Science and Technology Facilities Council

Roadmap for UK Particle Astrophysics 2022

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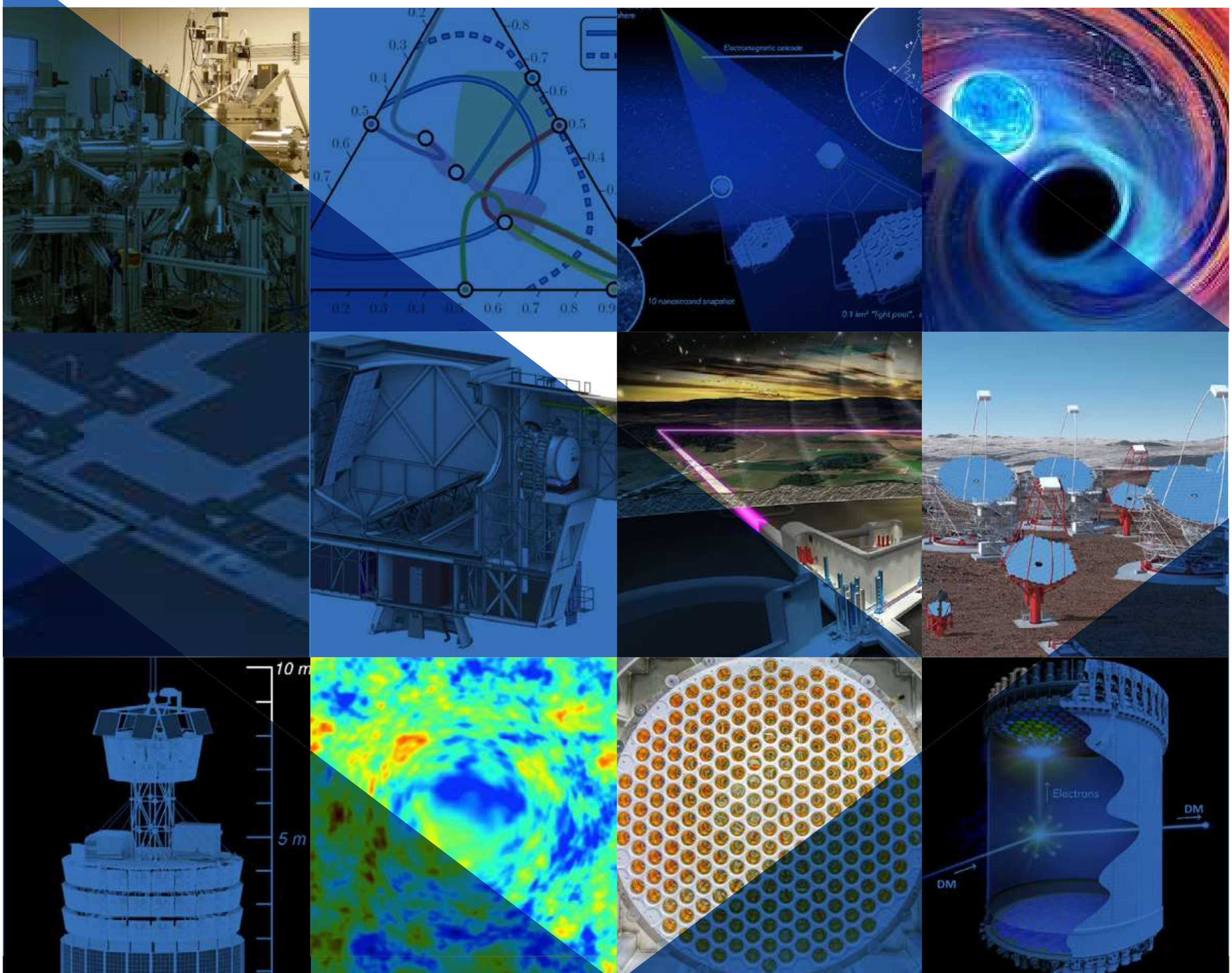

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1 Executive Summary

This roadmap provides an overview of UK Particle Astrophysics research, highlighting current strengths, opportunities for growth and areas for strategic investment. Particle Astrophysics research lies at the intersection of particle physics, astronomy and cosmology and has the potential to answer many STFC Science Challenges, particularly those related to fundamental models of particle and astrophysics. Significant recent breakthroughs include direct detection of multiple gravitational waves signals, observation of extra-galactic high-energy neutrinos and precision tests of cosmology through cosmic background radiation measurements.

The Particle Astrophysics Programme supports research across the areas of gravitational waves, very high energy gamma ray astronomy, neutrino astronomy, direct dark matter detection, the cosmic microwave background and underpinning theoretical research. There is tremendous potential for growth in all areas and the UK is well positioned to play leading roles. The current funding profile for Particle Astrophysics is not commensurate with the scale and importance of the research. Several areas are supported at sub-critical levels, whilst in others only a single project receives significant support. It is vitally important that funding levels for Particle Astrophysics, through significant strategic investments, are increased to ensure long-term UK leadership.

Gravitational wave observations have revolutionised our understanding of black holes and neutron stars, informed investigations of the fundamental nature of gravity, and contributed to multi-messenger astronomy. The UK has made critical instrumental, analysis and theoretical contributions to Advanced LIGO (aLIGO) and the highest priority remains UK leadership in operation, upgrade and exploitation of aLIGO. Next-generation observatories, Einstein Telescope and Cosmic Explorer, will enable gravitational wave observations of sources throughout the universe. Strategic investment in technology development, computational and modelling is critical to maintain UK leadership. LISA, scheduled for launch in 2034, will enable observation of low-frequency gravitational waves from sources such as super-massive black holes. STFC support for exploitation and development of theoretical and computational tools for LISA is required to ensure UK leadership. Pulsar timing arrays, sensitive to nano-Hertz gravitational waves, are likely to observe super-massive black hole mergers in the coming years. Currently the UK has a relatively minor involvement in Pulsar Timing Arrays and a modest investment could yield significant return.

Very high energy gamma-ray astronomy is key to understanding highly energetic non-thermal processes, such as particle acceleration by black holes as well as fundamental questions about possible Lorentz violations. The UK's primary involvement is through the Cherenkov Telescope Array (CTA), which improves on existing sensitivity by a factor of ten and will transform our understanding of the high-energy universe. It is vital that the UK contribute to CTA construction to ensure full scientific return from the project. The Southern Wide-field Gamma Ray Observatory is a proposed wide-field observatory which will be complementary to CTA. The UK has limited current involvement and, while a moderate investment could represent a significant stake, this should not come at the cost of CTA leadership. The High-Energy Stereoscopic System is the largest of the current generation of high-energy gamma astronomy instruments, in which the UK played a significant role historically, but does not warrant future support due to the high value of CTA.

Dark Matter. The observation of dark matter would be a landmark discovery in both astronomy and particle physics. The UK has a long track record in searching for Weakly Interacting Massive Particles (WIMPs), and continues to play a leading role in the current LUX-ZEPLIN (LZ) experiment, which uses a 7-tonne liquid xenon target and began data taking in 2021. By 2025, the LZ experiment is expected to improve the sensitivity to WIMPs by over an order of magnitude compared to current limits. The UK also has involvement in the 20-tonne DarkSide liquid argon experiment. Continued support for LZ and DarkSide remains a high priority. More sensitive future xenon and argon detectors are planned for 2030, and the UK should provide support for at least one future dark matter experiment. Alternative dark matter candidates include wave-like hidden sector dark matter, such as axions. Several projects have been funded by STFC through the Quantum Technologies for Fundamental Physics (QTFP) programme. These include the Quantum Sensors for the Hidden Sector (QSHS), Atom Interferometer Observatory and Network (AION) and Quantum-enhanced Interferometry (QI). It is important that additional funding, beyond the initial QTFP call, is identified to ensure a sustainable programme.

Neutrino Astronomy. Observations of neutrinos from astrophysical sources provide a unique view of their progenitors. They are the only messengers allowing us to identify to the high-energy objects beyond our galaxy above $\sim 50-100$ TeV and, as such, are an essential component of multi-messenger astronomy. Neutrino astronomy enables the observation of high energy sources, such as blazars and PeV particles, a search for cosmic neutrino background and additional neutrino flavours. The UK currently has involvement in three neutrino astronomy experiments: IceCube/IceCube-Gen2, ANITA/PUEO and P-ONE, with limited support for all of these projects through STFC. The IceCube-Gen2 observatory will make advances in important astrophysics questions, with an order of magnitude increase in neutrino detection rates compared to IceCube. The UK High-Energy Neutrino Consortium enables the UK community to consolidate effort towards significant support of a future large-scale observatory, as well as increased involvement in existing experiments.

Accurate measurements of the **Cosmic Microwave Background (CMB)** are critical for understanding early universe cosmology, the evolution of cosmic structure, and the particle content of the Universe. Data from the Planck mission, with key UK leadership, provided unprecedented precision measurements of the CMB. Future missions will probe unexplored regimes in polarization and on small scales, allowing powerful searches for primordial gravitational waves and new light relic particles, insights into the properties of neutrinos, and precise mapping of the cosmic mass and baryon distributions. The highest priority for UK CMB science is significant UK involvement in the Simons Observatory, a CMB observatory under construction in the Atacama Desert. This involvement is the cornerstone of UK CMB. The UK should subsequently target leading roles in upcoming ground-based experiments such as CMB-S4 and future satellite missions such as LiteBIRD, which, with significant improvements in sensitivity, will further advance CMB science goals.

Theoretical Particle Astrophysics is a vital part of the programme. It supports experimental and observational work by suggesting experimental directions to be pursued and providing detailed modelling required to fully exploit experimental data. The UK has a large, expert theoretical community which has provided significant input into dark matter, CMB and gravitational wave experiments and observations. However, there is a current lack of funding for theoretical research and the long-term success of the entire Particle Astrophysics programme will benefit from increased theoretical support, including the award of fellowships for those working on theory and modelling.

Technology Development, Underpinning Technology, Impact and Infrastructure. The cross-cutting nature of Particle Astrophysics results in myriad opportunities for technology development in instrumentation, detector technology, analysis techniques and at the theoretical frontier. Research infrastructure is shared with in neighbouring fields such as geophysics, quantum computing, optics and semiconductor research. Particle Astrophysics research has found industrial application in areas including healthcare, security and transportation. There is extensive outreach and public engagement activity, making the ground-breaking discoveries accessible to the public.

2 Overview

The field of Particle Astrophysics has enjoyed significant growth over recent years, with numerous breakthrough observations. In recent years, Particle Astrophysics has delivered numerous breakthrough observations, leading to significant international growth for the field. Unfortunately, despite our contributions to the field's success, ongoing funding constraints have meant that this growth has not been mirrored in the UK.

