) have collaborated through the International Pulsar Timing Array (IPTA) consortium. The UK plays a leading role in EPTA and IPTA, with contributions spanning data acquisition, noise characterisation, GW searches, and astrophysical interpretation. The UK also participates in the MeerKAT PTA, which will integrate into the Square Kilometre Array Observatory (SKAO) once operational.

In June 2023, EPTA (with UK contributions), NANOGrav, PPTA, and the Chinese PTA independently reported a low signal-to-noise detection of a stochastic GW background. This signal, attributed to supermassive black hole binaries, could also align with early-universe cosmological scenarios, though current data cannot distinguish between these origins. MeerKAT PTA has since published results consistent with earlier findings.

### 3.2.6 Gaia

Precise astrometric measurements of galactic star motions offer a unique method to probe GWs. Galaxy surveys such as Gaia, which observes approximately  $10^9$  stars in

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<sup>17</sup> Dooley, K.L., (for the LIGO Scientific Collaboration), "Overview of GEO 600", J. Phys.: Conf. Ser., 610 012015 (2015) <https://doi.org/10.1088/1742-6596/610/1/012015>

the Milky Way, can detect gravitational wave signals through the subtle deflection patterns they produce in the apparent positions of stars as their light travels to Earth<sup>18</sup>. These deflections, caused by the wave's interaction with spacetime, appear as minuscule “wiggles” in stellar positions.

To overcome the computational challenges of analysing the positions of  $10^9$  stars individually, statistical techniques developed by UK scientists<sup>19</sup> can be employed without significant loss of sensitivity. Gaia's astrometric observations are sensitive to gravitational waves in the low- to ultra-low-frequency range bridging the frequency gap between LISA and PTA experiments. This positions Gaia as a critical tool for detecting gravitational waves from sources such as supermassive black hole (SMBH) mergers and primordial relic gravitational waves.

Initial results are expected with Gaia Data Release 4 (2026), with enhanced sensitivity anticipated from Gaia Data Release 5 (2030/31).

### 3.2.7 Multi-Messenger Follow-up Programmes

A key science objective in gravitational-wave astronomy is to observe potential gravitational-wave events using other observatories, including traditional electromagnetic observatories, neutrino detectors and/or cosmic-ray detectors. This field of “multi-messenger astronomy” demonstrated its potential in August 2017 following the coincident, independent, rapid observation of GW170817/GRB170817A in both the LIGO+Virgo gravitational-wave observatories and the Fermi+INTEGRAL gamma-ray observatories. A sky map produced in the hours following this event, combining information from both observations, was subsequently used by numerous observatories to find the transient signal (AT2017gfo) across the electromagnetic spectrum. The paper describing this multi-messenger observation included authors from tens of UK-based institutes, representing both GW and electromagnetic expertise around the country<sup>20</sup>.

The most likely multi-messenger events in the next 5–10 years will be additional electromagnetic transients following the merger of binaries involving neutron stars, similar to GW170817. In addition to UK-based experts working on identifying gravitational-wave transients and producing rapid sky localization maps, the UK has an extensive community working on electromagnetic follow-up of gravitational-wave signals and a community who are experts in modelling such transients. Examples of where the UK has a significant presence in the GW electromagnetic follow-up program include:

- GOTO: The GOTO project consists of multiple wide-field telescopes on a single mount dedicated to following gravitational observations from LIGO and Virgo. GOTO is an STFC priority project that is predominantly based in, and led from, the UK. It has received significant investment from STFC.

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<sup>18</sup> e.g. S.A. Klioner, “Gaia Astrometry and Fundamental Physics”, EAS Publications Series, 67-68 (2014) 49-55, DOI: <https://doi.org/10.1051/eas/1567007>

<sup>19</sup> Moore et al, Phys. Rev. Lett. **119**, 261102

<sup>20</sup> Abbott. et al. Astrophys.J.Lett 848 (2017) 2, L12

- ENGRAVE: An international collaboration of over 250 researchers, over 50 of whom are based in the UK, using ESO facilities to follow up gravitational-wave transient signals.
- BlackGEM: BlackGEM is a wide-field telescope array dedicated to measuring the optical emission from merging compact objects. BlackGEM is led from the Netherlands, with multiple partner institutes based in the UK.

Alternative multi-messenger sources also exist, including the potential for observing supernovae, most likely in our own galaxy, jointly between gravitational-wave and electromagnetic observatories. The UK has extensive interest in supernova modelling, electromagnetic transient observation and unmodelled gravitational-wave source identification, which would make an area of significant interest if an observable multi-messenger supernova were to occur.

In addition to electromagnetic follow-up, there are now ongoing efforts to observe neutrinos coincident with gravitational-wave transients with IceCube and KM3NeT, both of which have a small level of UK involvement.

### **3.2.8 Theory, Computation, and Data Analysis**

The UK has enjoyed leadership in gravitational-wave theory/modelling and data analysis since the 1970s. The early development of data analysis algorithms influenced the strategies that were later adopted by the current international collaborations. The continued importance of the UK expertise in this area is evidenced by the range of internal leadership roles held within the LVK collaboration. Since the first GW detection in 2015, several new UK groups have been established. This broadens the data analysis landscape beyond the groups initially involved in the development of the LIGO instruments to include a range of new centres across the UK. The range of activities in these groups covers most aspects of data analysis for ground-based observations (including next-generation projects) and space-based GW astronomy with LISA. Recent developments in data analysis brings in machine-learning aspects to deal with the increase in observed signals anticipated in the 2030s. Data analysis efforts within the LVK envelope continue to be supported by STFC consolidated grants, but the available budget sets a constraint on future developments.

In terms of GW theory and modelling, the UK is well placed to continue playing a leading role in the international community. Examples include theory groups studying signals from black-hole binaries and waveform modelling for detection and parameter extraction, others focused on GWs from systems involving neutron stars and the modelling of extreme mass ratio binaries for LISA.

This is complemented by work elsewhere on alternative theories of gravity, numerical relativity simulations for exotic matter to work on wider cosmological aspects. Multi-messenger science aspects are explored, for example, via numerical simulations, together with the connection with particle physics and issues related to dark matter and cosmology. The above examples highlight a few of the key GW related science objectives being investigated in the UK, with evidence showing a growing number of groups engaging with GW science.

In short, UK groups have leading expertise across GW astronomy. The funding level for these efforts does not, however, seem comparable to investments made in, for example, the USA and the EU. This is particularly true for the development of cutting-edge numerical relativity simulations of realistic astrophysical systems (e.g. neutron star and black hole binaries), required for future GW astronomy. Current efforts are largely supported by individual fellowships (e.g. ERFs, URFs and ERC grants). This is less than ideal as it does not promote the long-term stability required for strategic developments over the next decade.

## 3.3 Towards a Global Gravitational Wave Network

### 3.3.1 Combined LIGO-Virgo-KAGRA Operations

The advanced detectors began operation in 2015 via a series of Observing runs, a timeline of which can be found at <https://observing.docs.ligo.org/plan/>. While the LIGO/Virgo/KAGRA detectors have had variation in when they have started science observations, the key dates of these runs (based on latest announcements), and some highlights include:

- Run O1 (LIGO) Sep15-Jan16. Detection of the first GW event, a binary black-hole merger.
- Run O2 (LIGO + Virgo) 2016-2017. Detection of the first EM counterpart (binary neutron star merger).
- Run O3 (LIGO+Virgo+KAGRA) 2019. Detection of the first neutron star – black hole merger.
- Run O4 (LIGO+Virgo (from Apr24+KAGRA) May23-Nov25. Detection of an object in the  $3 M_{\odot}$  -  $5 M_{\odot}$  mass-gap between neutron stars and black holes.
- Run O5. Planned from late 2027 to late 2030 in the A+ configuration<sup>21</sup>.

As of Jan 2025, the LIGO Livingston and Hanford detectors were operating with a binary neutron star sensitive range of around 160-170 Mpc<sup>22</sup>. Virgo was operating with a binary neutron star range of around 55 Mpc, while KAGRA was offline recovering from damage sustained during an earthquake.

### 3.3.2 Building the International Gravitational-Wave Network

The LIGO, Virgo, and KAGRA collaborations share all data and undertake all scientific analyses jointly under a shared Memorandum of Agreement. Recognising the opportunity to reduce duplication of decision-making procedures and collaborate more efficiently, the three Collaborations are working towards defining a new unified organisational structure that will bring all LVK groups together in a single global collaboration, the International Gravitational-Wave Network (IGWN). This unified collaboration will help the community to fully exploit the scientific potential of the LVK network by establishing shared scientific goals and prioritisations, integrating

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<sup>21</sup> A+ is the next major upgrade to aLIGO as described in Section 4.2.

<sup>22</sup> See the observatory status pages at [https://gwosc.org/detector\\_status/](https://gwosc.org/detector_status/).

infrastructure and operations across the network, and enabling more efficient sharing of resources.

An international committee (with two UK members) has been appointed to draft a charter and define the initial structure of the new collaboration. IGWN is expected to be fully operational in early 2027, before the start of the O5 run.

## **4 Current UK leadership in the GW area**

### **4.1 GW Science**

In the following sections we highlight some major areas of UK activity. This list is not exhaustive, and we do not discuss for instance topics such as detector characterisation, Inertial sensors, etc, where there is also significant activity. Perhaps the most notable leadership position the UK holds in GW domain is the position of spokesperson of the LIGO Scientific Collaboration (held by Professor Stephen Fairhurst, Cardiff University). Prof Fairhurst is the first LIGO spokesperson not based at a US institute.

#### **4.1.1 Theoretical Modelling and Data Analysis**

UK-based researchers have made significant contributions to waveform modelling, essential for developing accurate templates for gravitational wave detection and source characterisation. One of these contributions is in the development of highly accurate numerical relativity simulations, which are used to produce waveforms for the final stages of binary mergers, where analytical approximations break down due to the strong gravitational fields. This includes early contributions like the development of the BAM code for black-hole binary mergers and the Whisky relativistic fluids code for neutron star merger simulations (developed as part of an EU network effort involving several UK groups in the early 2000s), and recent efforts like the design of GRChombo, an advanced numerical relativity code for modelling complex spacetime dynamics. In addition, UK groups have made important contributions to the Black Hole Perturbation Toolkit, which supports the study of extreme mass-ratio inspirals (EMRIs). UK-based researchers also continue to contribute to the maintenance and development of the Einstein Toolkit, used for simulating binary systems, both in vacuum and including hydrodynamic and magnetohydrodynamic phenomena in astrophysical contexts.

UK teams have pioneered advances in phenomenological waveform models including several models within the IMRPhenom and Effective One Body families, widely used by researchers inside the LVK collaboration and independent groups. Furthermore, UK researchers are leading efforts in self-force calculations, which are crucial for modelling EMRIs for LISA and understanding the subtle gravitational interactions in these systems.

UK researchers have been instrumental in developing specialised algorithms using matched filtering and Bayesian inference for the identification and extraction of gravitational-wave signals from noisy data. These methods have been refined to handle the complex parameter space of compact binaries, enabling precise extraction of source characteristics such as the component masses and spins of merging black holes and

neutron stars. Examples of the key contributions the UK made are those to the development and maintenance of inference tools such as LALInference and Bilby, which are widely used in the LVK collaboration to perform advanced Bayesian parameter estimation. Additionally, the UK has made major contributions to PyCBC, a vital piece of software for detecting and analysing signals, and to GWpy, a versatile Python library that provides a unified interface for the analysis of gravitational-wave data. UK researchers are also at the forefront of using ML and advanced deep learning techniques, as demonstrated by the MLy pipeline (which is the first ML-based GW detection pipeline, adopted by the LVK and now used for low latency searches) and Dingo (also used by the LVK), which leverages these methods to replace or enhance traditional Bayesian sampling approaches, enabling faster and more efficient parameter estimation for large and complex datasets.

Complementing work on compact binary signals, UK researchers have also led efforts to detect continuous gravitational waves from pulsars, setting leading constraints on neutron star ellipticity and advancing methods for long-duration signal analysis.

#### **4.1.2 Gravitational Wave Science Exploitation**

Gravitational wave signals can be used to learn about astrophysical populations of stars and stellar binaries, and the process of (binary) compact object formation. Bayesian inference and parameter estimation on GW data can be used to estimate posterior distributions of source or population properties. These techniques are used by researchers at several UK institutions. For the interpretation of these results, (typically 1D) stellar evolution codes and population synthesis simulations are used. In addition to isolated binary evolution, UK researchers also contribute to modelling dynamically formed binaries—such as those assembled in dense stellar environments like globular clusters and nuclear star clusters—which provide an alternative formation channel for GW sources. UK-based scientists have been instrumental at the development of the population synthesis codes COMPASS and BPASS and played a role in developing POSYDON, which combines stellar evolution and population synthesis.

The UK has substantial expertise in gravitational-wave follow-up (see also sections 3.2.7 and 6.3.5). UK scientists played a key role in the first multi-messenger event, GW170817. For future detections, UK researchers lead efforts in developing toolkits for rapidly identifying and localising compact binary mergers and generating improved skymaps using Bayesian inference. The UK has active involvement in major electromagnetic follow-up of gravitational sources through projects such as GOTO, ENGRAVE, and BlackGEM.

UK scientists have used GW data from events like GW170817 to constrain the neutron star equation of state (EoS), revealing insights into their internal structure and maximum mass through constraints on the tidal deformation. UK researchers have also advanced simulations of merger events, including post-merger oscillations, offering a direct probe of ultra-dense matter. Teams including UK scientists have also explored connections to heavy element production via r-process nucleosynthesis, probed via multi-messenger observations.

Researchers in the UK have been active on several fronts in testing General Relativity (GR) using gravitational waves. Key areas of focus include propagation tests, where

UK-based scientists have played leading roles in setting tight constraints on the speed of gravitational waves, as well as investigating possible dispersion effects (such as frequency-dependent variations in wave propagation), particularly leveraging data from events like GW170817. Additionally, UK researchers are advancing the use of "dark sirens," gravitational wave signals without accompanying electromagnetic counterparts which are cross matched with galaxy catalogues. In this way, one can infer source distances and explore the universe's expansion, enabling new ways to probe deviations from GR. Teams including UK scientists also test alternative theories of gravity, such as scalar-tensor or vector-tensor models, through their production of additional polarisation states, including longitudinal or scalar modes.

UK researchers are advancing the use of gravitational waves to study early universe cosmology. Work on first-order phase transitions focuses on the gravitational waves generated through the collisions of bubbles of true vacuum, as well as the acoustic and turbulent motion of the primordial plasma during and after the transition. Such a probe would offer unique insights into the early universe's thermal history, serving as a direct window into epochs preceding photon (and neutrino) decoupling. Moreover, studies at UK institutions explore the gravitational radiation emitted by cosmic defects such as string networks, investigating their observational signatures and implications for cosmological models. These efforts provide critical predictions for both low-frequency experiments such as pulsar timing arrays and future gravitational-wave observatories such as LISA.

Lastly, UK researchers have explored the intersection of dark matter studies and GW research. In particular, researchers have explored how GWs can constrain properties of popular macroscopic dark matter candidates, such as primordial black holes and extended dark objects (including hypothetical objects such as boson stars), using data from ground-based detectors. Moreover, researchers have proposed that light new particles weakly coupled to stellar material affecting stellar evolution and black hole populations can be studied using gravitational wave catalogues. It has also been suggested that dark matter candidates can affect binary formation rates. At some UK institutions work has focused on utilising GW detection technologies to search for potential dark matter signatures.

## **4.2 GW Technologies and Instrumentation**

The UK has a long track record, dating back to the 1990s, in the delivery of R&D to the international GW community, covering aspects including suspension development, coating R&D and interferometric sensing & control.

In 2011, the Advanced LIGO UK consortium (University of Glasgow, University of Birmingham, Cardiff University, University of Sheffield, Rutherford Appleton Laboratory) delivered key suspension and sensing hardware under a capital award from STFC which was critical in improving the low frequency performance of the aLIGO observatories, such that their adoption directly enabled the first and subsequent detections of gravitational waves in 2015.

More recently, an STFC PPRP award (2018-2025) has enabled the UK (University of Glasgow, University of Birmingham, Cardiff University, University of Strathclyde,

Rutherford Appleton Laboratory) to deliver hardware for A+, the next major upgrade (O5) to aLIGO. The A+ upgrade will see an improvement in events rates by approximately x7 via the delivery of larger beamsplitter suspensions, optimised and upgraded fused silica suspensions, enhanced sensing and controls, a balanced homodyne readout compatible with non-classical detection, and core optics mirrors with upgraded coatings for both detectors. The UK deliverables are vital to the success of the A+ upgrade.

These activities have been pivotal in placing the UK as a partner in LIGO throughout the period of the first discoveries, with a seat for STFC on the LIGO oversight committee, and below we provide brief highlights of the UK R&D programme.

### **4.2.1 Monolithic Mirror Suspensions**

The role of a gravitational wave detector mirror suspension is both to provide a high level of seismic attenuation and to provide an exquisitely low level of thermal noise in the low frequency (<100 Hz) detection band. This is achieved via the use of four-stage quadruple pendulum suspensions with three vertical stages of passive isolation. The final stage, supporting the 40 kg mirror, is comprised entirely of fused silica which provides the thermal noise performance of  $10^{-19}\text{m/Hz}^{0.5}$  at 10 Hz. Furthermore, suspensions must provide exquisite control of angular and positional degrees of freedom via a separate reaction chain which allows the application of forces and torques from a quiet reference frame. Sensors comprise optical shadow detectors with sub-nanometre performance for local control (damping) of suspensions, while actuators include electromagnetic coil-magnet drives on the upper suspension stages and an electrostatic drive on the test mass.

The UK groups (Birmingham, Glasgow, Rutherford Appleton Laboratory) have a long track record in delivering hardware to the LIGO instruments. During the aLIGO installation (2010-2014), the team delivered the necessary hardware (suspensions, sensors and actuators) and training to support the build of the quadruple pendulum suspensions with a lower monolithic stage of fused silica. In the more recent A+ upgrade, the UK groups have delivered an upgraded larger diameter beam splitter suspension and technology to further improve and refine the production of fused silica fibres at the LIGO Hanford fibre pulling facility.

The UK is the recognised leader in gravitational wave suspensions design, installation and commissioning, and is playing a key role in transferring suspension modelling, installation, and commissioning knowledge to researchers at the Raja Ramana Centre for Advanced Technology, Indore for the LIGO-India detector. Research towards 3<sup>rd</sup> generation instruments include the development of optimised suspension structures and suspension of heavier masses up to 400 kg, and the development of novel tilt-insensitive 6-degree of freedom inertial sensors.

### **4.2.2 Coating Technology**

Coating thermal noise forms a critical limit to the sensitivity of gravitational wave detectors at their most sensitive frequencies. Improved coatings with reduced thermal noise are therefore essential to enable the required sensitivity improvements of the A+ detector and future 3<sup>rd</sup> generation instruments. UK coating expertise is centred in

Scotland with the Universities of Glasgow, Strathclyde and West of Scotland. The consortium has a long track record of world-leading R&D including techniques to understand the microscopic origin of loss in coatings and to develop alternative coating materials which are suitable for both room temperature detectors (aLIGO, A+, post O5 upgrades, Cosmic Explorer, Einstein Telescope high frequency) and cryogenic temperature detectors (e.g. Einstein Telescope low frequency).

Current research focusses on assessing the absorption, scatter and internal friction in amorphous glasses for aLIGO, including titania-doped tantala ( $\text{TiO}_2:\text{Ta}_2\text{O}_5$ ) as the high-index material and silica ( $\text{SiO}_2$ ) as the low-index material. Furthermore, the UK is pivotal in the down selection of the coating technology for A+, including R&D on titania-germania ( $\text{TiO}_2:\text{GeO}_2$ ), titania-silica ( $\text{TiO}_2:\text{SiO}_2$ ) and silicon nitride ( $\text{SiN}_x$ ) coatings. Research further focusses on materials of interest for future detectors operating at cryogenic temperatures, including the study of single-crystalline coatings (e.g. AlGaAs) grown epitaxially on a crystalline substrate, and then transferred and bonded to the substrate, and amorphous silicon.

The UK is pioneering a large test mass coatings facility with the Centre for Extreme Performance Optical Coatings (EPOC), the largest Ion Beam Deposition system in the world, to lead international development in the coatings area.

#### **4.2.3 Interferometer Sensing & Control**

The UK has unique expertise (University of Birmingham, Cardiff University, University of Glasgow) in the development of hardware for interferometric sensing and readout of aLIGO, A+ and future 3rd generation instruments. Work focusses on techniques to mitigate the coupling of control noise and laser noise into detector readout, the reduction of readout noise, the design of novel piezo and thermally actuated mirrors to adjust cavity astigmatism in the output beam path, and via the development of novel interferometric techniques to assess the thermal noise of coatings at both room temperature and cryogenic temperature.

The work extends further to the development of new lasers and optical components (adjustable mirrors and photodiodes) which can operate at longer wavelengths including 1550 nm and 1980 nm, which are of particular interest for the Einstein Telescope low frequency detector where silicon is opaque to the 1064 nm light of traditional Nd-YAG lasers.

The work highlighted above (Suspensions R&D, Coatings R&D and Interferometer Sensing & Control) will enable UK leadership in future 3rd generation instruments including the Einstein Telescope and Cosmic Explorer. A consortium of seven British universities, led by the University of Glasgow (Birmingham, Cardiff, Glasgow, Portsmouth, Southampton, Strathclyde and the West of Scotland) have secured a UKRI preliminary phase Infrastructure Proposal (2023-2026) to develop hardware and study how to efficiently process the data coming from these new instruments.

#### **4.2.4 Inertial Seismic Isolation Systems**

Ground vibrations limit the sensitivity of the ground-based gravitational wave detectors at low frequencies, potentially masking signals from intermediate-mass black holes, and reduce the localisation precision of the observatories. Achieving the design sensitivity of

the A# upgrade below 25 Hz requires improvements in active vibrational isolation technologies. An international effort to develop new inertial isolation technologies includes six-axis seismometers (Birmingham/Nikhef), beam rotation sensors (Washington), one-axis seismometers (Birmingham/Hannover), and suspension point interferometers (Stanford/Hannover).

The UK groups (Birmingham, Glasgow, Rutherford Appleton Laboratory) have a long track record in delivering sensors and actuators to the LIGO detectors. During the past 7 years, the UK has pioneered and developed novel optical seismometers for the LIGO active platforms with sub-pm sensitivity. During tests in the Birmingham seismic facility, the six-axis seismometer has demonstrated a significant improvement compared to the systems that are currently utilised in LIGO. The technology has been then successfully tested at the MIT LASTI (LIGO Advanced Systems Test Interferometer) facility, demonstrated state-of-the-art inertial isolation of the LIGO test platform, and has the potential to become pivotal in the selection of the inertial isolation technology for A#.

#### **4.2.5 Detector Characterisation**

UK researchers play a leading role in LIGO detector characterisation, which aims to improve the data quality of the instruments, vet instrumental data around the time of GW candidate events and develop analysis techniques to overcome periods of high instrumental noise. To this end, UK teams have built and maintained a comprehensive characterisation suite: they developed real-time transient-noise pipelines (Omicron to scan strain and auxiliary channels for excess-power bursts, and hveto to correlate those auxiliary triggers with strain glitches and generate safe, efficient veto segments), contributed ML-based glitch classification modules to the Gravity Spy framework, and integrated all data-quality flags via the DQSEGDB service.

## **5 International GW Area Reviews**

There have been several international reviews since 2020 of relevance to GW science. Several of these are summarised in the following subsections.

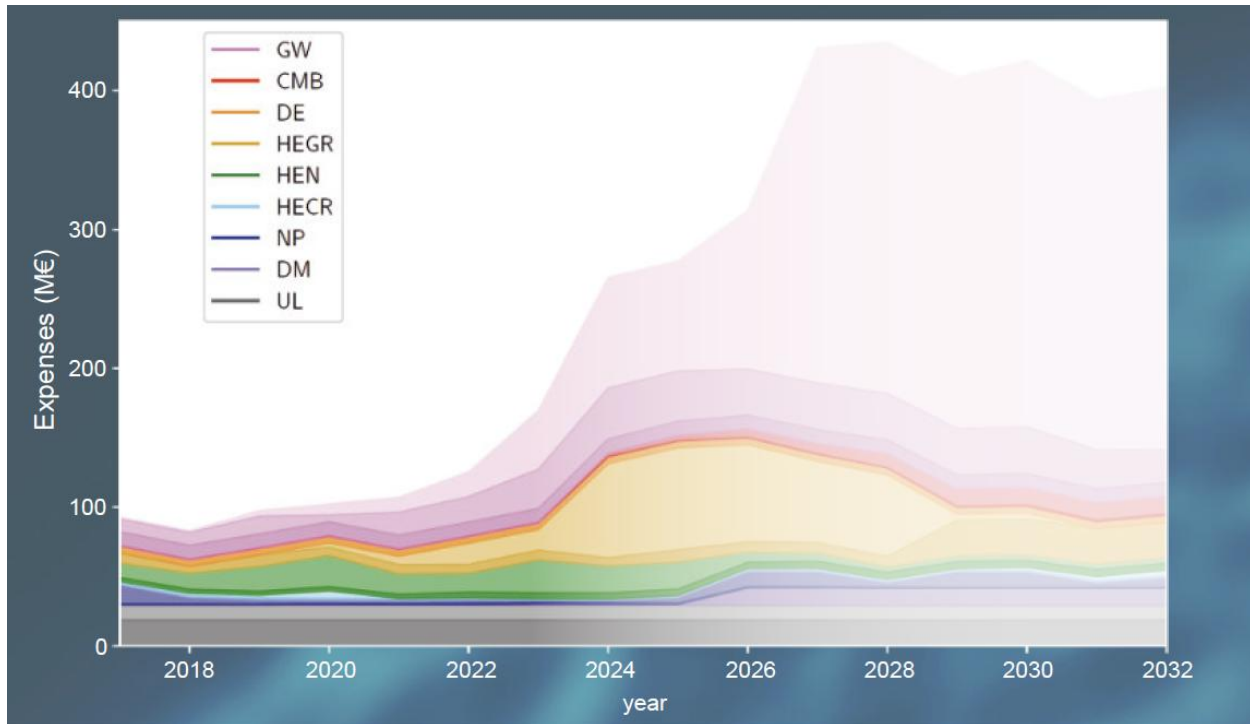


Figure 2: Estimate of realised and planned investment and exploitation expenditures in Astroparticle Physics (UL: underground laboratories, DM: Dark Matter experiments, NP: Neutrino Properties experiments, HEGR: High-Energy Cosmic Ray Observatories, HEN: High-Energy Neutrino observatories, HEGR: High-Energy Gamma Ray observatories and satellite missions DE: Dark-Energy observatories and satellite missions CMB: Cosmic Microwave Background observatories and satellite missions **GW: Gravitational Wave observatories and satellite missions.**) The exploitation is given by the darker shade for each colour and the investment budget by the lighter shade. For Gravitational Waves, three shadings have been used: dark for exploitation, middle tone for investments (to be) covered by the usual funding agencies and light for investments from exceptional sources, such as national, regional or EU (economic) structure funds. The part after 2023 has increasing uncertainties on the difference between planned and realised expenditures as time goes on. Credit: APPEC.

## 5.1 European Astroparticle Physics Strategy 2017-2026

The Astroparticle Physics European Consortium (APPEC)<sup>23</sup> mid-term (Sep 2023) update<sup>24</sup> of the APPEC 2017-2026 strategy covers a wide range of astroparticle science and facilities. In the area of GW, it noted the continued importance of actions to increase the participation of European groups in the development and construction of ET and the need to bridge developments between current 2<sup>nd</sup> generation facilities (here Virgo mentioned) and 3<sup>rd</sup> generation facilities (with a natural focus on ET). The report assessed the financial requirements across the astro-particle domain as shown in Figure 2. The APPEC report envisions a strong uplift in funding for GW science relative

<sup>23</sup> See <https://www.appec.org/> - The UK is a member of APPEC

<sup>24</sup> See <https://www.appec.org/mid-term-review/>

to other areas. The APPEC report noted that the funds required for the High Energy Gamma Ray facilities, primarily Cherenkov Telescope Array (CTA) are largely in place (the yellow 'bump' in Figure 2), whilst ET funding is at an earlier stage of commitment.

## 5.2 Astronet Report

This review<sup>25</sup>, organised by the main European funding agencies, noted the emerging importance of multi-messenger astronomy, and the vital role that LIGO, Virgo and KAGRA play in supporting this. The report noted the importance of new technologies, for instance in gravitational wave detectors coupled with next generation facilities such as ET in enabling the next breakthroughs in GW and multi-messenger astronomy.

## 5.3 NSF Report on Next-Generation Facilities (ET/CE)

The NSF's Mathematical and Physical Sciences (MPS) Advisory Committee<sup>26</sup> was charged with reviewing options for next generation GW detectors, being at least 10 times the sensitivity of the upgraded LIGO A+ facility. They noted in their March 2024 report<sup>27</sup>, that:

"[...] a next-generation detector network with such a significant sensitivity improvement will have a transformative impact on the nascent field of GW physics and astronomy by leading us into the era of precision GW and multi-messenger astrophysics."