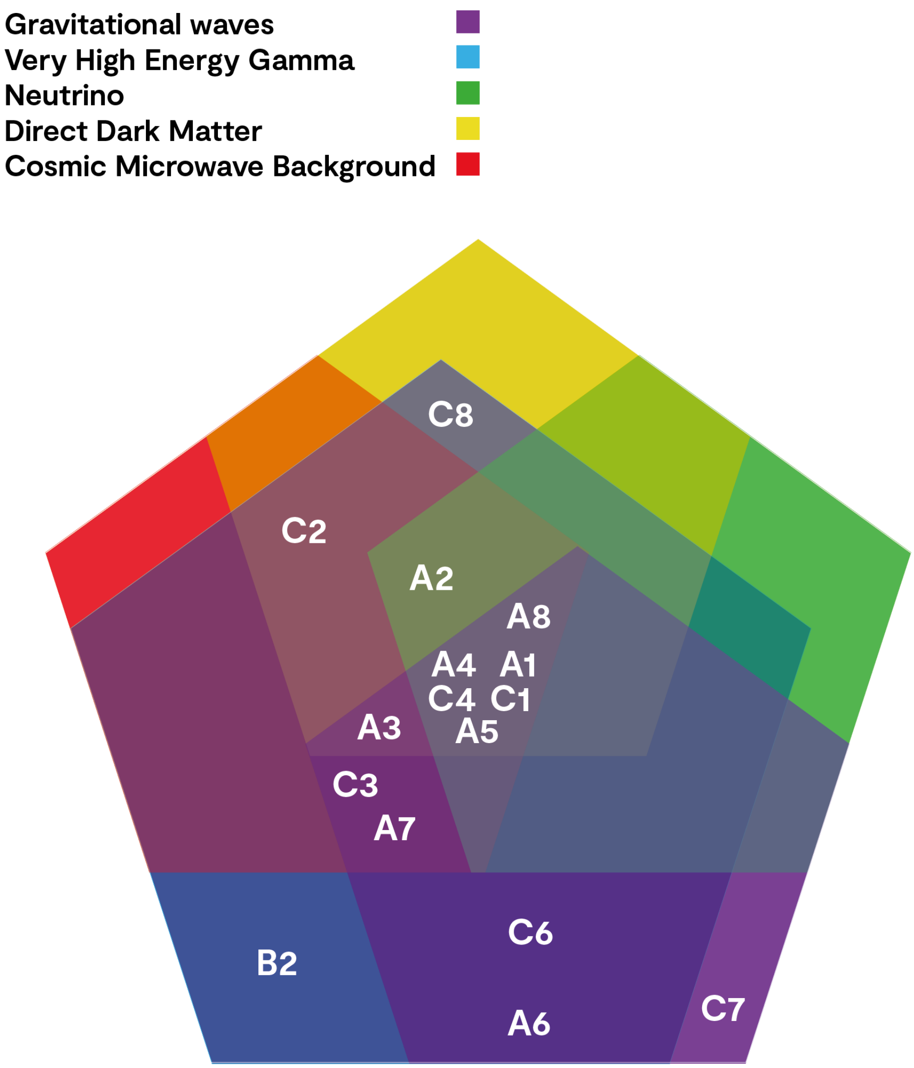
2.1 Scientific Highlights

In the past five years, UK scientists have played leading roles in

- The observation of close to 100 Gravitational Wave (GW) signals from coalescing binaries comprised of neutron stars and black holes. This includes the first multi-messenger observation of a neutron star merger (also observed as a gamma ray burst and subsequently seen across the electromagnetic spectrum), the first observation of neutron star–black hole binaries, and a population of black hole binaries.
- Ground-based Very High Energy Gamma Ray (VHE Gamma) instruments make crucial contributions to multi-messenger astronomy. These include the first detections of TeV photons from gamma-ray bursts. The identification of the gamma-ray blazar TXS056+0506 as the first high-probability PeV neutrino source was secured by IACT imaging of the associated TeV flare.
- Achieving the best sensitivity to WIMPs in 2016 with the LUX detector in strong competition with the PandaX and XENON collaborations. The next generation detector LZ was built and started taking data in 2021 aiming to improve the current WIMP world limits by over an order of magnitude by 2025. Searches for wave-like dark matter such as axions have been supported through the QTFP programme, including the QSHS, QI and AION projects.
- The first-ever identification of a likely point source of extragalactic high-energy neutrinos and cosmic rays (blazar TXS056+0506) using multi-messenger astronomy, with follow-up observation by gamma-ray, X-ray and optical telecopes. The addition of Gd to the world's largest underground neutrino detector, Super-Kamiokande, which allows it to aim for the first observation of Diffuse Supernova Neutrino Backgrounds.
- Extracting most precise measurements to date, with both Planck and AdvACT experiments, of the CMB power spectrum and lensing spectrum. This has allowed us to test Lambda Cold Dark Matter (LCDM) and inflation predictions at unprecedented accuracy; it has also provided the tightest bounds on neutrino masses and new light particles in the early universe.

2.2 Particle Astrophysics Science Goals

UK Research in Particle Astrophysics addresses a large fraction of the Science Challenges [2] identified by Science and Technology Facilities Council (STFC) as core to its programme. Particle Astrophysics provides significant input to both Science Challenges **A. How did the universe begin and how is it evolving?** and **C. What are the basic constituents of matter and how do they interact?** In many instances, Particle Astrophysics experiments provide unique observations which are complementary to those available from either astronomy or particle physics. The STFC Science Challenges which can be addressed by Particle Astrophysics observations are:



A1	What are the laws of physics operating in the early Universe?
A2	How did the initial structure in the universe form?
A3	How is the universe evolving and what roles do dark matter and dark energy play?
A4	When and how were the first stars, black holes and galaxies born?
A5	How do stars and galaxies evolve?
A6	How Do Nuclear Reactions Power Astrophysical Processes and Create the Chemical Elements?
A7	What is the True Nature of Gravity?
A8	What can gravitational waves and high-energy particles from space tell us about the universe?
B2	What effects do the Sun and other stars have on their local environment?
C1	What are the fundamental particles and fields?
C2	What are the fundamental laws and symmetries of physics?
C3	What is the nature of space-time?
C4	What is the nature of dark matter and dark energy?
C6	What is the nature of nuclear matter?
C7	Are there new phases of strongly interacting matter?
C8	Why is there more matter than antimatter?

A:1 What are the laws of physics operating in the early Universe? Tight constraints on early universe models are provided by measurements of the relic Dark Matter (DM) density, the GW background in the early Universe, and CMB measurements of B-mode polarization and spectral tilt. Searches for DM annihilation and axion-like particles using VHE Gamma signals, as well as searches for cosmic neutrino backgrounds, further constrain the models.

A:2. How did the initial structure in the universe form? Models describing the early structure of the universe are constrained by current observations of the DM spatial distribution, both via direct observation and via indirect detection using VHE Gamma signals. Measurements of the CMB and observation of lensing add information about the initial conditions for structure formation and probe structure growth. Searches for sterile and heavy neutrinos further constrain models that describe the structure formation, while GWs enable observations of supermassive Black Holes (BHs) and their seeds.

A:3. How is the universe evolving and what roles do dark matter and dark energy play? While DM experiments provide direct observations of DM and its role in the evolving universe, VHE Gamma observations can provide indirect detection of DM and its spatial distribution, constrain the Hubble constant, and measure the Intergalactic Magnetic Field (IGMF). GW signals show the imprint of DM and the standard sirens they represent can be used as probes of cosmology, and CMB provides cosmological parameter determination and searches for deviations from LCDM.

A:4. When and how were the first stars, black holes and galaxies born? Direct DM observations tightly constrain models of galaxy formation. The star-formation history of the universe can be accessed via measurements of the absorption of gamma rays on the extragalactic background light, and via reionization information from the cosmic microwave background. GW observations of black-hole mergers could give information on the formation of Population III stars and super-massive BHs. Neutrino astronomy contributes via searches for the diffuse supernovae neutrino background, supernovae monitoring and the identification of blazars.

A:5. How do stars and galaxies evolve? VHE Gamma provides understanding of feedback from accelerated particles and their role in the suppression of galaxy formation, while DM is critical for the evolution of galaxies. CMB observations constrain star formation via observations of dusty star forming galaxies and the cosmic infrared background. GWs provide observations of BH (from stellar mass to supermassive) and Neutron Star (NS) populations. Neutrinos observations are used to measure the metallicity of the sun, and in observations of neutrino emission from blazars and supernovae.

A:6. How Do Nuclear Reactions Power Astrophysical Processes and Create the Chemical Elements? Observations of VHE Gamma probe the highest energy processes in NS mergers. GWs provide for multi-messenger observations and enable measurements complementary to those from electromagnetic observations.

A:7. What is the True Nature of Gravity? GWs probe the strong-field nature of gravity, for example during BH mergers, the polarization content and speed of propagation of gravitaional waves. VHE Gamma observations of active galactic nuclei and Gamma Ray Bursts (GRBs) provide tests of Lorentz Invariance Violation. CMB observations test modifications to gravity via the integrated Sachs-Wolfe effect (ISW) and secondary anisotropies.

A:8. What can GWs and high-energy particles from space tell us about the universe? GWs provide direct observations of strong gravitational fields, particularly around BH and NS. CMB observation of B-modes from inflationary GWs probe early-universe physics. VHE Gamma observations probe Lorentz Invariance Violation from observations of Active Galactic Nuclei (AGN) and GRBs. Direct DM observations probe high-energy particles from DM annihilation and neutrino astronomy gives measurements of neutrino flux in the PeV region.

B:2. What effects do the Sun and other stars have on their local environment? Observations of high energy cosmic rays from supernovae give insight into their feedback into the local environment influencing star formation.

C:1. What are the fundamental particles and fields? DM candidates are new fundamental particles, so observation of DM will inevitably lead to discovery of new particles. Neutrino astronomy performs searches for sterile and heavy neutrinos. The CMB power spectrum is a sensitive probe of the number of light relic particles or neutrinos, while lensing also measures neutrino mass. VHE Gamma observations can provide indirect detection of DM; signatures of axion-like particles in AGN spectra; probes of magnetic fields in cosmic voids; and tests of Lorentz invariance violation. GW observations probe the fundamental nature of gravity, including the propagation speed and polarization content of GWs.

C:2. What are the fundamental laws and symmetries of physics? VHE Gamma observations will constrain or measure Lorentz invariance violation and signatures of Axion-Like Particles (ALPs) on gamma-ray spectra. Direct DM observations provide tests of symmetries in particle physics and CMB observations test for parity violation via polarization angle rotation, tests for other symmetries via correlation function properties.

C:3. What is the nature of space-time? VHE Gamma provide limits on (or observations of) Lorentz invariance violation, GW observations determine the polarization content of GWs and multi-messenger observations allow for measurement of the speed of GW progagation. CMB observations test modifications to gravity via the ISW and secondary anisotropies.

C:4. What is the nature of dark matter and dark energy? The primary goal of direct DM experiments is to observe DM interactions with ordinary matter. Neutrino Astronomy includes searches for sterile and heavy neutrinos, which may be good DM candidates. VHE Gamma observations are capable of indirect detection of DM and its spatial distribution, including searches for ALPs via effects on AGN spectra. CMB determines DM density, constrains DM interactions, mapping of DM distribution via lensing. CMB measurements and GW standard siren observations constrain dark energy equation of state.

C:6. What is the nature of nuclear matter? GW observations of NS mergers provide measurement of nuclear equation of state at very high densities. VHE Gamma observations provide measurements of the highest energy processes in neutron-star merger events.

C:7. Are there new phases of strongly interacting matter? GW observations will probe possible phase transitions to exotic matter phases, like de-confined quarks, during binary mergers.

C:8. Why is there more matter than antimatter? Direct DM measurements can be used for tests of Charge-Parity (CP)-violation in dark sector, while VHE Gamma provides measurement of the electron/positron spectrum as well as evidence for cosmic matter-antimatter annihilation.

2.3 International Context and other reviews

The majority of Particle Astrophysics research in the UK is undertaken in large, international collaborations. UK particle astrophysics is tightly integrated with European, US and global efforts, and the priorities laid out in this Roadmap are entirely consistent with those in the Astroparticle Physics European Consortium (APPEC) Roadmap [17]. In addition, areas of Particle Astrophysics maintain their own international roadmaps. The Gravitational Wave International Committee released a roadmap for Gravitational-wave physics and astronomy in the 2020s and 2030s [13]. The recommendations here are entirely consistent with the international vision, while also emphasizing the UK's unique strengths. In the area of Neutrino Astronomy, the priorities outlined in this roadmap form a subset of those in the 2021 IUPAP Neutrino Panel White Paper [12]. A dedicated APPEC Dark Matter report [14] was released in April 2021, and the European Consortium for Astroparticle Theory (EuCAPT) released the its White Paper [9] in October 2021. Again, the recommendations in this roadmap are consistent with the broader European strategy.

The U.S. National Academies' latest decadal survey was published in November 2021 [18]. Within the Medium-scale, Gamma-Ray Program, the panel endorsed U.S. participation in the Cherenkov Telescope Array ($70M), ranking it as a priority project and enabling the addition of 10 SCTs in the southern array, and the Southern Wide-Field Gamma-Ray Observatory ($20M), recognising both as important VHE observatories that will make major contributions to the multi-messenger Program for the 2020s. Among new large ground-based facilities, the panel ranked the CMB-S4 ground-based CMB experiment as its joint second priority; it was noted that CMB-S4 will serve as a powerful survey for mm-wave astrophysics as well as fundamental physics. In the area of neutrino astronomy, the panel listed the IceCube-Gen2 observatory as one of the "Large Programs that Forge the Frontiers", and endorsed it as important to many key survey scientific objectives, recognising that IceCube-Gen2 will see ten times the rate of neutrinos that were observed by IceCube, will detect sources five times fainter, and will extend the energy range by several orders of magnitude, thus resolving the bright, hard-spectrum, TeV–PeV diffuse background discovered by IceCube into discrete sources.

Particle Astrophysics research in the UK is complementary to other STFC-funded research. In particular, there are close ties to research in Particle Physics and Astronomy. Therefore, in areas where there is overlap between the fields, particularly Dark Matter research overlapping Particle Physics, and CMB research with Astronomy, we have ensured that the recommendations contained here are consistent with those in the Particle Physics [8] and Astronomy roadmaps. Furthermore, the 2022 Particle Astrophysics roadmap is a natural evolution of the 2016 Particle Astrophysics Roadmap [16]. The Particle Astrophysics Roadmap reflects recent STFC assessments of its research portfolio, most notably the 2020 STFC Balance of Programmes [5] and the 2020 Dark Matter Strategic Review [4].

Particle Astrophysics experiments often require significant infrastructure development. Consequently, several of the proposed future facilities are featured in the UK Research and Innovation (UKRI) 2020 review of The UK's Research and Innovation Infrastructure [6]. These include the Einstein Telescope, a proposed third-generation GW observatory in Europe and one of the highest-priority projects on the APPEC roadmap; the High-Altitude Water Cherenkov Observatory, the Southern Gamma-ray Survey Observatory, or the CTA; astrophysical neutrino observatories; the AION to probe as-yet mostly unexplored frequency bands of the GW spectrum; and the next-generation of direct dark matter searches. The UK is also considering hosting a next-generation dark matter experiment at Boulby Mine and has recently undertaken a feasibility study.

Timeline

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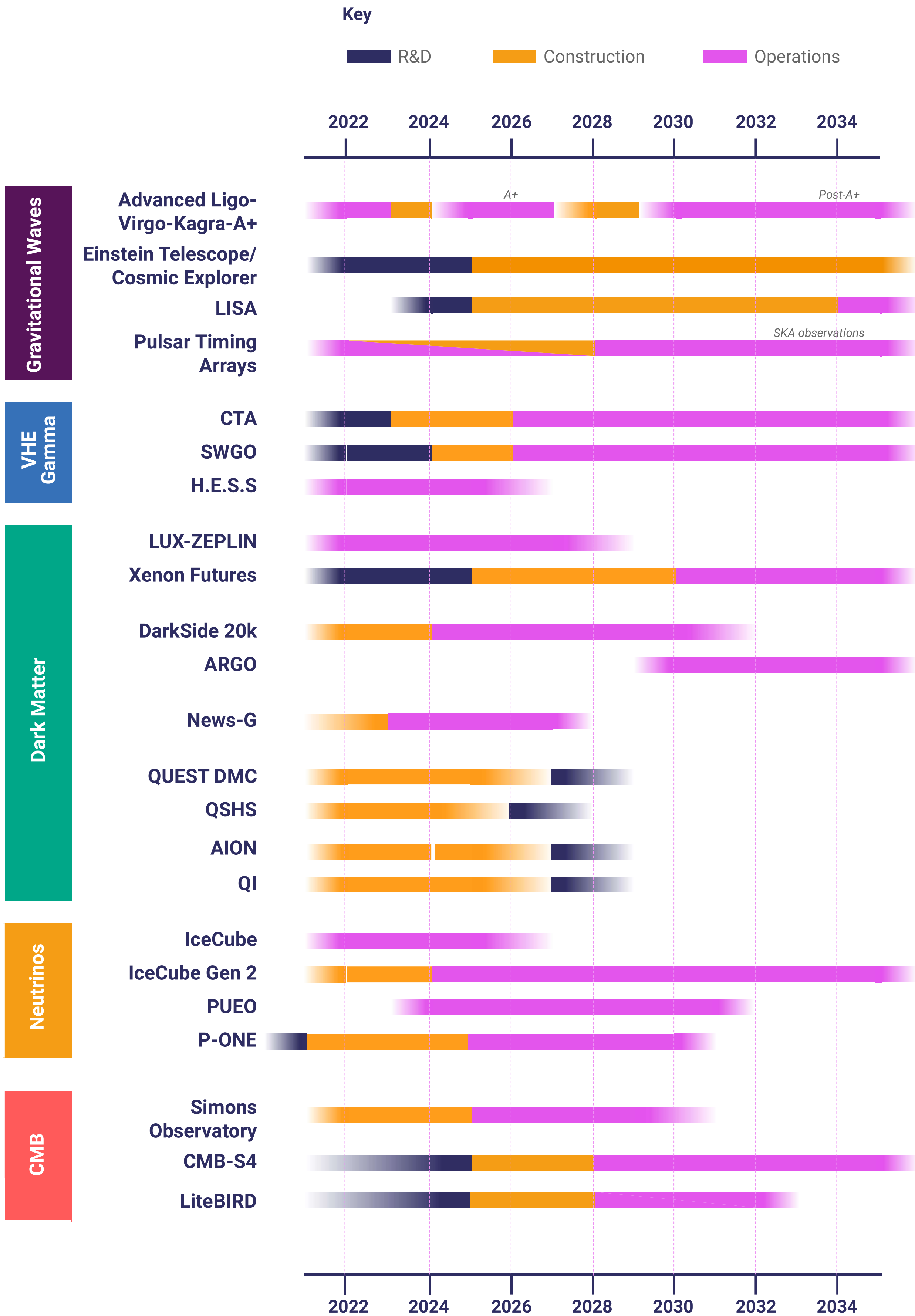

3 The Particle Astrophysics Programme

The UK Particle Astrophysics Program supports outstanding research across the areas of gravitational waves, VHE Gamma Ray astronomy, neutrino astronomy, direct dark matter detection and the cosmic microwave background.[1] Particle Astrophysics research has matured and expanded significantly in recent years and Particle Astrophysics is well-placed to provide answers to some of the major open questions in physics and astronomy in the coming years.

Particle Astrophysics has enormous potential for growth, in terms of the size of the UK community, its leadership roles in international experiments and in terms of addressing the burning scientific questions that cross into this field. It has become obvious that some of the most interesting questions about the universe are unlikely to be answered via experiments that are exclusively addressing Particle Physics or Astronomy, and that Particle Astrophysics observations provide a unique view of the universe. With its diverse range of complementary disciplines, Particle Astrophysics is having a combined impact on astronomy greater than the sum of the parts. The relatively new era of multi-messenger astronomy, in which the UK already has a defining role, has already demonstrated its potential to create new science breakthroughs.

The Particle Astrophysics budget in the UK is not commensurate with the scale and importance of the science questions, with the interest in the field from the UK community, or with the level of investment in other countries. The programme has become too narrow and attempts to resolve this within a very limited budget have squeezed supported activities to sub-critical levels and new activities cannot grow to levels that provide even a minimal chance for long term sustainability. There are areas, particularly neutrino astronomy, where funding is insufficient to support significant UK involvement in any large scale experiments or observations. In other areas of Particle Astrophysics, there is a distinct lack of breadth with, typically, only one project per science area receiving significant STFC funding. Particle Astrophysics funding is small, in comparison to both Particle Physics and Astronomy, so that relatively small shifts to Particle Astrophysics will have a dramatic effect.

UK researchers in Particle Astrophysics "punch well above their weight" in terms of contributions to research and leadership positions held in major scientific experiments relative to the funding available. Funding to date has allowed the UK to make major contributions to aLIGO construction and operations, and support construction of LZ and CTA. But the overall Particle Astrophysics funding is insufficient to support all these activities long-term and provide full return on investment for the UK.

Recommendation 3.1. We recommend re-balancing the overall STFC science portfolio to allow increased levels of funding for Particle Astrophysics. This will ensure continuing UK leadership within existing experiments, while also increasing the breadth and depth of Particle Astrophysics research.

To further strengthen the UK's participation in multi-messenger astronomy and maximise return on investment made in the medium term, a longer term strategic view needs to be taken on participation across the breadth of international Particle Astrophysics projects and opportunities.

[1] Cosmic microwave background research is a new addition to the roadmap since the 2016 edition. While CMB observations clearly form part of Particle Astrophysics, inclusion in the roadmap does not directly impact the funding source for CMB, or other areas of Particle Astrophysics.

Recommendation 3.2. We recommend that STFC should provide large, strategic investment in future Particle Astrophysics observatories and experiments to ensure continuing UK leadership in the long term.