"The discovery potential is tremendous in several cutting-edge research areas, specifically: probing black-hole formation and evolution back to the beginnings of star and galaxy formation and potentially to the early moments of our Universe, enabling a profound, quantitative exploration of quantum chromodynamics and neutron-rich matter, critically contributing to the resolution of the Hubble tension in cosmology, and revealing new physics through the exploration of dark matter and dark energy."

"Based on all considerations per the Subcommittee's charge, we provide the following recommended list of worldwide ngGW network configurations that deliver a sensitivity an order of magnitude better than the LIGO A+ design sensitivity, accounting for possible external constraints, specifically the availability of non-US detectors, ET and LIGO-India:

- CE40<sup>28</sup>, ET, LIGO-India
- CE40, ET
- CE40, CE20, LIGO-India
- CE40, CE20"

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<sup>25</sup> Astronet Roadmap 2022-2035, A Strategic Plan For European Astronomy, 2023, Editors: Amélie Saintonge, Anja C. Andersen, Claude Catala, Ronald Stark, ISBN: 978-1-3999-5162-3, [https://www.astronet-eu.org/?page\\_id=521](https://www.astronet-eu.org/?page_id=521)

<sup>26</sup> See <https://new.nsf.gov/mps/advisory-committee>

<sup>27</sup> Report at <https://nsf.gov-resources.nsf.gov/files/mpsac-nggw-subcommittee-report-2024-03-23-r.pdf>

<sup>28</sup> CE40 = Cosmic Explorer with 40km arm length / CE20 = Cosmic Explorer with 20km arm length

In the absence of ET, the committee concluded that there would need to be an investment in both 40 km and 20 km CE facilities. They also recommended that LIGO facilities be phased out once CE entered operations.

## 6 Progress Against the 2022 UK STFC PAAP roadmap

The key GW-specific recommendations from the most recent UK STFC PAAP 2022 roadmap<sup>29</sup>, forming key input into the current 2024/25 STFC Science Board PPAN roadmap development, are considered in turn.

**Recommendation 4.1.** aLIGO, including upgrades to A+ and post A+ sensitivity, remains the highest priority for the UK GW community. STFC should ensure that future funding enables UK scientists to maintain their long-standing leadership, in both the exploitation of aLIGO data and development of instrumental upgrades.

STFC have continued to support the aLIGO programme, through the dedicated A+ upgrade project collaboration between Glasgow, Cardiff, Birmingham, Warwick and Strathclyde, and through continuation of the GW consolidated grant scheme. STFC also continues to pay author fees to support UK participation in the LIGO Scientific Collaboration.

**Recommendation 4.2.** Investment in next-generation GW observatories is vital to maintain the UK's existing leadership in the field. In the short-term, this requires dedicated investment in next generation technology development and computational and modelling work required for precision GW astronomy. Longer term, the UK must provide a large-scale contribution to full project infrastructure costs to ensure continued priority access to gravitational wave data, and UK leadership in scientific exploitation. We recommend that STFC work with the GW community to develop a strong business case for a future bid to the UKRI Infrastructure Fund, in support of next generation GW Observatories.

STFC has funded the next-generation gravitational-wave infrastructure project, utilising preliminary award funding from the UKRI Infrastructure Fund. This project spans four years, starting in 2023.

Details of this project can be found here: [Infrastructure Fund projects – UKRI](#).

**Recommendation 4.3.** We strongly endorse the continued UK participation in LISA, funded by UKSA. STFC support for the preparation of science exploitation activities should be increased to be commensurate with the UK commitments and leadership roles in the mission hardware and science ground segment subsystems, supported by UKSA. As highlighted in the current funding clarification, “STFC Support for Gravitational Waves Research”, this would likely be via the Astronomy Grants Panel or a Statement of Interest to Science board.

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<sup>29</sup> See paper at <https://www.ukri.org/publications/particle-astrophysics-advisory-board-roadmap-2022/>

LISA was formally adopted by ESA on 25 January 2024, with construction to begin in 2025 and launch anticipated for 2035. The UKSA is now supporting UK participation in the construction of LISA, primarily through delivery of the LISA optical bench, and also in the development of the LISA ground segment.

**Recommendation 4.4.** The UK should maintain its involvement with EPTA and IPTA. STFC should seek to provide a modest investment to PTAs as this could represent a significant stake for the UK in nano-hertz gravitational wave astronomy.

There has been limited STFC support for UK involvement in EPTA. The EPTA<sup>30</sup> involves Jodrell Bank. Some UK researchers are also involved with the NANOGrav consortium<sup>31</sup>.

## 7 Evolution of the Current STFC GW Programme

### 7.1 Remit and Background

STFC published a clarification of support for gravitational-wave research in late 2023<sup>32</sup>, which details the interface and funding responsibilities between STFC's GW Consolidated Grant Panel and Astronomy Grants Panel, and the UK Space Agency.

Exploitation, R&D, and Operations activities, with a specific focus on activities within the LVK, are currently supported through the Gravitational Waves Consolidated Grant funding scheme, recently completed for awards starting in October 2025.

It is anticipated that the remainder of GW activities should seek support through the Astronomy Grants Panel, for small and large awards. Detector R&D and construction in support of space-based gravitational waves programmes sits under the management and responsibility of the UK Space Agency.

### 7.2 The UK Funding Environment

STFC Consolidated Grant Funding is shown in Appendix F, which contains a table that outlines the timing of current dedicated funding for Gravitational Waves programmes and details of uncommitted UKRI and STFC funding programmes, which present potential opportunities to secure additional funding.

Ongoing support for GW consolidated grants is anticipated, with the most recent 3-year programme awards spanning October 2025-2028, after which 4-year grant rounds are anticipated. The Astronomy large and small awards schemes are run annually; however, the large awards are a two-stage process and require progress through an outline phase, which introduces a lead-time for application preparation. The 2023

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<sup>30</sup> See EPTA at <https://www.epta.eu.org/>

<sup>31</sup> See NANOGrav at <https://nanograv.org/collaboration/partner-institutions>

<sup>32</sup> [ukri.org/wp-content/uploads/2023/09/STFC-14092023-Gravitational-Waves-Remit-2023-August-Final.pdf](https://ukri.org/wp-content/uploads/2023/09/STFC-14092023-Gravitational-Waves-Remit-2023-August-Final.pdf)

[Astronomy small awards](#) commits £12.7m per annum to 84 projects. The proportion of funded GW related projects is unclear.

It should be noted that the current Consolidated grant scheme has a single application point for all UK GW groups. This makes the community uniquely vulnerable to fluctuations in funding levels and introduces an unacceptable level of risk to the programme. This danger has been demonstrated by the most recent grant round, where an unanticipated reduction in funding has left many groups with PDRA positions funded for only 18 months over the period 2025-28. This will lead to potential loss of UK expertise and leadership in some core areas of gravitational wave R&D, at a critical time of growth of the field.

The introduction of staggered applications across the community would help address the risks from short-term fluctuations and should be considered when the remit of the Consolidated scheme is revisited.

From 2022 to 2025, the UKRI Infrastructure Fund is investing a total of £481 million into a portfolio of research and innovation infrastructure investments. STFC has been successful in securing funding from this opportunity and is currently supporting a preliminary award project “Next-gen GW: the next generation gravitational wave infrastructure”. This £8m project spans 4 years, starting in 2023. The full Infrastructure Fund presents an opportunity to follow-up on this preliminary award, and other large infrastructure opportunities; however, it has a lengthy lead-time, which can cause complications with international schedule alignment. The preliminary rounds are coordinated every year and the full rounds every other year. Subject to approval within STFC, applications for the fourth full round are anticipated to be submitted in 2025 to unlock funding from 2027 onwards, and applications for the fifth full round are anticipated in 2027.

It should be noted that any future funding opportunities described above are subject to spending review settlements and funding commitments from UKRI and STFC.

As recently discussed<sup>33</sup> by the UKRI-STFC CEO, Michele Dougherty, the spending review settlement for 2025/26 has created significant pressures and calls on STFC’s budget, already impacting the awards of the Gravitational Waves Consolidated Grant programme and it is understood that UKRI has submitted a flat-real bid for the next spending review, covering the period 2026/27-2029/30.

The recommendations in this report have been developed with an understanding of the requirements needed to support the continued world-leading success and growth of the gravitational-wave community in the UK, the delivery of these will be dependent upon the prioritisation of gravitational waves.

## 7.3 Community Evolution

STFC funding from 2016-2024 showed a growth in dedicated funding to gravitational waves through the consolidated grant programme. At the same time, there has been a growth in the size of the UK community engaged in the LVK GW programme, with an increase in both the number of institutions and participants. As an example metric,

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<sup>33</sup> See [presentation](#) at the April 2025 STFC Update at the APP and HEPP Town Hall

STFC tracks the payments of author fees; these have increased from 61 participants in 2020 to 161 participants in 2024.

Through the latest GW consolidated grant round (2021) ~33% of the total request from the UK community was funded by STFC. It is anticipated that a similar funding success rate will be achieved with the 2024 round.

A number of European countries have seen a significant growth in their support of GW science and facility development. In Italy there is a sizeable community and support especially in the context of the next generation ET project. Here significant funding (>€100M) is already supporting development studies for ET, with analysis and feasibility for the Sardinia site being evaluated<sup>34</sup>. In Germany the dedicated gravitational physics institute – the Albert Einstein Institute<sup>35</sup> – plays a key role in their GW science development. There is no equivalent GW focused research institute in the UK.

### 7.3.1 UK Science Productivity Metrics

An initial survey of growth of science papers covering the GW area was made.

The query<sup>36</sup> of Scopus of GW papers published globally (Figure 3) shows a sharp increase year on year since 2013. For comparison, a query of papers based on ESA space missions<sup>37</sup> (Figure 4) shows a sharp increase for Gaia based science reflecting the richness of its key data releases in 2018, 2020, and 2022/2023. However, in general there has only been a slow increase in the underlying paper publication rate from other missions. The increase may reflect the modest growth of the astronomical community over the last 20 years.

There is a clear increase in the publications in the GW area, with the growth being significant since the first observational detections of GW sources in 2015.

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<sup>34</sup> See The Italian ET site at <https://www.einstein-telescope.it/en/et-in-italy/>

<sup>35</sup> See AEI website at <https://www.aei.mpg.de/>

<sup>36</sup> Query at [www.scopus.com](http://www.scopus.com) with: TITLE ("gravitational wave " OR ligo OR virgo) AND KEY (" gravitational wave " OR ligo OR virgo) AND PUBYEAR > 2004

<sup>37</sup> See De Marchi and Parmer (2024) <https://arxiv.org/html/2402.12818v1> for a more in depth analysis of science publication rates from ESA missions for the period up to 2021.

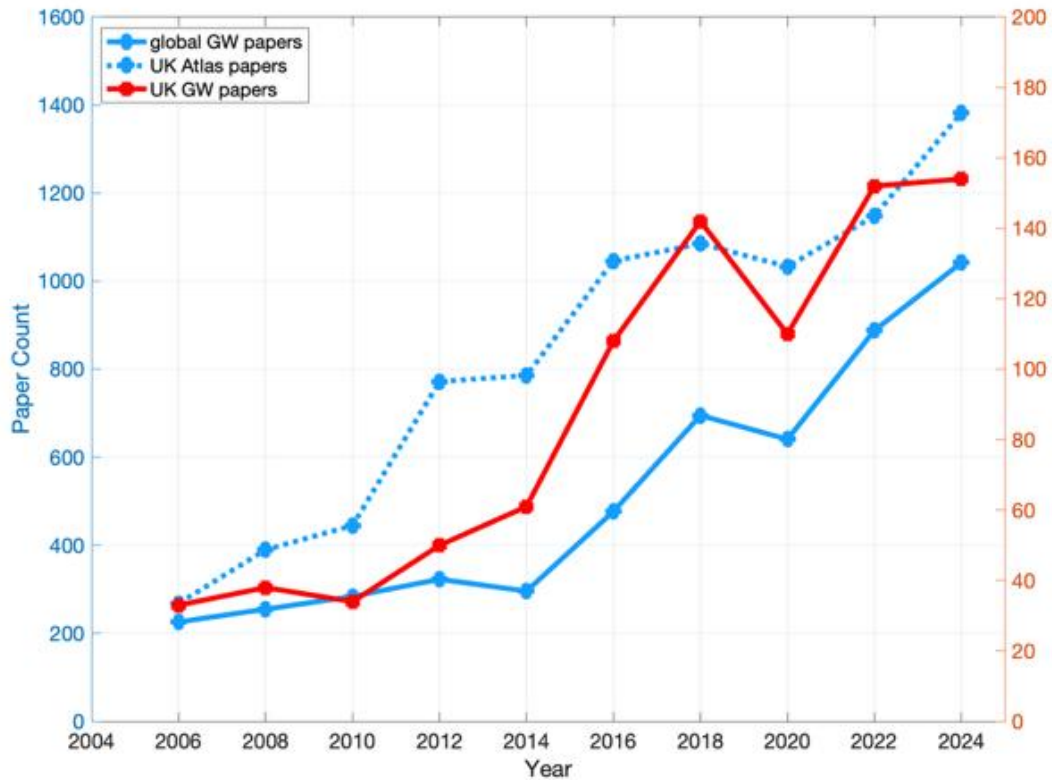


Figure 3: Scopus query returns for publications for the period 2004 to 2024. Solid blue: GW papers (all types) published globally, showing a roughly a 5x increase in publications per year with an increase around 2014/15. Red: GW papers (all types) published by UK-based authors (note different axis scale, in orange and on the right-hand-side of the plot). Dashed blue: UK authored ATLAS papers. The data but averaged over two-year bins.