Particle Astrophysics research sits at the crossroads of Particle Astrophysic and Astronomy. Consequently, there are times where Particle Astrophysics priorities and requirements are overshadowed by its larger, neighbouring fields. For example, even the STFC Science Goals outlined in Section 2.2 are written to address Astronomy challenges through question A: How did the universe begin and how is it evolving? and Particle Physics through question C: What are the basic constituents of matter and how do they interact? Particle Astrophysics naturally provides complementary answers to both sets of questions. Similarly, when it comes to funding Particle Astrophysics, this is often done through the Particle Physics Grants Panel (PPGP) or Astronomy Grants Panel (AGP). In principle, this provides an opportunity for Particle Astrophysics researchers to obtain funding from diverse sources. However, it is often the case that the funding panels contain limited expertise in Particle Astrophysics. Particularly concerning is theory; while panels might contain a dedicated theorist, they would typically not have Particle Astrophysics expertise.

Recommendation 3.3. STFC should ensure that Particle Astrophysics expertise is well represented on funding panels, particularly the PPGP Experimental and Theory and AGP Observation grant rounds. Particle Astrophysics priorities, as laid out in this roadmap, should be clearly communicated to the panel members, and the importance of long-term strategic investment emphasized.

The long-term success of Particle Astrophysics in the UK depends on the existence of a stable career path for researchers in the field. This includes provision of core skills and expertise to the current wave of PhD students and young researchers, greater funding stability for postdoctoral researchers and clear career development opportunities, particularly for those, such as technical and computing staff, who fall outside the standard academic trajectory. These steps are also likely to improve diversity across Particle Astrophysics researchers. While these concerns are generic across STFC areas, we nonetheless highlight their importance for Particle Astrophysics.

Recommendation 3.4. To improve career prospects and job security, STFC should move away from short term funding and towards support for longer term contracts and permanent positions. Funding should be targeted to improve career progression opportunities, particularly for Instrument Scientists, Research Software Engineers and others not following a standard academic path. STFC should ensure that more early-career fellowships are available, targeted at under-funded research areas and under-represented groups.

In recent years, the QTFP programme has provided funding to a number of new Particle Astrophysics experiments, primarily in dark matter detection, which would otherwise have been unavailable. These projects were jointly funded by STFC and the Engineering and Physical Sciences Research Council (EPSRC) with initial supported for 3.5 years, commencing in early 2021. At present, it is unclear how this support will be continued in the longer term. It it critical that continued funding for successful projects is made available, without a detrimental impact upon the existing programme which, as noted above, is already operating at a minimal feasible level. Those activities under the QTFP umbrella that have initial success, as defined by the usual academic and programmatic metrics, should be afforded opportunities for funding as they develop through exploitation and, where appropriate, the scale-up of experimental facilities that they have started to develop as initial prototypes.

Recommendation 3.5. The task of planning for a sustainable future for activities currently funded under QTFP programme should be prioritied by STFC, EPSRC and UKRI. A funding line for successful QTFP projects should be identified, which must not have a detrimental impact on the existing Particle Astrophysics programme.

The nature of Particle Astrophysics research is such that new ideas and developments steer researchers in the direction of new approaches and experiments. In some cases, these new directions mature to become well funded and scientifically important research directions. However, getting the research to this stage requires funding support. An agile and flexible approach to early phase research is crucial for encouraging early career researchers and for ensuring the research programme does not stagnate. The now-discontinued Project Research and Development (PRD) funding scheme provided a good avenue to support new research and we support its revival. There remains a need for lower level funding for prototype research and investigation. This could be funded at 100% agency cost so that these grants do not have to be overhead-bearing for Universities to approve them. The review process for this funding must be lightweight whilst also ensuring that proposals outside of existing research directions are given a fair hearing.

Recommendation 3.6. STFC should identify a mechanism to provide low-level funding to exploratory research for enable initial investigations. The revival of the previous PRD scheme would go some way towards filling this need. A second funding stream, with a funding cap in the low tens of thousands, to support very early stage development, should also be introduced.

The life-cycle of space instrumentation in the UK is serially funded via multiple agencies. Preparation work including modelling, simulations, and technology studies, etc., together with hardware research and development up to mission selection, are funded via STFC. After selection, UK Space Agency become responsible for funding the design and construction of space mission instruments/software/systems and post-launch support. Later, the funding remit again falls to STFC to provide for the exploitation of mission data. This cross agency funding mechanism, known as the "dual-key" approach, makes it essential that both agencies share matching strategic aims, and well coordinated funding and prioritisation processes, to ensure that adequate funding is in place to support the full lifetime of the mission thus ensuring a successful UK outcomes. This should include both the UK core involvement via ESA missions, plus the possibility for bi-lateral programmes which have been so productive in the past.

Recommendation 3.7. Cooperation between agencies supporting space missions should be fostered through cross-representation on relevant committees. Additionally, the funding mechanisms and processes underlying the dual-key approach should be made more transparent via monitoring and evaluation of regular published reports.

4 Gravitational Waves

The past decade has seen the coming of age of gravitational wave physics and astronomy. During that time, the advanced LIGO-Virgo-KAGRA observatories have begun observing and the Laser Interferometer Space Antenna (LISA) pathfinder mission was successfully undertaken. The first observation of gravitational waves from a black hole merger in 2015 was closely followed by a multi-messenger observation of a neutron star merger and the subsequent observation of a population 90 binary merger signals. Over the next decade, the sensitivity of the LIGO-Virgo-KAGRA network will improve, leading to daily observations of gravitational waves from binary mergers and likely observations of gravitational wave signals from asymmetric neutron stars, supernova explosions, astrophysical backgrounds or unexpected sources. The next generation of ground based observatories, Einstein Telescope (ET) and Cosmic Explorer (CE), are expected to begin operation in the mid-2030s providing significantly improved sensitivity. The LISA mission will launch in 2034 providing sensitivity to low frequency gravitational waves from sources such as merging super-massive black holes. Pulsar timing arrays observing in the nano-Hertz band have observed the possible signature of a gravitational wave background from super-massive black hole binaries. Continued observations, and sensitivity improvements afforded by the Square Kilometre Array (SKA) and precursors, will likely enable gravitational wave observations in the nano-Hertz band.

Gravitational Wave observatories are designed to elucidate "What can gravitational waves tell us about the universe" (A.8). They provide a unique capability to observe mergers of neutron star and black holes (from stellar mass to supermassive), 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 probe the nuclear processes involved in neutron star mergers and supernovae (A.6), and observations of neutron stars, both individually and in binaries, enable measurements of nuclear matter at extreme densities (C.6) and may, potentially, identify new states of matter such as quark or boson stars (C.7). Gravitational wave observations provide a direct probes 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).

4.1 Advanced LIGO

Status. aLIGO and Advanced LIGO plus (A+) are funded by STFC. aLIGO operational, A+ upgrade complete in 2025.

aLIGO consists of three 4 km laser interferometric GW detectors. Two of these detectors are operational and are located in the United States, with the third detector currently under construction in India. The first science data taking, from Sept 2015 to Jan 2016, yielded the first direct observation of gravitational waves. Subsequently, aLIGO has operated jointly with the advanced Virgo and KAGRA detectors as part of a global network. The aLIGO project is primarily funded by the US National Science Foundation. The UK has made significant contributions to aLIGO through the provision and installation of hardware, particularly the mirror suspensions, commissioning of the instruments, provision of computing resources and implementation and operation of analysis and interpretation pipelines. In addition, a number of UK scientists lead or have led instrumental, observational and operational working groups within the LIGO Scientific Collaboration. The fourth observing run is scheduled to commence in late 2022, at which time the global network is expected to observe several gravitational wave transients per week.

The A+ upgrade will increase aLIGO's detection rate for black hole and neutron star mergers by a factor of 4 to 7. UK research has developed several key technologies that underpin A+ including low dissipation optical coatings, monolithic silica suspensions and quantum-limited readout schemes. The UK community has assumed a lead role in the project thanks to a significant capital investment from STFC (£10.7 million). This contribution is scheduled to complete by Dec 2022, with installation completed in 2024. Data taking for the fifth observing run (at A+ sensitivity) will commence 2025. Further upgrades beyond A+, with heavier silica mirrors and longer suspension fibres, to enhance low frequency performance are expected by 2030. This may be followed by a cryogenic system operating at 120K. Design studies and prototyping are ongoing.

Over 100 researchers, including 40 academic faculty members, from institutions around the UK are members of the LIGO Scientific Collaboration. Indeed, over the last five years around a quarter of these researchers have held or currently hold influential leadership positions within the LIGO Scientific Collaboration. Comprehensive involvement in instrument science, operations, analysis and exploitation allows the UK to maintain the prominent role it has held since LIGO's inception three decades ago.

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.

4.2 Next generation GW observatories

The next generation GW observatories, ET and CE, will provide a factor of ten sensitivity improvement over aLIGO. They will be able to determine the nature of the densest matter in the universe through precision measurements of neutron-star mergers; reveal the universe's binary black hole population throughout cosmic time; provide an independent probe of the history of the expanding universe; explore warped space-time with unprecedented fidelity; and expand our knowledge of how massive stars live, die, and create the matter we see today. Observing jointly, the global ET-CE network will provide thousands of well-localized events each year for follow-up with telescopes which would help understand the central engine of gamma-ray jets and the formation of heavy elements in the Universe. Sources that are barely detectable by current detectors will be resolved with incredible precision.

4.2.1 Einstein Telescope

Status. Currently in design phase. Some research funded through STFC GW grant round.

ET [19] is a proposed third-generation GW observatory in Europe, envisioned as a set of underground interferometers whose arms form an equilateral triangle. ET will have ten times the distance reach of aLIGO across a broad frequency band, and be sensitive to GW frequencies as low as 2Hz. It will constitute a facility with infrastructure capable of delivering science for several decades. ET was included in the most recent ESFRI roadmap, and highlighted in the UK

Infrastructure Roadmap. The current timeline foresees the selection of the ET site in 2024, installation/commissioning completed in 2032 and beginning of observations in 2035. The UK has a strong presence in ET including consortium membership, R&D support and MoAs with ET project.

4.2.2 Cosmic Explorer (CE)

Status. Currently in design phase. Some research funded through STFC GW grant round.

CE is a concept for two 'L'-shaped GW observatories, likely to be located in the US, one with 40 km arms and the other with 20 km, that are designed to greatly deepen and clarify our ability to study the cosmos using GWs. The CE Horizon Study [15] lays out the detailed scientific goals and technical design of the CE detectors. The timeline foresees site selection and construction beginning later this decade, followed by commissioning and a first observing run around 2035.

The UK has substantive expertise across a range of technology and astrophysics areas that are highly relevant for both the CE and ET observatories. These include the design and development of ultra-low noise test masses and their suspensions both at room and cryogenic temperatures; design, fabrication and characterisation of mirror coatings of low optical and mechanical loss; cryogenic interferometry at wavelengths compatible with use of silicon optics; suspension control systems and interferometric sensors; novel seismic isolation systems. In many cases, UK scientists are uniquely well placed to deliver these developments to *both ET and CE*. UK Scientists have expertise in modelling, detection and gravitational wave astrophysics relevant for the next generation observatories. This includes precision modelling of signals from black-hole and neutron-star mergers; modelling of signals from individual neutron stars; determining the properties of dense nuclear matter; gravitational wave cosmology; performing surveys for merging black holes across the universe.

Given its strong track record, the UK is ideally placed to play a leading role in the design, construction, operation and science exploitation of CE and ET. However, the UK does not currently have dedicated investment strategy to position it as a leader of the next-generation experiments. Recently, other countries have invested significant amounts in both staff and dedicated next-generation GW facilities to ensure leadership in these projects. There has been good historical investment in hardware and facilities in the UK, providing a strong legacy which underpins the current support for future observatories. It is of paramount importance that the UK provide significant investment towards next-generation observatories to maintain its long-standing leadership in this field. In addition, the UK must increase its support for theoretical and numerical modelling of GW signals and development of GW detection and signal interpretation techniques. Theoretical and computational development is required now to ensure we have the tools to perform the precision GW astronomy enabled by the next generation observatories. The expected cost for full involvement in the next generation network is £10M for preparatory activities (2022-26) and £100-200M for contribution to full project infrastructure costs (2025-35).

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. STFC should submit a bid to the UKRI Infrastructure Fund to support next generation GW Observatories.

4.3 LISA

Status. Funded by United Kingdom Space Agency (UKSA). Expected launch in 2034. Science exploitation funded by STFC.

LISA is a gravitational-wave observatory operating in the low frequency (0.1 mHz - 0.1 Hz) region of the spectrum. LISA will observe the Galactic population of double white dwarfs with periods < 1 hr; neutron star and stellar mass black hole binaries in the low-redshift ($z < 0.1$) Universe; intermediate-mass (between 100 and 10^5 solar mass) black hole binary mergers; extreme mass ratio binaries (comprised of a Neutron star or stellar mass black holes orbiting just outside the horizon of a super-massive black hole) up to a redshift $z \sim 2$; massive black hole binaries throughout the Universe and a background of gravitational-waves from the very earliest moments of the Universe.

LISA is the European Space Agency (ESA) L-mission selected for the "Gravitational Universe" theme. The UK has been involved in the mission at the scientific and technology level, and its highly successful technology demonstration mission LISA-Pathfinder, from its inception. This includes the development of the mission concept that eventually led to the successful proposal to ESA [10]. LISA is currently in Phase A (due to be completed at the end of 2021), following which it will enter phase B1 leading to an anticipated adoption in 2024. After adoption, LISA will begin mission implementation. The expected launch is in 2034+ followed by a cruise and commissioning period lasting approximately 2 years. The mission is designed to provide an initial science measurement time of 4 years, with a potential extension to 10 years of post-commissioning operation. The UK's main contributions to the mission are the optical bench, solely a UK responsibility, and the ground segment. The cost for participation in the mission is provided by UKSA, and is anticipated to be approximately £25M for the optical bench and £17M for the ground segment up to launch.

Support for LISA science exploitation will be provided by STFC through consolidated grant funding. Prior to launch, this will focus on preparation for science exploitation in the areas of astrophysics, source modelling and complementary observational astronomy programmes. The current level of funding is approximately 1 FTE through the AGP. It is critical that at least this level of funding be maintained to ensure UK involvement in the mission. As for CE and ET, investment in the development of accurate GW models and data science techniques is required now to ensure the UK's ability to fully exploit the LISA data in the future.

Recommendation 4.3. We strongly endorse the continued UK participation in LISA, funded by UKSA. STFC support for science exploitation must, at a minimum, be maintained at the current level. Additional funding of theoretical and data analysis research is required to ensure UK leadership in exploitation of the LISA data. STFC should identify how this will be achieved and which other areas LISA funding should be tensioned against.

4.4 Pulsar Timing Arrays

Status. Operating. Not supported by STFC.

Pulsar Timing Arrays (PTAs) are sensitive to gravitational waves in the nano-Hz frequency range (the observational window is between 1nHz and 1 μHz). They extend the frequency coverage of GW below those covered by LISA and ground based observatories. Sources in the nano-Hz band are super-massive black hole binaries (10^6–10^9 solar masses) — crucial for our understanding of structure formation in the Universe, galaxy and black hole evolution — and more speculative early-Universe processes.

The European Pulsar Timing Array (EPTA) and International Pulsar Timing Array (IPTA) are in the operation and science exploitation phase. Data from pulsars observed over a decade-long baseline have been analysed and the results published and data from a baseline of 25+ years are being processed. Work is ongoing to carry out what will be the most sensitive search so far for gravitational waves in the nHz band. The sensitivity of EPTA and IPTA is currently being "upgraded" through improvements to receivers and data acquisition systems at the existing telescopes that form part of the array and the addition of new telescopes like FAST, MeerKAT, LOFAR and the GMRT which improve cadence and sensitivity. New millisecond pulsars (the tools for PTAs) are discovered by new surveys, with the number almost doubling in the last 5 years; timing programmes from SKA pathfinders and the full SKA contribute data to IPTA for gravitational wave searches.

UK academics have been at the forefront of EPTA and IPTA since their inception over a decade ago, and have played leading roles in the establishment of new techniques like the Large European Array for Pulsars (LEAP). Many of the analysis techniques to search for gravitational waves in PTA data have been developed in the UK and are now widely adopted by PTA projects around the world. The UK has expertise and responsibility for data collection (at Jodrell Bank, through LEAP and with MeerKAT), reduction and data combination in the wider EPTA (and IPTA) data set, pulsar noise characterisation, gravitational-wave data analysis, searches and astrophysical modelling. The UK is contributing to projects with SKA pathfinders (LOFAR and MeerKAT) to discover new millisecond pulsars and to undertake high precision timing. UK Scientists also play a leading role in the development of the pulsar capabilities for the SKA.

There is currently no co-ordinated funding approach in the UK to support activities in EPTA. The current level of funding is approximately one FTE, as well as £150k for the Lovell telescope. Secure, long-term funding would greatly benefit UK involvement in EPTA and enable stability and strategic planning. This is particularly important at this critical time when the sensitivity of PTAs is approaching the level to allow the first gravitational wave detection at nano-hertz frequencies.

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.

5 Very High Energy Gamma ray astronomy

VHE Gamma astronomy is key to a wide range of scientific investigations, focussing on highly energetic non-thermal processes such as: establishing the sources of the very highest energy (PeV) cosmic rays; particle acceleration by black holes and jets; and fundamental physics questions about dark matter and possible Lorentz violation. While space-based systems have the advantage of continuous operations, ground-based facilities can achieve huge effective area using imaging air Cherenkov telescope (IACT) or water Cherenkov techniques. The current IACT arrays, High-Energy Stereoscopic System (H.E.S.S.), MAGIC, and VERITAS, have demonstrated the huge physics potential at these energies as well as the maturity of the detection technique. The UK played a founding role in ground-based γ-ray astronomy and is now participating in the soon to be constructed CTA, H.E.S.S., and Southern Wide-field Gamma-ray Observatory (SWGO). The STFC PA programme provides funding for the design and construction of CTA, however support for science exploitation in gamma-ray astronomy has had to be found from other sources, including universities, quota studentships, and ODA funding.

5.1 Cherenkov Telescope Array

Status. Currently in Pre-Production phase. Construction slated to begin 2022. STFC supported.

The CTA is the next generation ground-based very high energy γ-ray astronomy observatory, comprising more than 100 telescopes located at sites in the northern and southern hemispheres. With 10 times higher sensitivity than current γ-ray telescope arrays, CTA will transform our understanding of the high-energy universe and will explore topics from fundamental physics, such as searches for dark matter and evidence for axions and quantum gravity, through to astrophysical questions, including particle acceleration, relativistic jets, and the role of high energy particles in star and galaxy formation. It will also be the first ground-based γ-ray observatory open to the worldwide astronomical and particle physics communities as a resource for data from unique, high-energy astronomical observations.

Three telescope configurations are required to cover the full CTA energy range (20 GeV to 300 TeV): 23 m Large-Sized Telescopes, (LST), 12 m diameter Medium-Sized Telescopes (MST), and 4 m diameter Small-Sized Telescopes (SST). The UK has participated in the CTA project since the initial letter of intent to ESFRI in 2005. Alongside the involvement of γ-ray astronomers and astroparticle physicists in the development of the CTA science tasks, including the key science projects, the UK groups took an early and leading role in the development of CTA instrumentation, focussing mainly on the camera for the novel two-mirror Schwarzchild-Couder design of Small-Sized Telescope (SST).

The SST array, to be sited at CTA-South, will comprise up to 70 telescopes spread over several square kilometres and provide sensitivity at the highest energies, from a few TeV to 300 TeV. The UK-CTA collaboration has played a leading role in the development of the Compact High Energy Camera (CHEC), which was selected with the Italian ASTRI-Horn telescope structure for the SST array. First light for silicon photomultiplier-based CHEC-S prototype was achieved on the ASTRI-Horn telescope in April 2019 at the Serra La Nave Observatory on Mount Etna in Sicily, and design finalization of the SST for the production phase is now underway.

The CTA Board of Governmental Representatives approved the CTA Observatory's Cost Book and Scientific & Technical Description in June 2021 and the establishment of CTAO as a European

Research Infrastructure Consortium (ERIC) is expected early 2023 with the SST Construction phase beginning mid-2023. The UK are planning to contribute 13 cameras for the 37 SSTs envisaged in the first "Alpha" construction phase at a cost of £5M spread over the period 2022-27.

The UK has 60 researchers in the CTA Consortium from 12 institutes, and the recently-held CTA UK Science Meeting, which took place in June 2021, attracted over 90 participants from 20 UK institutions. The level of access for this community to CTA science data and the key science programmes under our ESO membership would not be remotely comparable to that provided in the case of direct UK membership via provision of in-kind contributions to the CTA Observatory, as is currently planned.

Recommendation 5.1. To maintain UK leadership in VHE gamma-ray astronomy leadership over the next 10-20 years participation in CTA is essential. In the short term, investment is urgently needed in CTA construction to ensure UK access to the key science projects, allowing the UK community to maintain leading roles and benefit fully from CTA science returns. In the longer term, there may be upgrade investment needed for CTA, and continuing support will be required for exploitation and operation.

5.2 Southern Wide-field Gamma-ray Observatory

Status. Planned. Not currently supported by STFC.

IACTs and extensive air-shower arrays (EAS) such as HAWC are complementary techniques to study atmospheric showers. While IACTs such as CTA are highly sensitive relatively narrow field-of-view pointing instruments limited to night-time observation, SWGO will be a wide-field observatory with very high duty-cycle for mapping large scale emission as well as providing access to the full sky for transient and variable multi-wavelength and multi-messenger phenomena.

SWGO is aimed as a southern version of the current ground-based detector arrays HAWC, in Mexico, and LHAASO, in China. It will be a γ-ray observatory based on ground-level particle detection, with close to 100% duty cycle and order steradian field of view, located in South America at a latitude between 10 and 30 degrees south and an altitude of 4.4 km or higher. Based primarily on water Cherenkov detector units it will cover an energy range from 100s of GeV to 100s of TeV.

The SWGO Collaboration was founded in July 2019 by a group of about 40 institutions from 9 countries (including the UK) as an international R&D Project to develop what would be the first extensive air-shower array for γ-ray astronomy in the Southern Hemisphere providing unique access to the Galactic Centre. It will be highly complementary to CTA and to neutrino telescopes such as KM3Net and IceCube.