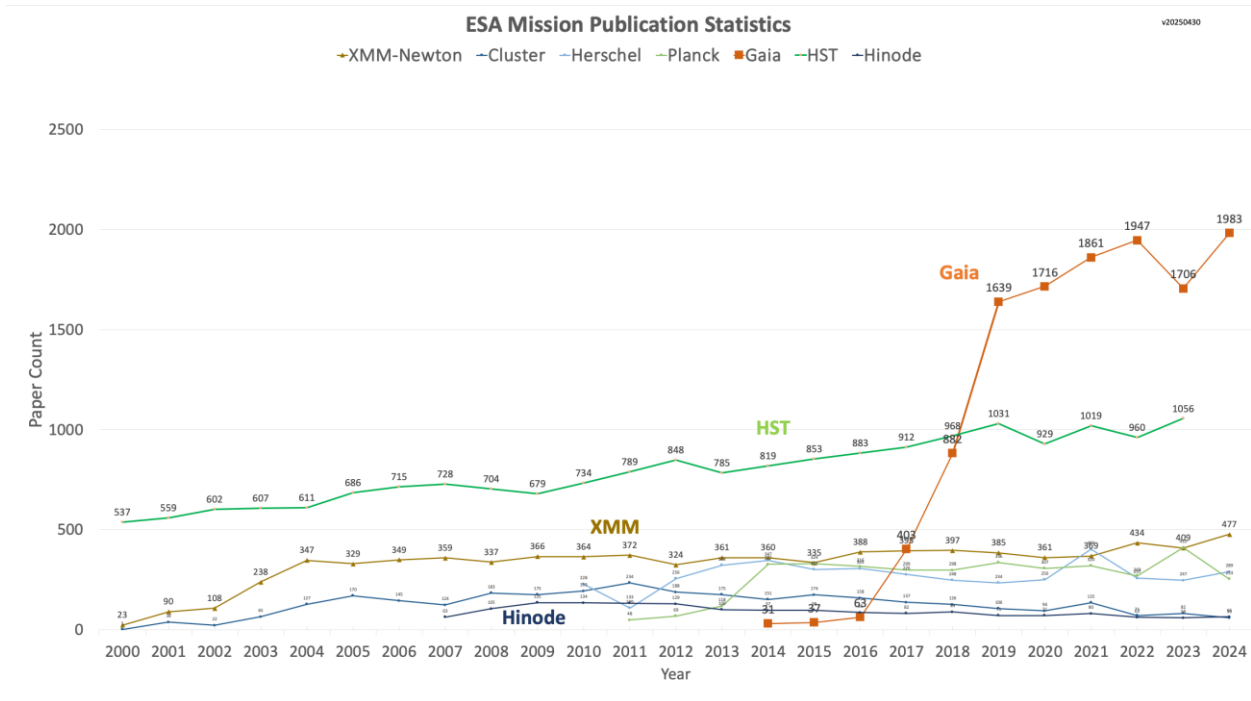


Figure 4: Peer reviewed paper counts from a selection of ESA’s most productive missions for the period 2000 to 2024. Most mission science publication rates have only increased slowly with time, perhaps reflecting the underlying growth of the science community. Gaia has seen the significant uptick in publications, this linked to the increasing richness of its data releases. (Source: De Marchi and Parmer, 2024, <https://arxiv.org/abs/2402.12818> and ESA mission publication libraries at <https://www.cosmos.esa.int/web/guest/mission-publications> )

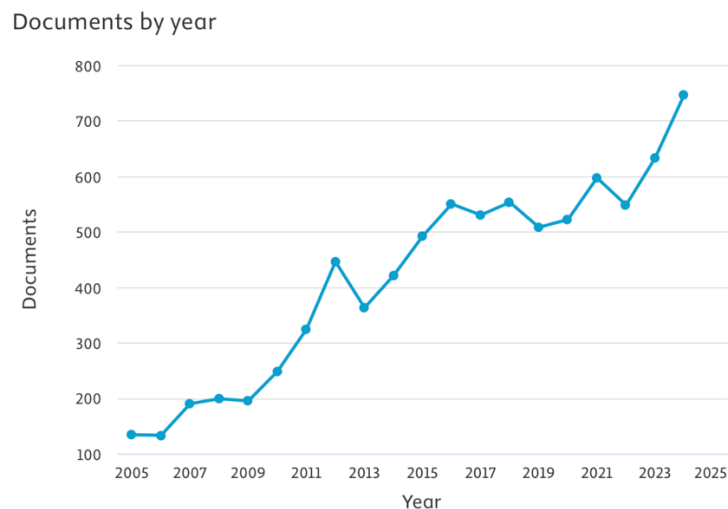


Figure 5: Scopus query TITLE-ABS-KEY-AUTH ( atlas ) AND ( LIMIT-TO ( AFFILCOUNTRY , "United Kingdom" ) ) returning UK authored ATLAS papers

The publication rate of GW papers with UK involvement has also increased as shown in Figure 3, with only a slight dip in the COVID period. As one comparison, Figure 5 gives an indication of UK paper return from ATLAS. The paper rate from ATLAS is approximately 7–8 times higher, reflecting the higher UK investment in exploitation and upgrades over the past two decades, in addition to the substantial earlier contribution to the construction of ATLAS, and to the CERN subscription. When focusing only on more recent exploitation and upgrade funding, the relative level of investment in gravitational wave science is not dramatically lower, and in this narrower context the two areas appear broadly comparable in terms of value for money. It should also be noted that paper counts alone do not capture the full range or impact of scientific return, and with upgrades such as LIGO A+ the GW programme is expected to deliver significantly more in the near future. ~~Figure 5 gives an indication of UK paper return from ATLAS. The paper rate from ATLAS is approximately 7–8 times higher, but this from a significantly higher UK investment. In this context, GW science is in the same value for money regime, and this before the expected science return from recent investment in upgrades to current GW facilities such as LIGO A+.~~

## 8 GW Facilities Under Development

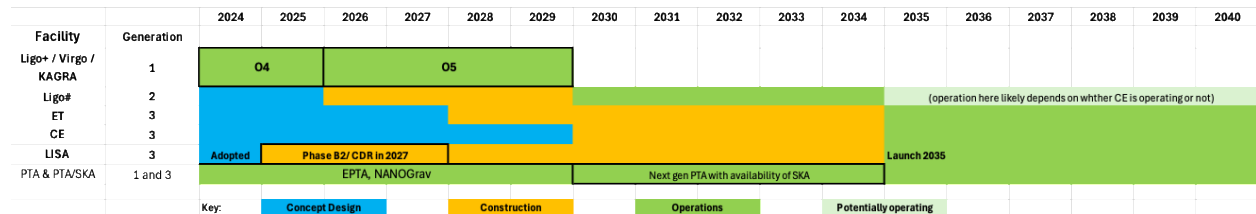


Figure 6: Overview of GW next generation timelines. Note that the development of next generation PTA depends on the availability of SKA, which is funded independently outwith of the other GW facilities discussed here.

The following sections include upcoming developments for next generation GW facilities in the coming decade. These cover the high to low frequency domains. Hitherto, UK STFC GW specific investment has focused on the high frequency domain. Investment in lower frequency facilities, e.g. PTAs and CMB experiments, has not been driven primarily by GW science considerations, but there has been key support for relevant data analysis efforts. Figure 6 gives an overview of timelines for the major new projects. It is clear that in the high frequency domain the key date is in the mid 2030's when CE and or ET are targeting commencement of operations (dependent on funding decisions required in the near term). The timeline for LISA is more secure in that the mission has now been formally adopted by ESA with a launch date in 2035.

In the following subsections each facility is discussed.

### 8.1 Upgrades to A+ (post O5 upgrades: A#)

The LIGO Scientific Collaboration is currently looking at ways to improve detector sensitivity in the gap between the end of O5 (>2030) and the start of data taking with 3rd generation instruments (>2035). This post O5 upgrade is being developed as the A# configuration.

The current baseline includes a quadruple pendulum suspension with 100 kg optics and suspension fibres operating at stresses up to a factor x3 (2.5 GPa) higher than aLIGO. Improved mirror coatings with lower mechanical loss and absorption will be used, allowing the arm cavity power to be increased to around 1.5MW. Combined with 10dB of squeezed light injection, it is anticipated that event rates for binary neutron stars and neutron star black hole binaries will be 4x the A+ rate, and binary black holes will be 3x the A+ rate. Low frequency improvements, via UK-led upgrades of the suspensions and seismic isolation system, will allow 6 minutes of early warning for a binary neutron star merger with SNR 8 at the distance of GW170817.

In addition to the enhanced astrophysical data, the A# upgrade is on the critical technology path for proving the 3G technology, prior to installation in CE and ET.

## 8.2 Cosmic Explorer

Cosmic Explorer (CE)<sup>38</sup> is a next-generation (3rd generation) observatory concept designed to significantly enhance and refine gravitational-wave observations of the cosmos. It represents the planned U.S. contribution to the global network of next-generation ground-based gravitational-wave observatories. The design concept for Cosmic Explorer includes two facilities, one with dimensions of 40 km on a side and the other 20 km on a side, each housing a single L-shaped detector. The technology focusses on an upscaling of the proven aLIGO technology including 1064nm laser light, active/passive seismic isolation systems and heavy (400kg) fused silica optics.

In conjunction with other future detectors, such as LISA and the Einstein Telescope, Cosmic Explorer will have the capability to investigate the nature of the densest matter in the universe, uncover the populations of binary black holes and neutron stars across cosmic time, provide an independent method for probing the history of the universe's expansion, explore the characteristics of warped spacetime with unprecedented accuracy, and enhance our understanding of the life cycles of massive stars, their deaths, and the formation of the matter observed today.

Sources that are barely detectable by Advanced LIGO, Advanced Virgo, and KAGRA will be resolved with remarkable precision. This dramatic increase in the number of detected sources — potentially up to millions annually — and the high fidelity of observations will have far-reaching implications for physics and astronomy. By probing deep into the gravitational-wave sky, Cosmic Explorer will offer a unique opportunity for new and unforeseen discoveries.

The recent (March 2024) report from the NSF MPS AC Subcommittee on Next-Generation Gravitational-Wave Detector Concepts recommended an aggressive timeline for CE development, with construction in the period 2030-2035 and operations from 2035.

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<sup>38</sup> Punturo, M., et al. The Einstein Telescope: A third-generation gravitational wave observatory. *Class. Quant. Grav.*, 2010, <https://iopscience.iop.org/article/10.1088/0264-9381/27/19/194002>

## 8.3 Einstein Telescope

The Einstein Telescope (ET)<sup>39</sup> is a proposed third-generation gravitational wave (GW) observatory in Europe. It aims to build on the achievements of current second-generation laser-interferometric detectors, such as Advanced Virgo and Advanced LIGO, whose groundbreaking discoveries of merging black holes and neutron stars over the past ten years have initiated a new era in gravitational-wave astronomy.

The ET, operating as a dual cold/warm detector, will improve sensitivity by extending the interferometer's arm length to 10 km and integrating various advanced technologies. These enhancements include a cryogenic system designed to cool essential optical components to 10-20 K, novel quantum technologies to minimise fluctuations in light, an extensive array of infrastructural and active noise mitigation techniques to reduce environmental disturbances, and heavy fused silica test masses to minimise radiation pressure noise. The ET will have a detection range that is ten times greater than that of the Advanced LIGO (aLIGO) across a broad frequency spectrum from 2Hz - several kHz. It will serve as a long-term research facility with infrastructure designed to support scientific investigations for several decades.

The ET has been included in the latest ESFRI roadmap and featured in the UK Infrastructure Roadmap. The current schedule (see Figure 7), as provided in the Euregio Meuse-Rhine site candidacy bid, anticipates site selection for the ET by 2026, with installation and commissioning completed by 2032 and the commencement of observations in 2035.

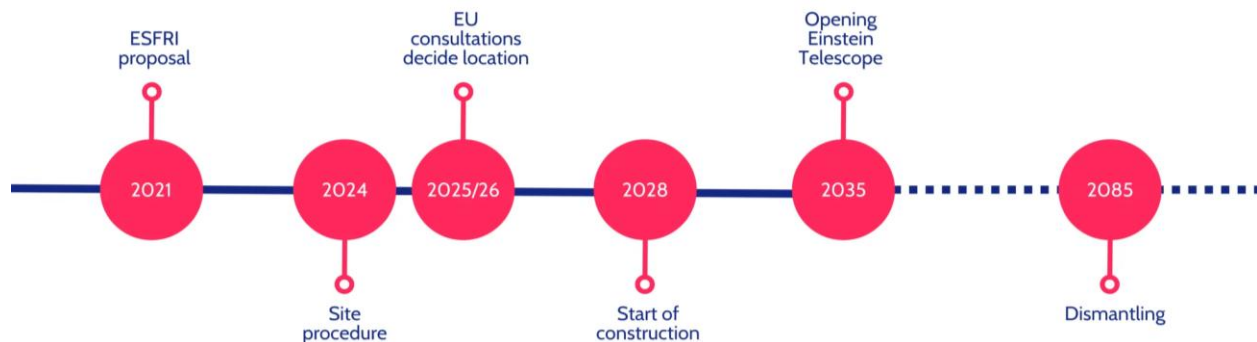


Figure 7: Current timeline for ET development (see <https://www.einsteintelelescope-emr.eu/en/organisation-and-timeline/> ) from the Euregio Meuse-Rhine site candidacy bid.

The ET [Blue Book](#)<sup>40</sup> provides a comprehensive review of ET's scientific promise. This includes many areas of UK strength, such as probing the astrophysical population of black holes and neutron stars: ET will detect every NS/BH binary merger back to the Big

<sup>39</sup> Evans, M., et al. A Horizon Study for Cosmic Explorer: Science, Observatories, and Community, Arxiv, 2021, <https://doi.org/10.48550/arXiv.2109.09882>

<sup>40</sup> <https://arxiv.org/abs/2503.12263>

Bang, of order  $10^5$  events per year. Tens to hundreds of NS/NS and NS/BH binaries per year will also be visible to electromagnetic observatories; multi-messenger observations of these systems will yield groundbreaking advances in our understanding of dense hadronic matter and the QCD phase diagram. The UK community also has world-leading expertise crucial to the development of the precision waveforms needed by ET for full exploitation of these observations, for example in gravitational self-force calculations and phenomenological models.

## 8.4 LISA

The Laser Interferometer Space Antenna (LISA) is the ESA “L-class” mission (with contributions from NASA) selected for the “Gravitational Universe” theme.

### 8.4.1 LISA Pathfinder

ESA’s LISA Pathfinder was a crucial technology demonstrator, to test the viability of core technologies needed for LISA. LISA Pathfinder was launched in December 2015 with the aim to test in-flight the concept of low-frequency GW detection. The spacecraft placed two test masses in a near-perfect gravitational free-fall, and controlled and measured their motion with unprecedented accuracy in a technique known as “drag-free control”, whereby the position of one of the proof masses was sensed via a capacitive readout, and thrusters were used to ensure the spacecraft followed the test mass.

Key objectives of the mission were:

- to demonstrate, in a space environment, that free-falling bodies follow geodesics, by more than two orders of magnitude better than any past, present or planned mission;
- to demonstrate drag-free and attitude control in a spacecraft with two free proof masses;
- to test feasibility of laser interferometry with picometre resolution at low frequency, approaching  $10^{-12}$  m Hz<sup>-1/2</sup> in the frequency band 1–30 mHz;
- to test the endurance of the different instruments and hardware in the space environment.