The SWGO collaboration includes four UK institutes, and an SWGO-UK proposal was submitted as an STFC infrastructure project but was not prioritized in 2020. An SWGO-UK project would maintain and build on the expertise in γ-ray astronomy instrumentation and science fostered in the UK through our involvement in the CTA observatory, which is soon to go into its construction phase.

Recommendation 5.2. In the medium term, SWGO presents an important opportunity for VHE gamma-ray astronomy extending to PeV energies, with its unique coverage of the Galactic centre, where a modest investment in 2024-26 could represent a significant stake for the UK. However, this cannot replace the science returns and impact from CTA membership and should be given lower priority.

5.3 High-Energy Stereoscopic System

Status. Running. Not supported by STFC.

H.E.S.S., situated in Namibia, is the largest of the current generation of ground-based imaging air Cherenkov experiments (the others being MAGIC on La Palma and VERITAS in Arizona). H.E.S.S. consists of four 12-m telescopes, and one 28-m telescope, which is the largest γ-ray telescope in the world. The 28-m telescope is now equipped with a prototype CTA camera, giving unparalleled sensitivity at low energies, which has allowed recent breakthrough results in observations of GRBs from the ground.

The UK has had significant historical leadership in H.E.S.S., and today two UK institutes are full members. H.E.S.S. has a long record of high-impact results, including 13 publications with over 200 citations each, and was the recipient of the AAS Rossi Prize in 2010. Science output remains world-leading, including two papers in Nature and one in Science in the past two years. The UK has significant science leadership in current H.E.S.S. operations, with a leading roles in the Science Working Group on Jets (i.e., AGN physics and associated fundamental physics from AGN observations) and active on GRBs. UK institutes fill two places on the Collaboration Board and Steering Committee.

In the run-up to CTA construction, H.E.S.S. provides unique training for STFC Doctoral Training Partnership students in VHE γ-ray astrophysics observations and analysis. At present, four STFC-funded UK Ph.D. students are active H.E.S.S. members, including participating in night and day shifts, and seven Ph.D. students in total at UK institutions have been members in the past two years.

Additionally, there is a novel technology transfer project underway at present, using UAVs for H.E.S.S. telescope calibration. This is led by a UK institute in collaboration with UK industry with funding from AGP consolidated grant and the Royal Society and is under consideration for CTA and other future projects.

STFC support is provided for observatory operations and astronomy postdocs via a GCRF award, and from institutional support from the participating institutes.

H.E.S.S. is the most capable VHE γ-ray telescope system currently in operation, has a high level of activity and scientific output, and very good value for money in the run-up to CTA construction. However, H.E.S.S.-specific activities should not form part of the prioritised Roadmap for STFC support, due to the high value of CTA.

Recommendation 5.3. H.E.S.S. is the most capable VHE gamma-ray telescope system currently in operation, but should not form part of the prioritised Roadmap for STFC support due to the high value of CTA.

6 Dark Matter

There is a wealth of indirect experimental evidence for the existence of dark matter via its gravitational interactions with observable baryonic matter, and through the observed cosmic background radiation anisotropy. There are many possibilities for dark matter, and indeed the solution may involve several constituents. Two well motivated ideas for cold dark matter are WIMPs and much lighter wave-like hidden sector candidates of which the Quantum Chromodynamics (QCD) axion is a prominent example. Direct search experiments for WIMPs and axions are both supported in the UK. Though direct dark matter searches aim to discover dark matter, they also test particle physics theories by limiting parameter space predicted for dark matter particles. The UK dark matter community grew substantially since the last Particle Astrophysics Roadmap in 2016. This growth reflects scientific interest in direct dark matter searches, some migration of effort from collider experiments, and widening landscape of dark matter models and experimental techniques. The diversification is essential in the long term but it requires a careful consideration to balance it with the focused effort which has proved to deliver world-leading results.

Direct dark matter searches endeavour to answer the questions: "What is the nature of dark matter and dark energy?" (C.4) and "What role does dark matter play in the universe evolution?" (A.3). Properties of dark matter candidates affect formation of the initial structure in the universe (A.2), and formation and evolution of galaxies (A.4, A5). Astrophysical observations contradict the assumption that dark matter could be formed from known particles of the Standard Model, therefore a discovery of dark matter would transform our understanding of fundamental particles and fields (C.1) and laws in the early universe (A.1).

6.1 Direct Searches for WIMPs

Pioneering experimental work on direct detectors for WIMPs was based in the UK, and subsequently several generations of ever-more-sensitive direct WIMP searches have been supported by STFC, with the latest UK activity being through leading contributions to large international collaborations. We summarize here direct search experiments having UK agency support. This is a highly competitive field, and several international collaborations are competing to reach ever greater sensitivities using larger detector masses. Three prominent detector technologies in the latest generation of direct searches involve liquid xenon and liquid argon targets, and solid state germanium detectors. It is anticipated that future detectors will eventually detect a coherent scattering of neutrinos on target nuclei ("neutrino floor"). Both the USA P5 [20] report and APPEC Dark Matter [14] report recommend enhanced support of experiments which are able to reach down to the "neutrino floor" on the shortest timescale. To search for WIMPs at greater sensitivity than this, directionally sensitive detectors at very high target mass would likely be required.

Both the STFC Particle Astrophysics Programe Evaluation [3] and the 2020 Dark Matter Strategic Review [4] recommend significant increases in funding for DM searches to capitalise on the extensive UK expertise in dark matter research. The Boulby Feasibility Study funded by the 2019 STFC Opportunities call prepared pre-conceptual design and cost estimates for developing the UK underground lab into a facility able to host a major international project. Though this would be a great opportunity, it should not jeopardise UK participation in world-leading experiments not based in Boulby.

6.1.1 LUX-ZEPLIN

Status. Operating. Construction and exploitation supported by STFC.

Recent improvements in the sensitivity to spin-independent dark matter interactions were made by 3 competing xenon-based experiments: LUX, XENON, PandaX. Using ZEPLIN expertise, UK groups made a significant contribution to LUX. LZ is a direct detection experiment searching for the scattering of dark matter particles in a 7-tonne liquid xenon target. The experiment will start acquiring physics data in 2021 after completing the final stages of commissioning at SURF in South Dakota (USA). The UK Construction Project was completed in 2019 on schedule and within budget, and the exploitation effort is now supported through the PPGP(E) Consolidated Grants. The 9 UK institutes contribute around 25% of the 250-strong LZ collaboration which includes 35 institutes from the USA, UK, Portugal and Korea.

LZ offers a broad and exciting science case for various dark matter interactions including spin-independent and spin-dependent ones. A best SI sensitivity of $1.4 \cdot 10^{-48}$ cm^2 for 40 GeV WIMPs and a mass reach to 3 GeV with standard analysis techniques are expected to be achieved in the 1,000 live-day exposure by 2025/26. New analysis techniques will further decrease the energy threshold for both nuclear recoil and electron recoil interactions to O(keV) or below, resulting in even better sensitivity for low mass dark matter particles. LZ can make a first detection of the coherent nuclear scattering of ^{8}B solar neutrinos and perform a competitive search for neutrinoless double beta (0NBB) decay in ^{136}Xe and other isotopes.

Several possible upgrade paths are being discussed but they have not been formalised.

6.1.2 Liquid Xenon Rare Event Observatory (XENON FUTURES)

Status. Planned. Supported by STFC for R&D activities.

The current experiments exploring the WIMP mass range will either discover dark matter or set further constraints. If dark matter is discovered then a multi-tonne detector will be required to study its properties. If no discovery is made then a detector with maximal discovery potential is a natural follow up of the current programme. A next-generation experiment utilising $50-100$ tonnes of liquid xenon (LXe) will provide many opportunities for studies of dark matter and neutrino physics [7]. The main goal is to search for dark matter in wide mass range (0.1–10000 GeV) and reach the "neutrino floor". The coherent neutrino-nucleus scattering (CNNS) represents an irreducible background for the dark matter searches but also these flavour-blind measurements will study the ^{8}B solar and atmospheric neutrinos, and neutrinos from a nearby supernova. A doping with light elements (H_2, D_2) could improve the sensitivity to light particles. The 0NBB sensitivity could be improved by ^{136}Xe doping and using lower radioactivity photon sensors like SiPMs.

An MOU has been signed by 104 research group leaders from 16 countries representing the XENON/DARWIN and LZ collaborations to work together on the design, construction, and operation of a new multi-tonne scale xenon dark matter detector. The UK is very well represented in the newly formed steering committee to ensure a significant contribution to the planned experiment.

The project is supported in UK until 2024 with 10 UK institutions participating. It is expected that it will be followed by a 2-year Pre-Construction Project and this will lead to a capital-intensive 4-year Construction Project planned to start in 2025. Data-taking would take place for around 10 years until late 2030s. A site for the experiment has not been chosen yet and the Boulby mine could be a possible host.

6.1.3 DarkSide

Status. Under construction. Supported by STFC for R&D activities.

UK groups are involved in dark matter searches with liquid argon targets. Additional suppression of background is possible using pulse shape discrimination which has been demonstrated by DEAP-3600 and DarkSide-50 experiments. The detector DarkSide-20k which is currently under construction at LNGS (Italy) will use 20 tonnes of liquid argon in fiducial volume to reach the sensitivity $7.4 \cdot 10^{-48}$ cm^2 for 1 TeV WIMPs with 200 t×year exposure.

The DarkSide-UK project leverages the UK's world-leading silicon detector integration capability to grow UK leadership in production of large silicon photo-multiplier (SiPM) arrays for future liquid noble dark matter experiments and the DUNE module of opportunity. Substantial knowledge exchange with the DarkSide collaboration allows R&D to be kick-started on the SiPM module (PDM) from the state-of-the-art. The R&D includes a production process for PDMs with low radioactivity and VUV sensitivity, and integration of electronics including 3D integration strategies. The PDMs will be characterised in a cryogenic platform at liquid nitrogen temperature and installed at the DarkSide experiment to be used for dark matter searches. The UK has responsibility for delivery of 2,500 PDMs for the instrumentation of the DarkSide-20k experiment ($\sim$25% of the total). The project was approved by STFC Science Board in 2020 with 14 collaborating institutions in the UK. DarkSide has secured major capital funding in Italy, the USA, Canada, Poland, Spain, France, Russia, and a capital funding bid in China is in progress. DarkSide-20k commissioning is planned for 2024 with data-taking through to 2030.

The Global Argon Dark Matter Collaboration (GADMC) was formed in 2016 with the aim of developing the ARGO detector as the next stage beyond DarkSide. The preliminary ARGO configuration calls for a 400 tonne purified underground argon target. Exploitation of ARGO is planned for $2030 - 2040+$.

Recommendation 6.1. Support LZ operations/exploitation as the highest priority. Support DarkSide-20k operation/exploitation upon successful completion of the construction phase.

Recommendation 6.2. Support UK participation with a significant leadership role in design, construction and operation of at least one large-scale direct dark matter search experiment. STFC should ensure that decisions are made in a timely manner so that leadership roles are possible.

6.1.4 DarkSphere

Status. Under construction. Support from STFC through consolidated grants.

DarkSPHERE will explore the nature of DM using Spherical Proportional Counters (SPCs) to search for light DM candidates in the $0.05 - 10$ GeV mass region, with sensitivity reaching the 'solar neutrino floor'. As part of the international NEWS-G collaboration, which has major UK leadership and expertise in areas that underpin the primary physics goal, UK groups contribute to the construction and physics exploitation of ECUME, a 140 cm diameter SPC fully electroformed underground at SNOLAB, which is under construction and will start taking data in 2023. The UK groups will leverage the expertise from ECUME to build DarkSPHERE, a 300 cm SPC fully electroformed underground at the Boulby Underground Laboratory, with the construction starting in 2024 and 6 UK institutions participating.

6.1.5 QUEST-DMC

Status. Under Construction. Supported by the UKRI QTFP programme.

The QUEST-DMC project will search for light DM candidates in the sub-GeV mass range using a quantum-amplified superfluid helium-3 calorimeter. The fully funded Phase 1 of the project will include a six month dark matter search campaign in the Lancaster ULT facility. A currently unfunded Phase 2 aims to scale up the experiment and expand the search mass range, targeting the Boulby Undergound Laboratory as the host site. In addition to the dark matter activities, Phase 1 of QUEST-DMC will test the nucleation theory of phase transitions in the quantum vacuum of the early universe.

Recommendation 6.3. STFC should develop a clear strategy for supporting R&D efforts aimed at widening the accessible range of masses and interactions of particle dark matter, which would include low-level seed-corn funding and mechanisms to transition to larger-scale experiments.

6.2 Direct Searches for wave-like hidden sector dark matter

Starting in the 1970s with theoretical studies of the relationships between particle couplings and masses, the idea grew up that very light particles might have correspondingly faint couplings to standard model fields, and might therefore evade detection in accelerators. Hidden sector dark matter consisting of ultra-light (lighter than 1 eV) particles have a long de Broglie wavelength and require a very large number density to reach the observed local halo mass density for dark matter. These properties imply that ultra-light hidden sector dark matter acts coherently as massive fields with wave-like properties. Direct detection of these particles involves coherent conversion rather than kinematic single particle interactions as with WIMPs. The most prominent example of hidden sector dark matter is the QCD axion, which, were it to exist, could simultaneously solve the dark matter problem and the strong CP problem of QCD.

Interest in the hidden sector dark matter hypothesis has been ramping up rapidly in the last five years. In 2019, UKRI responded to this growing interest, launching the QTFP call and funded seven projects exploiting quantum technologies for fundamental physics purposes, initially supporting these projects for 3.5 years. Three of these projects aim to search for hidden sector dark matter. A further call for quantum technology development to support STFC fundamental science through a number of smaller, £0.5M, 2 year projects is currently open.

It is clear that in general the relatively new territory explored by ultra sensitive detectors exploiting the special properties of matter predicted by quantum mechanics is a new and rapidly growing area of interest. The number and variety of projects proposed under QTFP supports this statement. It could be that a new low energy frontier of new physics close to the vacuum state is opened up in this area.

6.2.1 Quantum Sensors for the Hidden Sector

Status. Under Construction. Supported by the UKRI QTFP programme.

The QSHS group aims to build a UK facility probing the hidden sector of light wave-like dark matter candidates including axions, ALPs and hidden sector particles. Hidden sector dark matter could exist at a range of sub electron volt masses, with QCD axions particularly well motivated by the long standing strong CP problem.

Detection utilises millikelvin temperature ultra low noise quantum electronics coupled to tunable microwave electromagnetic resonant structures. QSHS is developing a UK target instrumented with quantum electronics and readout to instrument resonant detectors for axions, ALPs and hidden sector photons in a demonstrator apparatus in a UK-based test stand. This test stand will initially target axions in the mass range $20 - 40\,\mu$eV with a resonant target threaded by an 8T magnetic field.

The longer term aim is a UK-based large scale detector. Towards this aim, QSHS is collaborating with the ADMX experiment, with an MoU already signed committing to joint research on resonant structures and data analysis.

6.2.2 AION

Status. Under Construction. Supported by the UKRI QTFP programme.

The Atomic Interferometric Observatory and Network (AION) project plans to construct a staged series of differential atom interferometers ('gradiometers') using clouds of cold strontium atoms. A goal of the initial funding period is to construct a 10m instrument in Oxford. These experiments achieve sensitivity to ultra-light hidden sector fields with masses of order 10^{-14} eV through their contribution to the phase shift of the atoms.

The proposed longer baseline successor instruments, AION-100 and AION-km, are potentially sensitive to a broader range of hidden sector particle masses and types, as well as gravitational waves in the previously unexplored mid-frequency band ranging from several mHz to a few Hz, and could provide new tests of the equivalence principle. AION has partnered with the 100m MAGIS interferometer in the US and an agreement to share R&D and data has been agreed. Other uses of cold atoms in space are also being explored, and UK groups are participating in the proposal of a new M-class mission called STE-QUEST that will be submitted in the 2022 open call from ESA in the context of the Voyage 2050 programme. Like AION and MAGIS, STE-QUEST will be based on cold-atom technology and synergies between terrestrial and space-based experiments are being explored.

6.2.3 Quantum-enhanced Interferometry

Status. Under Construction. Supported by the UKRI QTFP programme.

The QI project utilises techniques developed by the quantum hubs and the gravitational-wave community to search for dark matter candidates and signature of quantization in space-time and gravity. ALPs lighter than 10^{-9} eV are targeted by exploring a novel coupling mechanism of (galactic halo) ALPs to light (via polarization rotation) in a dedicated interferometer. The project also develops a new TES sensor as part of the UK contribution to the international 'ALPs' experiment at DESY. The ALPs experiment searches for ALPs independent of the galactic halo, being a so-called 'light-shining-through-a-wall' experiment. A third experiment in the QI project predominantly targets quantization of space-time, but is also sensitive to scalar field dark matter. All of these can be scaled to larger facilities in different ways, to increase future discover potential.

Recommendation 6.4. STFC should continue to support hidden sector direct dark matter research and grow the new research community in this area through further funding calls beyond the initial QTFP call, to sustain this research in the longer term. This funding must be made available from sources other than those presently supporting particle astrophysics.

7 Neutrino Astronomy

The area of neutrino physics covered by the Particle Astrophysics community can be summarised as neutrinos from astrophysical sources, which are some of our best messengers, carrying fewer complications than photons due to the absence of interactions along their path. Despite being difficult to detect, neutrinos are already providing information that is being correlated with other sources of information such as gravitational waves and UHE cosmic rays, helping to identify astrophysical sources for astrophysical and cosmological events and effects. The next 10, 20 and 30 years will bring more data from astrophysical neutrinos that will be crucial to unravelling questions that are being addressed currently.

Other neutrino research is typically covered under the remit of particle physics, including neutrinoless double-beta decay, neutrino mass, and long- and short-baseline oscillation experiments; however, many of those experiments also contribute to research of neutrinos from astrophysical sources, such as the solar neutrino programme at SNO+ that may help to determine the metallicity of the sun, and involvement in supernovae monitoring programmes such as the international programme SNEWS. Upcoming experiments DUNE and Hyper-Kamiokande that are funded by STFC through Projects Peer Review Panel (PPRP) at present will look for diffuse supernovae backgrounds, solar neutrinos and astrophysical neutrinos. All of these experiments will have involvement in SNEWS.

Neutrino astrophysics is central to several STFC Science Challenge Questions, for example: opening windows to the early universe and its formation through searches for Cosmic Neutrino Backgrounds, sterile neutrinos and heavy neutrinos (A1, A2); determining how stars, black holes and galaxies form through identifying blazars (A4); determining the metallicity of the sun to enable a better understanding of the evolution of stars (A5); measurement of the neutrino flux in the PeV region to determine what these ultra-high-energy particles can tell us about the universe (A8); and identifying the fundamental particles through sterile and heavy neutrino searches (C1).

7.1 UK High-Energy Neutrino Consortium

Astrophysical high-energy neutrinos can explore the highest energy universe through multi-messenger astronomy. They are the only messengers allowing us to point back to the high-energy objects beyond our galaxy above $\sim 50-100$ TeV. This unique ability was used to discover the first high-energy neutrino point source, blazar TXS056+0506. Topics of astrophysical high-energy neutrinos include the mechanism of the highest-energy engine in the universe, the origin of ultra-high-energy cosmic rays, the search for the highest-energy processes such as the GZK cut off, and the study of fundamental physics.

The UK is currently involved with three experiments in neutrino astrophysics: IceCube - IceCubeGen2, ANITA/PUEO and Pacific Ocean Neutrino Explorer (P-ONE), with project R&D and exploitation effort at a low level funded by a mixture of STFC, Royal Society and charitable funding. The UK High-Energy Neutrino (UHEN) consortium is working toward consolidating the UK effort in a few targeted areas on each of these experiments, and looking to see how the UK effort can be both expanded and focussed on a single future observatory-scale experiment. The current leading candidates for such a future experiment include an upgraded optical and radio Cherenkov experiment at the South Pole; a distributed network of optical Cherenkov detector modules, most likely ocean-based; and a distributed network of radio Cherenkov detector modules, either on the surface (e.g. a tau-neutrino mountain-side experiment) or in the ice. Construction would start after the end of the current R&D experiments (e.g. after 2025). No large-scale future experiment is currently approved.

For the future large-scale experiment, the consortium is forming and during the next few years would expect to down-select a project and submit a SOI for either the construction or a pre-construction phase in the event of a staged experiment. The UK already has interest and expertise in several areas and, with funding, could contribute to existing collaborations in ways that will help to focus the UK community and provide training, experience and data for the current students and PDRAs: data acquisition and triggering, particularly for the radio Cherenkov experiments which are moving to full-bandwidth digital beamforming triggers, building on the UK's heritage in microwave astronomy; using ultra-high energy neutrinos to search Beyond-the-Standard-Model physics by using Bayesian statistics; establishing a new calibration for IceCube and IceCube-Gen2 utilizing UK high-performance computation (IRIS, GridPP) for simulation and reconstruction; providing P-ONE sensitivity studies, event reconstruction based on convolutional neural networks, modelling of background bio-luminescence and data analysis of the pilot strings (STRAW and STRAWb); simulations and analyses of ultra-high energy neutrino searches with radio Cherenkov experiments based in Antarctica.

7.1.1 IceCube/IceCube-Gen2

Status. Running. Not supported by STFC except for CG.

IceCube is an international experiment using the optical Cherenkov technique at the South Pole that has reached a mature stage of its exploitation and has ~ 300 collaborators. It is the largest running neutrino experiment and is world-leading around the PeV energy scale. IceCube is a flagship experiment in neutrino and multimessenger astronomy thanks to the discovery of very high energy cosmic neutrinos and the detection of the first likely source of high-energy neutrinos, a blazar that was also observed with gamma rays and lower energy photons. IceCube recently reported the detection of a cascade of high-energy particles (a particle shower) consistent with being created at the Glashow resonance by the interaction of a very high-energy astrophysical antineutrino. IceCube is also a multipurpose research facility with outstanding precision measurements in neutrino physics and exceptional contributions to cosmic ray physics, dark matter searches, and glaciology. The first stage of the IceCube-Gen2 (2030s fully instrumented), called IceCube-Upgrade, is funded to install seven new strings (2024 operation start). By roughly doubling the instrumentation already deployed, the telescope will achieve a tenfold increase in volume to about 10 cubic kilometers, aiming at an order of magnitude increase in neutrino detection rates. IceCube-Gen2 will provide an unprecedented view of the high-energy universe.