The mission finished on 30 June 2017, having successfully demonstrated the technology to build ESA's future gravitational wave observatory in space. Indeed, the mission performance demonstrated would allow for a space-based GW observatory with a sensitivity close to what was originally foreseen for LISA<sup>41</sup>.

### 8.4.2 The LISA Mission

LISA will consist of three satellites trailing the Earth in its orbit. The satellites will form an equilateral triangle, with each satellite separated by the other 2 by approximately 2.5 million kilometres. Two test masses will be situated in each satellite and the separation

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<sup>41</sup> Armano, M., *et al.*, “Sub-Femto-*g* Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results”, *Phys. Rev. Lett.* 116, 231101 (2016) DOI: <https://doi.org/10.1103/PhysRevLett.116.231101>

between them will be sensed by laser links, forming an interferometer with sensitivity to gravitational waves in the frequency range 0.1mHz to 1Hz.

This frequency range, inaccessible from the ground, will allow the observation of numerous new sources, leading to significant advances in astronomy, cosmology and fundamental physics. LISA's primary science goals include:

- Studying the formation and evolution of compact binary stars in the Milky Way.
- Tracing the origin, growth and merger history of massive black holes across cosmic times.
- Probing the dynamics of dense nuclear clusters using extreme mass-ratio inspirals
- Understanding the astrophysics of stellar origin black holes
- Exploring the fundamental nature of gravity and black holes.
- Probing the expansion rate of the Universe
- Searching for stochastic gravitational wave background and understanding their implications for the early Universe
- Searching for gravitational-wave bursts and unforeseen sources.

The UKSA currently provides support to the UK's involvement in the core LISA mission through two elements. First, the design of the six optical benches, a core element of the laser metrology. Second, the UK's contribution to LISA's science ground segment, taking the raw data from the LISA satellite and producing a catalogue of sources. However, the UKSA does not fund science exploitation, and the UK's interest in LISA science exploitation is significant. Currently ~170 members of the LISA consortium (almost 10% of the total membership) are based in the UK.

## 8.5 Pulsar Timing Projects

Pulsar Timing Arrays (PTAs) use millisecond pulsars as precise clocks to detect ultra-low-frequency gravitational waves, with the UK playing a leading role in efforts such as EPTA, IPTA, and the MeerKAT PTA, which will become part of the SKA Observatory. In June 2023, several PTAs—including those with UK involvement—reported tentative evidence for a stochastic gravitational wave background, likely from supermassive black hole binaries, with MeerKAT PTA later publishing consistent results. Future objectives include refining the GW background detection, characterising its properties, and achieving the first direct observation of a supermassive black hole binary. Sensitivity improvements are anticipated from ongoing PTA data integration and the inclusion of MeerKAT observations, with transformative potential as SKAO becomes operational. Despite the UK's central role, limited STFC support constrains efforts to fully exploit these opportunities.

In the context of GW science, PTA related funding has mainly focussed on support for the relevant data analysis effort. Investment has also been made into several of the participating radio facilities that form the PTA networks. For instance, the EPTA includes Jodrell Bank amongst its telescopes, which has been STFC funded.

## 8.6 Low Frequency Experiments

The UK has a long tradition of research – both theoretical and observational – into the cosmic microwave background (CMB). Recent strategic investment in the Simons Observatory ensures that this effort is continued into the next decade. Specifically, the Simons collaboration involves six UK groups working to understand the nature of the Universe a fraction of a second after the Big Bang. Accurate measurements of the CMB may unveil the presence of the so-called B-modes, representing ultra-low frequency gravitational waves. Such a detection would be truly groundbreaking as it would shed light on anisotropies of the Universe at birth. However, current estimates suggest that this will be a challenge. The main objectives of the Simons observations are to test models for inflation and understand the nature of dark matter and dark energy. An observation of a gravitational-wave signal would be an added bonus.

## **8.7 Matter-Wave GW Detectors**

Atom interferometers would operate in the deci-Hertz frequency range (0.1–1 Hz), bridging the detection gap between ground-based laser interferometers like LIGO/Virgo/KAGRA and space-based detectors like LISA. By enabling observations in this intermediate band, they contribute to comprehensive multi-waveband GW astronomy.

Sensitivity to GWs can be achieved through matter-wave interference patterns, with large momentum transfer techniques enhancing detection capabilities. Gradiometer configurations, using interferometers separated by hundreds of metres to kilometres, provide the strain sensitivity required for GW detection while suppressing common-mode noise through differential measurements.

Several experimental programmes, including MAGIS-100 in the US, AION in the UK, MIGA in France, and ZAIGA in China, are advancing key technologies. Near-term pathfinder experiments at the 10–100 metre scale will inform the design of kilometre-scale detectors, with the aim of achieving GW detection sensitivity by the mid-2030s. Although, it is understood that these aims may be perceived to be optimistic.

# **9 UK Capability and Capacity for Participation**

## **9.1 GW Theory Development**

The UK has significant expertise in modelling the dynamics of (near-equal mass) compact object binaries. UK-based researchers have been instrumental in developing numerical relativity techniques and analytic approximations that accurately describe the inspiral, merger, and ringdown phases of binary systems. This theoretical groundwork is essential for constructing gravitational wave templates used in matched filtering techniques to detect and analyse signals in gravitational wave experiments.

UK researchers are pioneering the use of statistical and machine learning methods to identify and characterize GW sources, a critical capability as the field advances towards multi-messenger astronomy. These techniques improve the detection and analysis of weak signals, enable real-time alerts for follow-up observations, and help uncover the astrophysical processes behind these events.

Beyond compact binary mergers, the UK has played a leading role in the search for continuous gravitational waves, a major scientific motivation behind the construction of LIGO. These signals, expected from rapidly rotating neutron stars, provide a unique probe of dense matter physics and neutron star interiors. With current instruments reaching sensitivities where the first detections may be imminent—supported by theoretical modelling and population studies—a sustained UK effort in this area will be key to leading the exploration of this new discovery space.

Moreover, the UK is a global leader in self-force calculations, which are crucial for understanding the motion of small compact objects, such as stellar-mass black holes, in the strong gravitational fields of supermassive black holes. These calculations involve accounting for the gravitational back-reaction effects that the small object's own field exerts on its motion, providing highly accurate waveforms for extreme mass-ratio inspirals (EMRIs). EMRIs are expected to be key sources for the future space-based LISA mission. Researchers in the UK are pioneering the development of sophisticated computational techniques and analytical methods for self-force calculations, contributing significantly to our theoretical understanding of these complex systems. Research in this area is typically pioneered by individuals or small groups of scientists active in particle (astro-)physics or cosmology.

In addition, UK theorists are at the forefront of exploring exotic sources of gravitational waves, such as first order phase transitions in the early Universe, cosmic string networks, and modifications to general relativity. These theoretical investigations are vital for broadening the scope of gravitational wave astronomy and for testing the fundamental laws of physics under extreme conditions. The UK's capacity in this area integrates expertise from cosmology, high-energy physics, and astrophysics, and this area is typically pursued by researchers within groups covered by Particle Physics Theory Consolidated Grants.

## **9.2 GW Instrumentation Technology**

The UK is internationally respected as a provider of hardware for the ground-based detector network. UK groups have previously designed, prototyped and commissioned the 40kg core optics suspension and the beam splitter suspension for aLIGO, developed under an STFC capital award. The fused silica suspensions were critical for improving the low frequency noise of the detectors, enabling the first detection of gravitational waves in 2015

The planned aLIGO A+ upgrade will deliver an improvement in event rate of up to x7. Enabled via an STFC PPRP award, the UK is delivering core components including a larger beamsplitter suspension to reduce clipping losses, optimised and upgraded fused silica suspensions, a balanced homodyne readout and a fused silica output mode cleaner.

The UK is uniquely placed to pioneer the technology required for future detectors including post O5 upgrades to A+ (e.g. LIGO A#), LIGO India, and third generation detectors such as the Einstein Telescope and Cosmic Explorer. Funding support for these activities falls into the following remit;

- R&D for the current LIGO programme, which supports the continuous improvement, optimisation and development of the existing LIGO detectors is supported via the consolidated grant programme
- R&D for 3<sup>rd</sup> generation detectors is currently supported under a UKRI preliminary phase Infrastructure Proposal (2023-2026). Longer term, there is an opportunity for the UK to provide a large-scale contribution to the full project infrastructure costs, securing UK leadership in scientific exploitation.

Cosmic Explorer (CE) and Einstein Telescope (ET) are now entering a design phase which will detail the technologies required to enhance strain sensitivity by an order of magnitude, compared to current detectors. This step change in performance requires extremely stringent requirements on the technological solutions for the instruments in the areas of suspension design, inertial seismic isolation, optical coatings and interferometer sensing and control.

The UK ambition will be to build on our proven expertise in these technological areas to develop conceptual designs for the relevant subsystems for CE and ET. The currently running “NextGen GW project” (October 2023 to September 2026) will enable the UK to co-develop the Conceptual Design of the next generation of gravitational-wave observatory infrastructure, with the aim to de-risk key technological solutions for the next generation GW detector network. Longer term, the ambition will be to consolidate the UK’s leading position in GW hardware development, positioning us to make a major capital contribution to a third-generation network.

### 9.3 GW Related Computation

The unprecedented sensitivity of upcoming instruments means that gravitational-wave astronomy will become theory limited unless progress is also made on a range of theory issues. Notably, the development of precise waveform templates relies on numerical simulation carried out on the largest available computers. UK groups have leading expertise on simulating dynamical problems in relativistic gravity (from problems involving black holes and neutron stars, to cosmology, more exotic objects and also alternative gravity scenarios). UK groups have established international leadership in code development on high-performance computing systems and are now building towards the transition to exascale computing. The community involve representatives of a broad range of simulation technology, from the Einstein Toolkit, GRTeclyn/GRChombo, MHDuet/Simflowny and the newly developed code ExaGRyPE. Expected developments include extending gri-based codes to GPU support (e.g., AMReX), and the aim to establish a common benchmarking and data pre- and postprocessing ecosystem, essential for reproducible and reliable science.

Another computational challenge arises from the mere wealth of signals expected in next-generation instruments. The detection of tens of thousands of compact binary mergers (black holes and neutron stars) each year with e.g. LISA, ET and CE will reshape our understanding of astrophysical populations going back to the formation of the first stars in the Universe. However, to make progress we need to develop appropriate digital infrastructure. The cost of algorithms to search for and analyse detection candidates scales with the number of events and the signal-to-noise ratio, both of which will be dramatically larger for future instruments. Current data analysis

pipelines and algorithms are poorly suited to the anticipated computational demand, so it is imperative that the community develops new tools and novel data analysis algorithms. This effort must be data-science driven, likely drawing on cutting edge artificial intelligence technology and tools suited to big data. New machine learning tools, again amenable to GPU technology, are expected to improve the accuracy and efficiency of the analyses but the required development will require a focussed effort. The UK has provided one of the largest contributions to GW computing over the past decade, through provision of computing resources at Cardiff and research software engineering support at Cardiff and Portsmouth. This provision is widely recognized in the LVK. Continued support for large scale computing, the staff to deliver this computing, and research software engineers to ensure that we are effectively using it, both for modelling simulations and data analysis efforts, is an absolute requirement as we move to the next-generation era.

## 9.4 GW Follow-Up

The UK has extensive expertise in gravitational-wave follow-up. From the gravitational-wave astronomy side the UK plays a leading role in operating one of the toolkits for rapidly identifying and localizing compact binary mergers in gravitational-wave data. In addition, the UK has numerous experts working on producing improved skymaps using Bayesian inference within roughly an hour of a transient being observed. On the electromagnetic astronomy side, the UK has extensive involvement in transient astronomy with numerous centres of excellence. There is significant involvement in projects focused on electromagnetic follow up of gravitational-wave events, including leading the GOTO project, comprising almost 25% of the staff effort towards ENGRAVE and having significant contributions towards other projects, such as BlackGEM.

UK researchers already made significant contributions towards the first gravitational wave multi-messenger event (GW170817) and are well positioned to make similarly significant contributions to future missions.

## 9.5 Future GW Impact

The field of gravitational wave detection aligns strongly to the [UKRI Strategy \(2022-2027\)](#) and [STFC Strategic Delivery Plan \(2022-2025\)](#). Through investment in “**World-class people**”, the UK has developed a skilled workforce distributed across the UK, who have established recognised leadership roles within international programmes, and are considered a partner of choice for current and future programmes of activity. Through “**World-class innovation**”, “**World-class ideas**” and “**World-class impacts**”, the UK investment into gravitational waves ensures both a continuous generation of research and technology, with applications providing benefits across sectors and disciplines, and a continuous harnessing of this cutting-edge technology to support the exploration fundamental knowledge and our understanding of our universe.

In the following sections the impact potential, along with some challenges, from GW investment in terms of increasing the UK skill base, economic activity, and societal and cultural richness is discussed.

### 9.5.1 People

Over the past decade, the UK's gravitational wave science community has experienced notable growth. A number of UK Institutions have expanded their research groups, integrating expertise in astrophysics, data analysis, and detector engineering. This expansion is evidenced by the increasing number of researchers, international leadership roles (more below) and publications (as described above). Moreover, a number of new GW groups have been established, which have made valuable contributions across a range of areas. These smaller groups face significant challenges in gaining visibility, securing funding, and establishing long-term stability in a competitive research landscape. Addressing these challenges is essential for maintaining the UK's leadership in GW science, and targeted support from UKRI will be crucial in ensuring that these newer groups can thrive and continue to contribute to the field's growth. The increasing number of researchers, international leadership roles (more below), and publications (as described above) underscore the strength of the UK community, but sustained investment will be needed to fully realise its potential.

Based on the 2024 GW Community Questionnaire described in subsection 4.3.2 (see also appendix E), the UK gravitational wave science community has grown significantly across all key categories of personnel. The number of staff members has increased, with many groups now reporting larger teams compared to 2020. A modest growth in permanent researchers has been complemented by a marked rise in researchers on fixed-term contracts. The most substantial growth has been observed among students, whose numbers have risen sharply. While this growth highlights the field's ability to attract new talent, it raises concerns about retention. The modest increase in permanent researchers suggests limited opportunities for long-term career progression, which could lead to a loss of expertise as individuals leave the field for more stable roles elsewhere, including abroad. Ensuring sustainable growth will require greater focus on creating permanent positions to retain skilled researchers and capitalize on the investment in training and development. Without addressing this challenge, the UK risks losing talented individuals critical to its continued leadership in gravitational wave science, particularly in next-generation initiatives like the Einstein Telescope and LISA.

The UK plays a significant leadership role in international GW collaborations, with researchers holding prominent positions in major projects and consortia. For example, in the LSC, the head of the Observational Science Division is affiliated with Cardiff University, and UK-based researchers head several working groups. The UK is represented in the LISA executive, the board, and the LISA science team 2024-2027.

In GW (doctoral) training programs students build expertise in both theoretical and practical aspects of the field. Additionally, research training programs provide early-career researchers with opportunities to develop specialised skills which are highly transferable to other sectors, including finance, artificial intelligence, and quantum technologies. Collaborative projects with industry in areas such as optics, quantum sensors, and advanced manufacturing (more below) also create direct career pathways outside of academia.

## 9.5.2 Industry

In a field that is constantly pushing the technological boundaries of data analysis and experimental techniques, it is not surprising that there are many examples of translating the cutting-edge R&D into other sectors and industry. The UK has been actively engaged in translating and exploiting GW-related technologies for commercial and societal benefit within the UK, and beyond, including developing countries. Below we highlight some selected cases.

### Optical Sensing

Working with Birmingham Enterprise, the Birmingham gravitational wave group has commercialised sensors and control systems, which have been sold ( $\approx$  £400k) to Beijing Normal University, Liege University, and Maastricht University. The group are working with SmarAct GmbH on new interferometric position sensors for fundamental physics experiments, including LIGO. Expertise in position sensing and inertial isolation of active platforms and cryostats has generated a new collaboration with the Universities of Nottingham, Newcastle, and Heidelberg on experimental studies of quantum vortices in helium II films, with the potential of commercial applications of inertial sensors in complex mechanical systems. Two Quantum Technology for Fundamental Physics projects have stemmed from this gravitational wave programme. The Quantum-enhanced Interferometry for New Physics has led to a novel dark-matter detector concept; and the Birmingham detector has now achieved world-leading sensitivity by more than an order of magnitude in axion-photon interaction.

The group has proposed a concept for an axion "DarkGEO" detector at the GEO600 facility which could reach a sensitivity unmatched by any other competitor, and a novel concept of photon counting interferometry for axion searches. The Birmingham-led network of clocks for measuring the stability of fundamental constants exploits LIGO vibration isolation technology with cryogenic solutions for high-precision spectroscopy.

**MEMS Gravimetry:** Inspired by the R&D on monolithic suspensions for aLIGO, the University of Glasgow has been pioneering the development of a new type of MicroElectroMechanicalSensor (MEMS). The "Wee-g" MEMS gravimeter is the world's first MEMS gravimeter, with sufficient long-term stability to undertake gravity surveying in the fields of defence & security, environmental monitoring and civil engineering. Supported via the EPSRC National Quantum Technology Programme, H2020 and STFC, the team have secured >£5M funding since 2015, engaging with companies including QinetiQ, DSTL, Ministry of Defence, RSK, BP, Schlumberger and Metatek. There are currently four devices operating on active volcanoes (three on Mt Etna, Italy and one on Poas, Costa Rica) and a remote water table monitoring station in Shanmoy, Ireland. The device is a mature field instrument, having undertaken field surveys in six countries, and a spinout company is being formed in 2024 to commercialise the technology.

**Coating Technology:** In May 2020, the National Manufacturing Institute Scotland (NMIS) approved £2M initial capital investment to this consortium to establish the Extreme Performance Optical Coatings Centre (EPOC) within the Inchinnan Innovation District (by Glasgow Airport). The facility was fully established in 2022, funded by the

High Value Manufacturing Catapult and the Universities of Strathclyde, Glasgow and the West of Scotland. EPOC is an industry-facing centre to enable the transfer of coating technology from GW research into the UK Photonics sector, while providing world-leading coating deposition facilities for GW research and the potential to supply coated mirrors for future GW detectors. Some highlights to date include provision of state-of-the-art optical coatings to the Quantum Technologies for Fundamental Physics programme, provision of 689nm cavity optics to BT for their quantum clocks, testing of diamond-like carbon coatings produced from the processes developed within the GW programme for use in prosthetic heart valve leaflets.

**Novel gas sensors:** The University of the West of Scotland (UWS) has invested significantly over recent years to provide university-based state of the art facilities that can be used to enhance the UK's optical industries competitiveness, providing enhanced optical coating performance, cost reduction and development of new market applications. Novel work on plasma ion-assisted electron-beam deposition of optical coatings has enabled engagement with Helia Photonics, Orion Photonics and Umicore Coating Services, and Rochester University (US) now include university inspired coating techniques onto their large-scale optics for laser inertial fusion confinement at Lawrence Livermore & Laboratory. Recently, a UWS spinout, AlbaSense Ltd, is offering novel Microwave Plasma Assisted Sputtering (MPAS™) processes to provide low stress room-temperature processing, for the production of medical gas sensors for use during anesthesia.

**Stem Cell differentiation:** The use of laser interferometry and seismic sensing techniques have been exploited by University of Strathclyde in the discovery and development of “nanokicking”, where precise nanoscale displacements are used to control the differentiation of stem cells. The ability to grow bone from a patient's own stem cells has led to two clinical trials of surgical bone graft, for landmine survivors. The patented Nanokick bioreactor is undergoing an additional clinical study to investigate the direct application of nano-vibration to treat osteoporosis in patients with spinal injury.

**OPTOS:** application of Bayesian inference and Deep Learning techniques at University of Glasgow have been employed for artefact detection and feature recognition in Optos ophthalmoscopes. Collaborative work has explored the limits of ultra-widefield scanning laser ophthalmologic cameras, looking at new ways to improve the clarity of eye images and improve patient care. Ultimately, this has enhanced quality assurance procedures at Optos, such as creating real time monitors of quality assurance metrics and led to cost savings of approximately enabling a direct cost savings of ~US\$250k/annum for the company.

### 9.5.3 Public Outreach

UK researchers have inspired engagement across educational levels through activities such as public lectures by prominent figures in the community. Participation in events like the Royal Society [Summer Science Exhibition](#) has introduced gravitational wave science to broad audiences. School-focused initiatives include workshops where students simulate gravitational wave detection, sparking interest in STEM subjects and encouraging diversity in the field.

The following is a non-exhaustive list of examples of GW related EPO projects that are either currently ongoing or have recently taken place in the UK:

- Birmingham hosts “gwoptics.com”<sup>42</sup> which hosts a number of GW-related EPO activities and games of which SpaceTimeQuest is one popular example. In addition the Finesse program provides a simplified digital twin of a ground based observatory aiding and illustrating design decisions.
- Cardiff hosts the BlackHoleHunter online game<sup>43</sup>.
- Portsmouth hosts the Tactile Universe project<sup>44</sup>, aiming to make astronomy accessible to the visually impaired and blind community. This includes a gravitational wave module including 3D gravitational-wave models that have been effectively used across the UK.
- Gravitational-wave astronomers have utilized the GalaxyZoo citizen science platform to allow members of the public to directly contribute to research. Projects which significant UK involvement include: GravitySpy, which prompts users to classify “glitches” (transient instrumental noise artefacts in the data) by looking at time-frequency visualizations of the data. Kilonova Seekers, which asks users to classify observations made by the GOTO telescope, with the aim to detect kilonova signals.
- Numerous outreach talks (e.g. at astronomy societies), regular University outreach days and shows etc.
- Cardiff University developed educational workshops using real GW data, targeted at GCSE and A-Level physics students, allowing them to apply their knowledge in a way which reflects real-world research. The Cardiff team held these workshops with over 30 schools across the UK, and directly engaged over 970 students, with feedback demonstrating greater understanding of the topic and increased relevance of their studies to cutting-edge science.
- Teacher professional development sessions trained over 400 teachers across the UK and internationally, increasing teacher awareness of the subject and providing classroom-ready resources.
- Cardiff researchers contributed their expertise to the comic series *Ada’s Adventures in Science*. The comic uses a real-life example to tell a story about a young girl’s journey from school student to research scientist working on gravitational waves. A public Kickstarter campaign raised £7,000 to distribute 15,000 copies to schools and educators across 17 countries in five languages, with over 50% of copies going to disadvantaged pupils.
- UK universities collaborating via a LIGO India Newton-Bhabha (2017-2021) award have undertaken a wide variety of outreach activities including;
  - Glasgow researchers developed a pop-up book called “Listen to the Universe”. Taking the reader into a journey of discovering gravitational waves, Lila explains to her brother what gravitational waves are, how they

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<sup>42</sup> See <https://www.gwoptics.org/>

<sup>43</sup> See <https://blackholehunter.org/game.html>

<sup>44</sup> See <https://tactileuniverse.org/>

- originate, Einstein's theory as well as taking us to see the LIGO India site and inside a detector!
- Southampton researchers launched the book titled "A gentle wizard". The book tells the story about a young boy who meets Albert Einstein and the unexpected friendship they share. Together they explore Einstein's ideas on space, time and gravity.
  - Glasgow researchers developed the "LIGO in your hands" interferometer. A highly portable and interactive Michelson interferometer, that is ideal for demonstrating the essential parts of a gravitational wave detector and it can be used as a tool for teaching interferometry and interference, feedback and control, or even as a demonstration tool for precision measurement.
  - Southampton researchers produced outreach leaflets that show how gravitational waves are produced and how the next generation LIGO-India observatory will be able to detect these cosmic events. An English version has already been produced along with translations to Hindi and Bengali.
  - Birmingham researchers translated the Space Time Quest game into Hindi.

## 10 Key Recommendations for the STFC GW Programme

The panel have taken as input earlier reviews of the GW landscape, and also considered themes that have emerged from the summer 2024 community questionnaire that they commissioned. The questionnaire and outcomes are described in Appendix A.5 "The 2024 GW Community Questionnaire".

The following recommendations, are presented with one top level recommendation and then a set of thematic organised recommendations.

An indication of the scale of the likely funding required for each recommendation is also given, these values based on current and anticipated facility operation and development costs. For future projects (e.g. CE/ET) the values have a higher degree of uncertainty. The figures should be read as being 'order of magnitude' values only.

**1: Key:** Recognising the vital role that researchers in the UK have played in the rapid advances in Gravitational Wave (GW) research, it is essential that GW research and development is funded at a level necessary to maintain UK leadership in current and next generation GW observatories, both ground and space based.

**Narrative:** This is the meta recommendation. Build on UK strength in this rapidly expanding research area. Ground and space-based gravitational wave observatories complement each other in frequency sensitivity. Ground-based detectors are designed to detect high-frequency gravitational waves from events such as merging neutron stars or stellar-mass black holes. Space-based detectors are sensitive to lower-frequency waves, which include signals from merging supermassive black holes, compact binaries with long orbital periods, and potential primordial GW backgrounds. If only one category

is funded, critical discoveries—such as insights into massive black hole evolution or tests of general relativity across vastly different scales—would be impossible to achieve.

Below the panel highlights further key recommendations for the ground-based and space-based community, together with broader opportunities of the field.

**2: Ground-based A:** In order to ensure the maximum scientific return to the UK, funding is required to underpin UK participation in the Advanced LIGO upgrades (post A+, A#) programme, as an essential pre-requisite in preparation for the next leap in GW facilities with ET/CE. This is through consolidated group funding and capital contributions to specific development.

[Investment at the ~£12.5M /year is envisaged.]

**Narrative:** In order to maintain UK technical and science leadership it is essential that the UK continue to invest in key ground-based GW facility development in the near term.

This will ensure the vitality of the UK scientific and technical expertise base in the near term, in the period of definition of next generation facilities and early stage implementation of those facilities. The level of funding required enables UK delivery of its existing and planned commitments to the Advanced LIGO programme, to ensure the maximum science benefit to the UK from the final operational LIGO system. This final LIGO upgrade programme will enable the LIGO and LVK observational runs to reach the detection floor as limited by the LIGO arm lengths, a vital pre-cursor in advance of the deployment of next generation facilities.

**3: Ground-based B:** Funding commitments will be required in the near future to support the UK community through until a major investment decision. This will help secure UK leadership in one, or both, of the next generation GW ground facilities: either Einstein Telescope (ET) or Cosmic Explorer (CE).

[Investment at the ~£4M /year is envisaged for initial investment in ET and/or CE.]

**Narrative:** The next generation GW ground-based facilities ET and CE are planned to become operational in the mid to late 2030's. Consortium building activities are currently underway. Responsibilities within the consortia will be defined in the next three years, hence preparatory planning, consortia building and early stage design, feasibility study and potential prototyping/ modelling is now required. The UK is well positioned to take a key role in either ET or CE.

**4: Ground-based C:** A major funding investment in infrastructure and people at the ~£200M level will be required to secure a significant leadership role in CE or ET. This will require support through a specific UK Gov funding line, e.g. the UKRI Infrastructure Fund (IF). Preparatory funding should be provided to enable the generation of the IF proposal (assuming that STFC 'have' prioritised a GW IF bid for submission).

[Investment at the ~£200M level is envisaged for the UK contribution to the next generation facility, this over the construction phase. Preparatory funding at the £100K/yr level in advance of construction for IF bid generation activities such as community workshops and a proposal writing team retreat.]

**Implementation Timeline:** 2025/2026: evaluate CE or ET for decision on which should be the main focus of an IF bid. 2026/2027 prepare strong IF bid (with focus on CE and/or ET). 2027 IF bid submission. Need to consider funding the gap between 2027-2029 (IF funds are not likely to be available before 2029).

**Narrative:** Preparation funding is required in order to develop a competitive UKRI-IF proposal in order to ensure the highest quality justification for what would be a competitive funding competition. This includes community building and full case development. The indicative investment sum of ~£200M for the UK for the construction of the phase is based on the need to participate at the ~10% level within project (ET or CE). This would ensure a leading role for the UK in defining the science and project priorities for the facility. At this stage, total construction phase estimates for both next generation facilities are somewhat uncertain. However, in the case of ET, the current estimate for its construction phase is of order €2 billion<sup>45</sup>.

**5: Ground-based D:** STFC should change the scope and process of its current consolidated grant funding mechanism for Gravitational Wave research such that it supports all aspects of ground-based gravitational-wave observations, including instrumentation development, detector characterisation, data analysis and relevant theoretical modelling, for current and future generations of instruments. Specific updates to the funding mechanism should be defined by STFC taking into account detailed community feedback.

[No additional financial commitment.]

**Narrative:** Current constraints on the scope of the GW consolidated grant (which limit funding to support of LIGO/Virgo/KAGRA) will need to be relaxed to allow funding of future next-generation GW facilities. The scope should also include a wider range of development activities, such as support for theory and computational techniques that will be required to fully exploit these facilities. It is also noted that all UK GW groups currently respond to a single consolidated grant call, which introduces unnecessary risk to the system. The introduction of a staggered scheme should be considered alongside the proposed changes to the scope.

**6: Space-based A:** LISA science exploitation investment will be required from UKRI in order to ensure full UK science exploitation of the UKSA/ESA investment in the construction and operation of LISA.

[UKRI funding, to supplement that from UKSA, required at the ~£2.5M/ year level pre-launch of LISA.]

**Narrative:** ESA have recently adopted the LISA mission, and a Multi Launch Agreement (MLA) has now been signed. This commits ESA and the National Agencies to funding the development and operations of LISA, with an estimated launch in 2035. UKSA support of LISA includes participation in the LISA Ground Segment. This ensures delivery of the LISA data products. However, no funding is available to support the development of advanced data in access facilities, advanced data products (integrating

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<sup>45</sup> For construction cost estimates for ET, see <https://www.einsteintelelescope-emr.eu/en/faq/> under 'Who will pay for the Einstein Telescope?'

EM follow up data for instance), science access training workshops and so forth. Such activity, if required, would need support via STFC, potentially through a specific LISA related bid to PPRP.

**7: Space-based B:** Improve cross council coordination by convening a UKRI-STFC/UKSA GW advisory panel.

[No additional financial commitment.]

**Narrative:** In order to maximise the science opportunities offered by LISA it is essential that support is provided not only for the mission itself, but also the underpinning modelling technology and broader multi-messenger aspects. The current funding arrangement does not seem adequate in this respect. A cross-council dialogue is required to identify the best way forward.

**8: Community A:** It is essential that membership of STFC grant review panels (e.g. AGP) includes expertise in the GW data/theory area for both ground and space-based applications.

[No additional financial commitment.]

**Narrative:** The current funding arrangement for GW astronomy, with consolidated grant funding supporting only current detector activities and broader theory/simulation/multi-messenger efforts funded by (small) AGP grants will likely need to change as the field develops. In the short term, an enhanced GW expertise on all relevant review panels is required to ensure that the broader area does not suffer. This is particularly important as GW science is a rapidly developing area with connections across astronomy.

**9: Community B:** Support for other GW technologies should be kept under review (e.g. IPTA participation, Quantum technologies), with initial involvement that can expand in response to demonstrated technology advances.

[Funding required at the ~£1M/ year level to support translational activity.]

**Narrative:** Currently other GW facilities mainly probe the low frequency range targeting a more limited range of astrophysical sources (e.g. super massive black holes). Key aspects of the relevant astrophysics will be (at least partially) addressed by LISA, alongside facilities that have their own established funding mechanisms (e.g. SKA). For the latter, there has to be a clear avenue for supporting science exploitation and the development of data analysis algorithms.

**10: Community C:** Building a strong UK GW science community through the formation of a GW:UK interest group.

[Funding at the £100K/ year level.]

**Narrative:** The first steps have been taken through the generation of this report, where active community engagement has been undertaken.

- Initial input via the GW community survey
- Feedback on the draft strategy from the community at the open meeting in Jan 2025.
- In the case of no external significant funding for future GW facility involvement through e.g. IF, then a minimum investment scenario should be generated to

ensure that the UK is not locked out of GW science in the 2030s. Community engagement in determining the priorities for this worst-case scenario will be more effective if the community is already engaged in this GW strategy development process.

- A GW:UK group has been formed ([GW:UK](#)) and will start with a series of online seminars/discussion series in June 2025.

## 10.1 Key Decision Timelines for participation

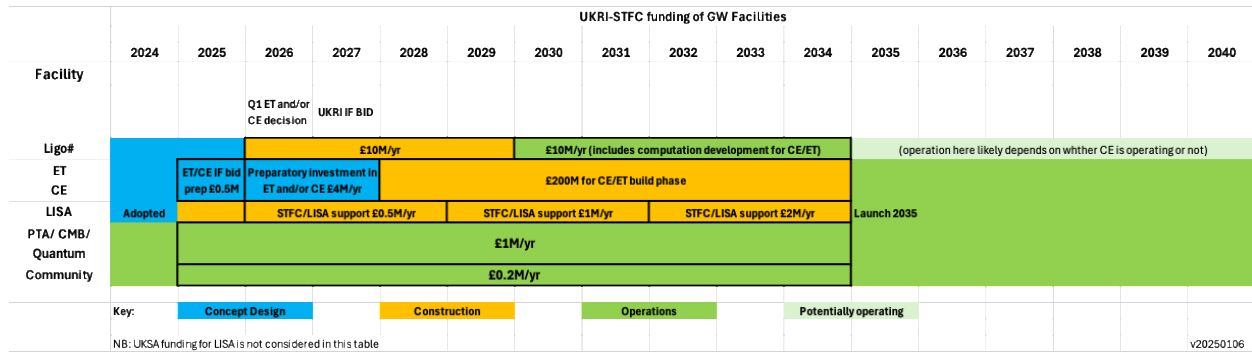


Figure 8: Funding scenarios

The summary of investment following from the recommendations is given in Figure 88. The key upcoming milestone is decision on the shape and form of a STFC Infrastructure bid to UKRI to support investment in ET and/or CE.

Here it assumed that the UKRI bid will be submitted to a potential upcoming 2027 IF round. In the coming year (2025 to early 2026), a decision by the community will be required on the shape and form of the IF bid, which will likely involve deciding on whether to aim for participation in either ET or CE at the ~£200M level (construction cost UK contribution).

## Appendix A Acronyms

LVK The LIGO - Virgo - KAGRA collaboration

STFC Science and Technologies Facilities Council, a constituent of UKRI

PAAP STFC 's Particle Astrophysics Advisory Board

PPAN STFC's Particle Physics, Astronomy and Nuclear Physics programme

UKRI UK Research and Innovation

## Appendix B Panel Membership

- Nils Andersson (University of Southampton) [NA]
- Djuna Croon (Durham University) [DC]
- Giles Hammond (University of Glasgow) [GH]
- Ian Harry (University of Portsmouth) [IH]
- Patrick Sutton (Cardiff University) [PS]
- Nicholas Walton (University of Cambridge) [NW], Panel Chair

In attendance from STFC:

- Helen Beadman (Associate Director, Nuclear Physics and Particle Astrophysics) [HB]
- Melanie Kidd (Programme Manager, Nuclear Physics and Particle Astrophysics) [MK]
- Jamie Parkin (Head of Nuclear Physics and Particle Astrophysics) [JP]

Additional input to the report:

- Chris McCabe (Kings College London)
- Alberto Vecchio (University of Birmingham)

## Appendix C Review Terms of Reference

### Review of the Gravitational Waves Research Programme

#### Background

UKRI-STFC is the primary funder of support for Gravitational Waves (GW) research and innovation in the UK. Through iterations of the GW consolidated grants (CGs), individual projects, and applications to the UKRI Infrastructure Fund, STFC has supported investment in both the current generation of GW detectors and observation runs, at the LIGO-Virgo-KAGRA observatories, and development of detectors towards the next generation of GW detectors.

At present, the STFC GW CGs focus on R&D, exploitation, and operations at LIGO with the exploitation of GW data for astronomy and cosmology now sitting within the Astronomy CG. However, the longer-term strategy for support for the experimental programme in GW needs to be established to ensure that STFC can prioritise and respond to opportunities in the developing international landscape and prioritise GWs appropriately within the financially constrained core programme.

STFC is seeking to convene a small bespoke panel to develop a report on UK GW research containing recommendations to STFC for UK future strategy and investment.

### **Terms of Reference**

The main purpose of the exercise is to conduct a light-touch strategic review of the GW research field, to establish a clear strategy for longer term UK investment over the next five to ten years:

- Review the UK GW landscape, highlighting current UK participation, leadership and capability.
- Consider the recommendations of the latest UK (PAAP) roadmap, in the context of the international landscape (APPEC Roadmap and US P5 report).
- Explore the developmental and design status of the next generation projects, including the potential opportunities and critical timepoints for UK decisions to participate.
- Review the developing technological landscape, including the emergence of novel quantum technologies and analysis techniques relevant to GW, and explore their potential disruptive impact on the field in the coming years.
- Develop a long-term strategy for future investment that:
  - considers future opportunities, potentially allowing for an interleaving programme,
  - maintains a UK presence at the cutting edge of the field,
  - drives innovation in novel and potentially disruptive technologies,
  - provides options for participation in international projects, subject to UK capability, capacity and budgetary constraints.

### **Questions to be considered**

The review of the landscape in the UK will aim to address the following questions:

- What are the current opportunities for GWs?
- For the next generation projects, what are the scientific drivers for participating in each project? What are the opportunities for the UK specifically to participate?
- Where does the UK currently lead or have the potential to have the greatest impact?
- Does the UK have the capability / capacity needed to exploit each opportunity?
- When are key decisions and timepoints required for STFC / UK participation in all projects?
- What recommendations would this advisory group offer regarding participation in international projects, subject to available funding? For example, what would be recommended in a reduced/flat/uplifted budget scenario.

## **Appendix D      Review Panel Process**

### **Initial Evidence Gathering**

- Community questionnaire: June 2024
- Review of recent roadmaps
- Updates on major projects

- Draft report issued 10 January 2025

### **Community Review**

- Community meeting: 16 January 2025
- Feedback from community on draft report: 9 February 2025

### **Final Report**

- Finalise report incorporating feedback from community meeting
- Issue final report: July 2025

## **Appendix E The 2024 GW Community Questionnaire**

**10.1.1 A community questionnaire was launched in June 2024 to complement production of this review, with the intention of identifying the current interests and drivers of the UK Gravitational Waves community. The questions explored both group and community sizes, recruitment interests, and future focus for research plans in the UK. This survey is potentially limited in the scope and may not represent all research groups or individual drivers for the future of GW in the UK. 35 responses were received, with 23% respondents representing Heads of Group, 57% Academics, 9% Researchers, and 11% other.**

The questionnaire questions were:

- Question 1: What is your name? [35 responses]
- Question 2: What is your email address? [35 responses]
- Question 3: What is your organisation? [35 responses]
- Question 4: Please select a role? [35 responses]
- Question 5: If 'other' please specify your role [4 responses]
- Question 6: Are you answering as an individual or on behalf of a group? [35 responses]
- Question 7: Considering astrophysics research in the broadest terms at your research institute, what is the group size (including researchers, post graduate students, and others) [35 responses]
- Question 8: For the research team carrying out work relevant to Gravitational Waves (science or technology), please detail the composition of your current research group. [35 responses]
  - Group composition: Researchers (Permanent), Researchers (Fixed Contract), Students, Other
- Question 9: By comparison, to the best of your knowledge, what was the group composition in 2020? [35 responses]

- Group composition (2020): Researchers (Permanent), Researchers (Fixed Contract), Students, Other
- Question 10: If your group were hiring faculty staff (three years ago / today / in three years' time), in what GW-related field would you possibly describe the role(s)? [35 responses]
- Question 11: Please provide any other comments [24 responses]
- Question 12: Which of the following are you already participating in? Areas of interest ... [35 responses]
- Question 13: If you are considering involvement in future gravitational waves programmes, which would you prioritise? [35 responses]
  - Future participation in: Current generation ground-based gravitational waves (LIGO/Virgo/KAGRA); Next-generation ground-based gravitational waves (e.g. Einstein Telescope, Cosmic Explorer); Space-based gravitational waves (LISA); Pulsar Timing (e.g. IPTA/EPTA/Nanograv); Cosmic Microwave Background; Electro-magnetic follow up; Atom interferometry; Generic underpinning technology; Generic underpinning theory/modelling/simulations; Other
- Question 14: If your group were considering involvement in future gravitational waves programmes, in which areas would the group anticipate requesting funding? [35 responses]
- Question 15: What are the issues that are impeding the development of the gravitational waves field, from your perspective? [33 responses]
- Question 16: To allow the review panel to consider all scenarios, please describe the impact you would foresee, if the UK did not fund any gravitational waves related research. [34 responses]
- Question 17: Do you have any further comments you wish to raise? [17 responses]

### **Key points from the community questionnaire.**

In response to Q8 it is clear that the majority of recent faculty staff hires are currently linked to research and expertise related to current generation ground-based GW facilities (e.g. LIGO). However, there is a clear expectation that future staff hires will be linked to next generation ground based GW facilities (e.g. ET). See Figure 9, Figure 10 and Figure 11 for detail.

**Hiring - Three years ago**

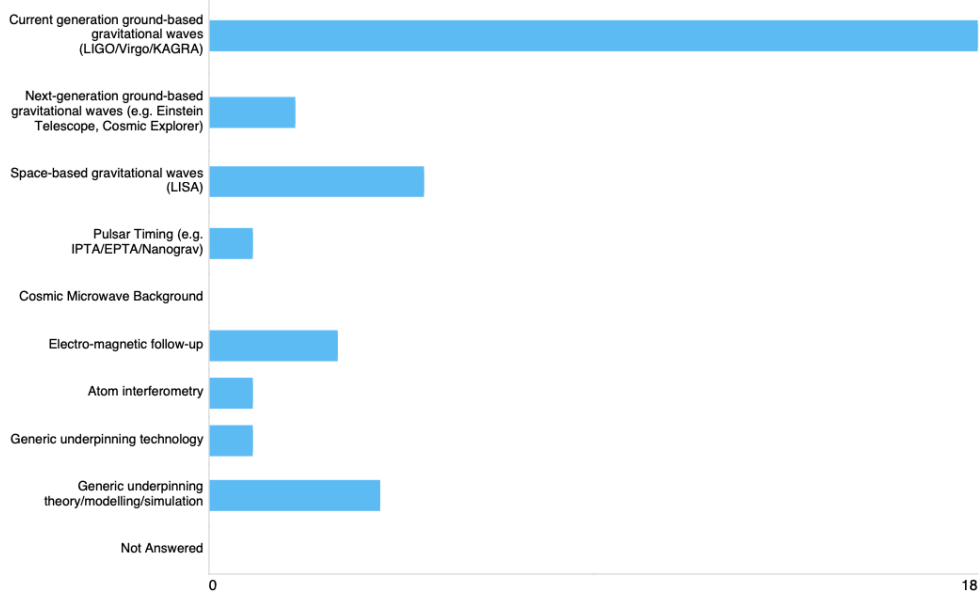


Figure 9: Question 10: If your group were hiring faculty staff (three years ago / today / in three years' time), in what GW-related field would you possibly describe the role(s): Hiring - three years ago.

**Hiring - Present day**

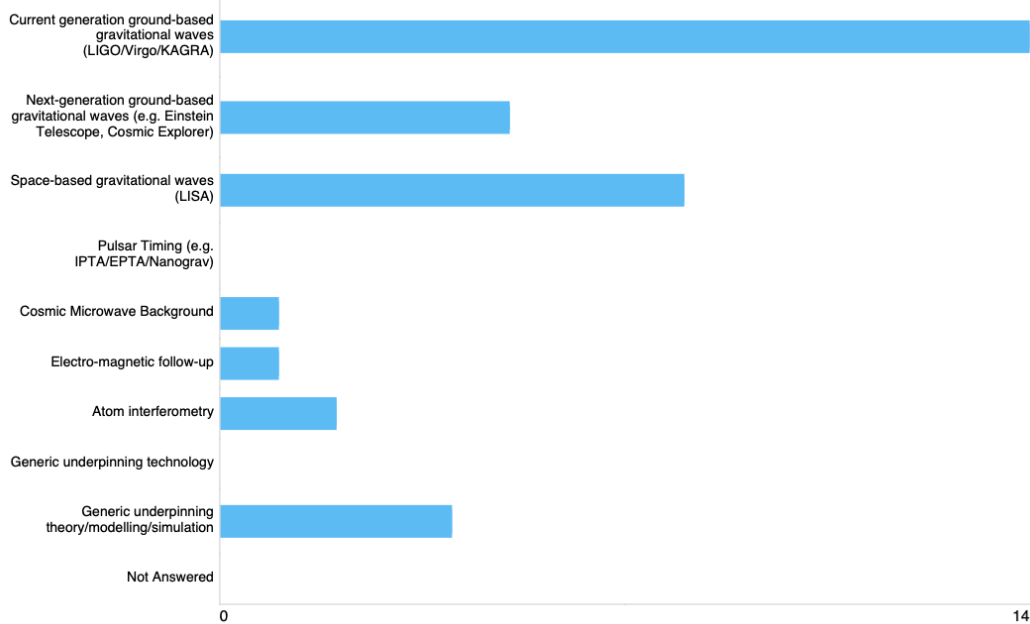


Figure 10: Question 10: If your group were hiring faculty staff (three years ago / today / in three years' time), in what GW-related field would you possibly describe the role(s): Hiring - present day.

**Hiring - Three years from now**

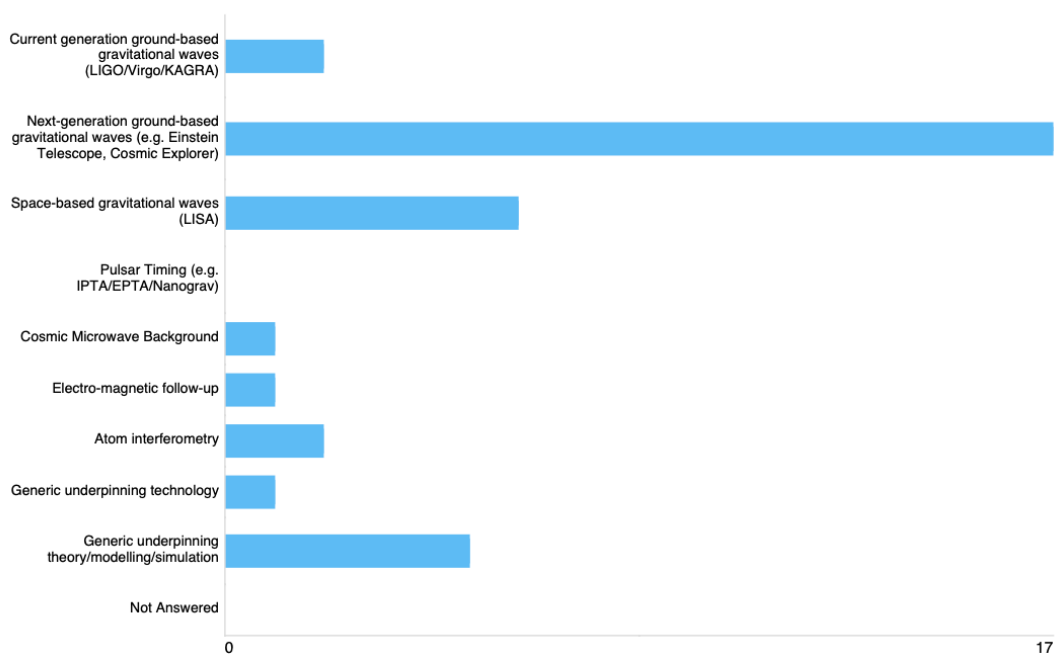


Figure 11: Question 10: If your group were hiring faculty staff (three years ago / today / in three years' time), in what GW-related field would you possibly describe the role(s): Hiring - three years from now.

In answer to Q12, the main areas of research and participation are currently in the high frequency experiments (e.g. LIGO, ET, LISA) and underpinning theory/ modelling. There is less involvement in other areas such as PTAs. See Table 1.

Table 1: Question 12: Which of the following are you already participating in?

Option	Total	Percent
Current generation ground-based gravitational waves (e.g. LIGO/Virgo/KAGRA)	24	68.57%
Next-generation gravitational waves (e.g. Einstein Telescope, Cosmic Explorer)	25	71.43%
Space-based gravitational waves (e.g. LISA)	20	57.14%
Pulsar Timing (e.g. IPTA/EPTA/Nanograv)	1	2.86%
Cosmic Microwave Background	5	14.29%
Electro-magnetic follow up	3	8.57%
Atom interferometry	2	5.71%
Generic underpinning technology	4	11.43%
Generic underpinning theory/modelling/simulations	14	40.00%
Not Answered	0	0.00%

In answer to priorities for future GW facilities, there is a clear preference for continuing access to current (high-frequency) ground based facilities (e.g. LIGO/Virgo), with next generation facilities (e.g. ET/CE) the next priority. LISA is also seen as important. There was less interest in the respondents in low frequency facilities (E.g. PTA and CMB experiments for GW research). See Table 2 for details.

Table 2: Question 13: If you are considering involvement in future gravitational waves programmes, which would you prioritise?

	<b>Top Priority</b>	<b>Second choice</b>	<b>Third choice</b>	<b>Not answered</b>
<b>Current generation ground-based gravitational waves (LIGO/Virgo/KAGRA)</b>	45	14	1	37
<b>Next-generation ground-based gravitational waves (e.g. Einstein Telescope, Cosmic Explorer)</b>	5	51	29	14
<b>Future participation - Space-based gravitational waves (LISA)</b>	17	17	49	17
<b>Pulsar Timing (e.g. IPTA/EPTA/Nanograv)</b>	0	3	3	94
<b>Cosmic Microwave Background</b>	3	3	3	91

In terms of expected demands for future funding request, the main areas would be LIGO/Virgo, CE/ET, LISA, and theory/simulations. See Figure 12 for details.

**Gravitational Waves areas choices**

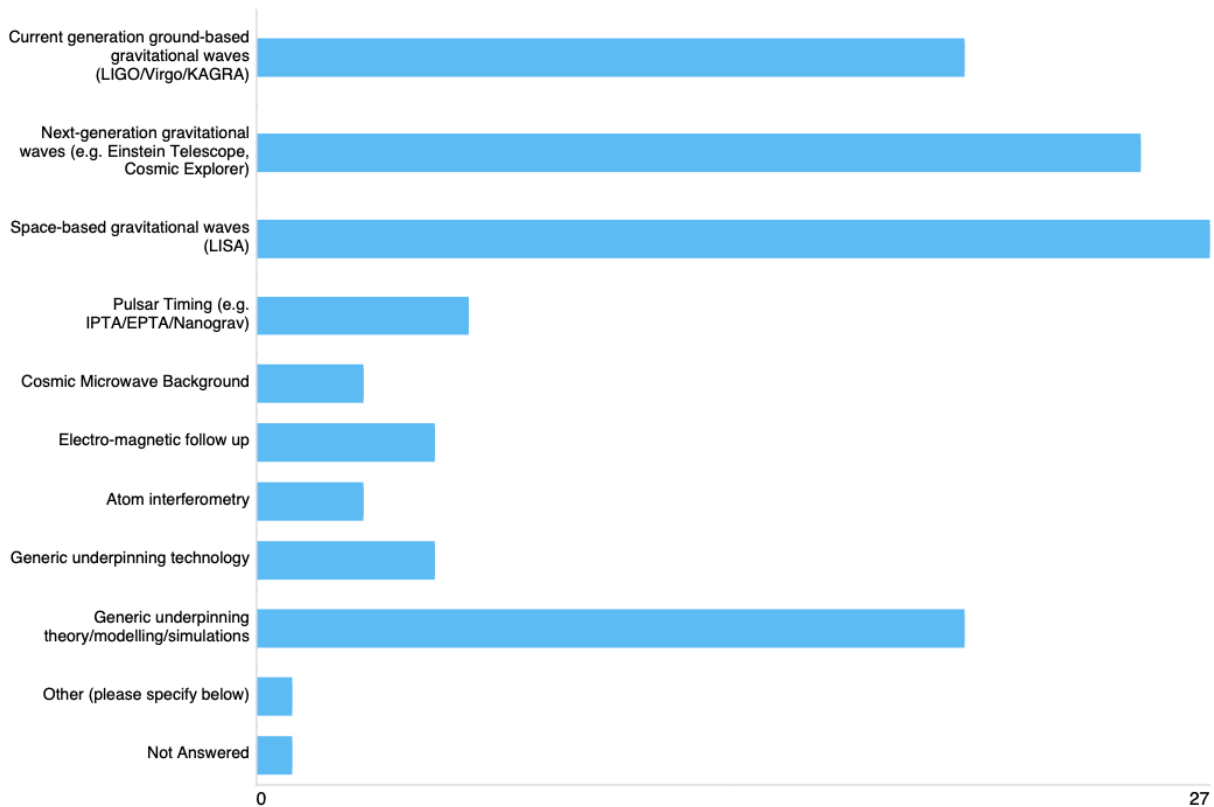


Figure 12: Question 14: If your group were considering involvement in future gravitational waves programmes, in which areas would the group anticipate requesting funding

In response to Question 15 there were concerns as to funding mechanisms to allow effective participation in international GW projects (e.g. it can be difficult to fund support activities for exploitation of LISA). It was noted how GW science might progress more effectively if there were a more formal partnership of the various current experiments (e.g. LIGO/Virgo/KARGA etc evolve into a more established single international entity, somewhat analogous to SKAO for instance). There was also considerable concern at the limited level of resources available to support GW research in the UK.

In response to Question 16 there was a more or less uniform view that not funding GW research (and development of GW facilities), would be extremely damaging. Not only to UK science in this emerging domain, but also more generally, damaging UK reputation as a partner in science collaborations ore widely. There was of course the realisation that future GW experiments will have a significant cost, and that careful project oversight will be required.

## Appendix F List of contributors

As part of the development of this review, and on behalf of the panel, STFC conducted two community engagement activities to inform and shape the content presented.

These activities comprised:

- An online consultation survey conducted in 2024, which received responses from 35 unique participants.
- A community meeting held at the Institute of Physics in January 2025, attended by 37 participants.

These engagement efforts elicited contributions from representatives affiliated with the following UK institutions:

- Cardiff University
- University of Birmingham
- King's College London
- Queen Mary University of London
- University of Portsmouth
- University of Cambridge
- University of Warwick
- University of Southampton
- Imperial College London
- University of Oxford
- University of Nottingham
- University of East Anglia
- University of Strathclyde
- University College London
- Royal Holloway, University of London
- The University of Sheffield
- The University of Manchester

A list of individual respondents and participants who consented to be acknowledged for their involvement in either activity is provided below, in no particular order:

Name	Institution
Christopher Berry	Institute for Gravitational Research, University of Glasgow
Sheila Rowan	Institute for Gravitational Research, University of Glasgow
Justin Greenhalgh	UKRI STFC
Scott Melville	Queen Mary University of London
David H Shoemaker	Massachusetts Institute of Technology, Kavli Institute
Thomas Sotiriou	Nottingham Centre of Gravity, University of Nottingham
Leor Barack	University of Southampton
Katy Clough	Queen Mary University of London

Sir James Hough	Institute for Gravitational Research, University of Glasgow
Daniel Mortlock	Imperial College London
David Alonso	University of Oxford
Prof Martin Hendry	University of Glasgow
David Wands	Institute of Cosmology and Gravitation, University of Portsmouth
Chris Nixon	University of Leeds
Christopher J Moore	Institute of Astronomy and Department of Applied Mathematics and Theoretical Physics, University of Cambridge
Jocelyn Bell Burnell	University of Oxford
Stephen Green	University of Nottingham
Mark Hannam	Cardiff University
James Alvey	University of Cambridge
Gregory Ashton	Royal Holloway, University of London
Angus Bell	Institute for Gravitational Research, University of Glasgow
Hartmut Grote	Cardiff University
Alice Breeveld	UCL Mullard Space Science Laboratory
Graham Woan	University of Glasgow
Laura Nuttall	University of Portsmouth
Stephen Fairhurst	Cardiff University
Carlo Contaldi	Theoretical Physics Group, Imperial College London
Ian Jones	Mathematical Sciences, University of Southampton
Miguel Bezares Figueroa	University of Nottingham
Patricia Schmidt	University of Birmingham
Mariana Andrea Fazio	University of Strathclyde

## Appendix G STFC Consolidated Grant Funding

Boxes in green indicate committed funding from UKRI to live and previously projects. Orange boxes indicate future potential commitment. The £6.2m consolidated grant funding in green pre-dates the start of this image and spans the period from 2016-2021

Further to the information above, STFC also funds gravitational waves research through the Astronomy Small and Large awards panels, which meet annually.

Any future funding, including UKRI Infrastructure Funding, STFC GW Consolidated Grants, and Astronomy small and large awards are subject to confirmation of funding. There are no guarantees for funding allocations.

	2020/21	2021/22	2022/23	2023/24	2024/25	2025/26	2026/27	2027/28	2028/29	2029/30	2030/31	2031/32	2032/33	2033/34	2034/35	2035/36
<b>Activities included in 10 YP</b>																
<b>Exploitation and operations</b>																
GW Consolidated Grant (2016 and 2020)	£6.2m		£12.0m													
<b>R&amp;D and Construction</b>																
ALIGO+ Upgrade Project	£10.5m															
Next Generation Gravitational Waves					£8.0m											
<b>Anticipated opportunities included in 10 YP</b>																
<b>Exploitation and operations</b>																
GW Consolidated Grant 2024 - £10m							£7m									
GW Consolidated Grant 2027 (4 years)									TBC							
GW Consolidated Grant 2031 (4 years)															TBC	