7.1.2 ANITA/PUEO

Status. Running. Not supported by STFC except for CG.

ANITA/PUEO is a balloon experiment using the radio Cherenkov technique in Antarctica that is both proving the feasibility of the technique and providing world-leading results above the EeV energy scale. PUEO has improved sensitivity compared to ANITA and is an approved NASA mission with a flight scheduled for December 2024. ANITA/PUEO has ~ 30 collaborators, mostly in the US with some involvement in the UK and Asia.

7.1.3 Pacific Ocean Neutrino Explorer

Status. Proto-collaboration. Test string construction 2021. Securing funding for the installation of the first 10 strings for P-ONE.

P-ONE is a new initiative for the staged construction of a multi-cubic-kilometre neutrino telescope in the deep Pacific Ocean underwater infrastructure of Ocean Networks Canada. P-ONE is establishing a formal collaboration and so far includes ~ 40 scientists from Canada, Germany, and the UK. Two pathfinder missions have published water-quality and deployment results. The project is supported by Ocean Network Canada (ONC). At present, a global effort is underway to explore the sky at the highest energies in order to reveal the most powerful cosmic accelerators. The contributing parties are the neutrino telescopes ANTARES (12 strings) in operation since 2008, KM3NeT under construction in the Mediterranean, the Gigaton Volume Detector (GVD) under construction at Lake Baikal, Russia, IceCube-Gen2 at the South Pole, and the new initiative P-ONE. If they were combined and used as a single distributed planetary instrument, it would cover almost the entire sky and the detection probability would improve by up to two orders of magnitude with respect to the one IceCube has today.

Recommendation 7.1. UHEN represents a concerted effort by members of the community to support one large-scale future neutrino astronomy experiment, as was recommended in the 2016 Particle Astrophysics roadmap and by the STFC Science Board. We recommend that the consortium continues to grow and broaden its support within the UK community. We also recommend that STFC supports this effort through appropriate funding, both for the near-term experiments that require travel and computing funding in order to maintain a community of trained early-career scientists, and PPRP funding to enable the UK to play a significant role in a longer-term large-scale experiment.

7.2 Quantum Technologies for Neutrino Mass

Status. Early R&D. Supported by STFC.

A laboratory measurement of the absolute neutrino mass is one of the most important experimental challenges that remains in particle physics. Current leading techniques employed in the KATRIN experiment cannot probe neutrino mass scales below 200 meV. Reaching better sensitivities is motivated by the two mass scales: one corresponding to the inverted mass ordering ($m_\nu > 50$ meV) and the other to normal mass ordering ($m_\nu > 9$ meV). The overarching goal of the Quantum Technologies for Neutrino Mass (QTNM) project is to use recent breakthroughs in quantum technologies to carry out an experiment capable of a guaranteed measurement of neutrino mass even in the worst case scenario of m_ν O(10 meV). To do this QTNM will employ a novel technology known as Cyclotron Radiation Emission Spectroscopy to carry out a study of unprecedented accurate of the energy spectrum of electrons emitted in Tritium beta decay around the end-point. In addition, this technique will yield unique sensitivity to the existence of sterile neutrinos by studying lower energy parts of the beta spectrum.

QTNM is considered to be primarily in the PP remit. The intention is to host the experiment on UK soil, and the UK holds leading roles in the project. As such, we would welcome its inclusion as part of the Particle Physics roadmap.

8 Cosmic Microwave Background

The success of the Planck satellite, with UK leadership in key areas, has led to major advances in CMB cosmology. However, the CMB still contains a wealth of unexploited information. Over the next decade, CMB experiments will map the microwave sky to new precision in polarization and on small angular scales in order to pursue several key scientific goals. Searches for large-scale B-mode polarization signals from inflationary gravitational waves will provide new insights into the early universe, constraining physics at energy scales a trillion times higher than at the Large Hadron Collider. Experiments are seeking to improve current B-mode constraints, parameterized by the tensor-to-scalar ratio r, by more than an order of magnitude to $\sigma(r) \sim 10^{-3}$; such measurements will allow us to exclude a broad class of large-field inflation models – or will provide a revolutionary first detection of gravitational waves from the early universe. Using high-precision small-scale power spectra, CMB surveys will greatly advance the search for new light relic particles that are undetectable in current laboratory experiments. Upcoming experiments will soon approach thresholds where they will have some sensitivity even to particles that decoupled at the earliest times (well before the quark-hadron phase transition), providing new insights into beyond-the-standard-model physics. Surveys will also employ the CMB as a "backlight" to precisely map the distribution of mass and baryons across our Universe through lensing and scattering effects. This will unlock powerful new measurements of the neutrino mass and constrain dark energy phenomenology. Further into the future, satellites performing spectral distortion measurements can test inflationary predictions in a novel small-scale regime and search for energy injection by new physics.

CMB measurements will not only constrain fundamental physics, but will also serve as a powerful probe of astrophysics: upcoming surveys will precisely determine the properties of gas around and within galaxies and clusters, constrain star formation at high redshifts via emission from dusty star-forming galaxies, and provide new insights into reionization as well as radio sources and transients.

CMB research can thus address several STFC Science Challenge Questions, including: searching for primordial gravitational waves (A:8) to constrain inflation and the early universe (A:1); constraining the Universe's particle and field content (C:1) by seeking signatures of new light relic particles; probing initial conditions and structure formation (A:2) with power spectra and lensing; constraining non-standard dark energy and dark matter properties and testing the standard cosmological model and Einstein gravity (A:3, C:3, C:4); providing insights into star formation and reionization (A:4, A:5).

8.1 Ground-based CMB Experiments

8.1.1 Simons Observatory

Status. Construction underway. Some STFC support for exploitation. Plans for major UK involvement via SO:UK are advanced and under final review.

Advances in the CMB field in the next 5-10 years will be driven by ground-based experiments at the two sites with the best atmospheric conditions: the Simons Observatory (SO) in Chile and the South Pole Observatory at the pole. Broad UK community involvement has coalesced around the SO and indeed UK researchers already hold several leadership roles within the SO collaboration.

The SO is a US-led CMB observatory which is currently under construction for deployment in the Atacama Desert in northern Chile. SO has several primary scientific objectives. Using B-mode polarization, SO will search for inflationary gravitational wave signals with a target of $\sigma(r) \sim 0.003$. SO will also seek new light relic particles, providing bounds nearly four times tighter than Planck. More broadly, SO will obtain new constraints on neutrino masses, astrophysics, dark energy, and dark matter with high precision analyses of CMB secondary anisotropies.

The SO telescopes are divided into one high-resolution 6m Large Aperture Telescope and an array of three 0.5m Small Aperture Telescopes focused on measuring large scales. With 60000 superconducting transition edge sensing bolometers, SO will map the CMB sky in six frequency bands ranging from 27-280 GHz. The telescopes are currently under construction at Vertex in Germany, and the receivers are currently under construction at various SO institutions in the US and around the world. A phased deployment of hardware to Chile is set to begin in 2022, with full operations scheduled to begin in 2024. SO will then start its nominal 5-year survey, with an expected completion date of 2029. The analysis of the SO data is expected to extend several years beyond that end-of-survey date.

The construction and deployment of the SO telescopes & receivers is funded by the Simons Foundation (at \$72.5M). The foundation has additionally committed ≈50% (\$20M) of the funding SO needs for its operations and data analysis phase. SO is actively seeking the remaining ≈50%.

The SO:UK project is a £10M proposal from a consortium of UK CMB scientists to make a major UK contribution to SO, including both data pipeline and hardware contributions. The project is of central importance to the UK CMB research programme in the near future. SO:UK has previously been assessed by Science Board and PPRP and is currently in a STFC-funded Phase A study. The anticipated UK contributions are the following: i) provision of a UK Data Centre, responsible for delivering the Science-Ready Data Products for SO; ii) construction of a KIDs high-frequency (220/280 GHz) optics tube for the SO Large Aperture Telescope, demonstrating key UK technical expertise; and iii) major contributions to algorithm development for SO data pipelines. A more ambitious hardware contribution is also being considered. UK scientists currently hold several leadership roles in the SO Analysis Working Groups and the Theory and Analysis Committee; as first SO observations approach, increased funding for exploitation via AGP is important for preserving the UK's leading role in this area.

8.1.2 CMB-S4

Status. Reference design completed. Recommended for U.S. agency funding. No direct STFC support.

CMB-S4 is an ambitious, near-future ground-based CMB experiment, which is envisioned as a successor to current ground-based efforts such as the Atacama Cosmology Telescope, South Pole Telescope, BICEP/Keck, SO, and the South Pole Observatory. By deploying an order of magnitude more detectors than current-generation experiments, CMB-S4 will improve CMB polarization measurements significantly, reaching several key targets in fundamental physics and astrophysics. CMB-S4 goals include: probing inflationary gravitational wave B-modes precisely enough to either set an upper limit of $r < 0.001$ at 95% C.L., ruling out large classes of inflation models, or detect this primordial signal; searching for light relic particles with some sensitivity even to particles that decoupled well before the quark-hadron phase transition; detecting tens of thousands of galaxy clusters and mapping mass and baryons over more than half of the sky at high precision. CMB-S4 also has several astrophysical science goals in areas such as transient and source science.

To achieve these goals the S4 project will deploy telescope arrays to both sites with the best atmospheric conditions, the South Pole and the Atacama Desert in Chile. The telescopes will rely on a total of $\sim 500,000$ detectors and will observe at up to 9 frequencies between 20 and 270 GHz. An array of small aperture telescopes will be deployed at the South Pole to integrate down to great depth over 3% of the sky; this will be complemented by the South Pole large aperture telescope, which will focus on cleaning the polarization from lensing noise on the same area. An array of large aperture telescopes will also be deployed to Chile and will undertake a wide survey over 60% of the sky that will enable constraints on light relics as well as cluster and mass mapping. First light may be as early as 2027, while full CMB-S4 science observations are expected to begin towards the end of this decade. A seven-year survey is planned.

CMB-S4 is intended to be a joint US DOE and NSF project. It has been recommended as a priority for DOE funding by the 2014 Particle Physics Project Prioritization Panel (P5); NSF funding is also expected following CMB-S4's endorsement by the recent US astronomy and astrophysics decadal survey (CMB-S4 was ranked the joint second priority for new large ground-based facilities).

In-kind contributions to the CMB-S4 project from international partners are explicitly anticipated and welcomed, which should provide opportunities for significant UK involvement. Although UK participation is currently restricted to collaboration membership as well as a small number of leadership positions, broader UK contributions could build on UK leadership in current experiments such as SO and in dedicated low-frequency telescopes such as C-BASS. Possible UK contributions could include optical components, a data centre and/or a dedicated, advanced low-frequency instrument; contributions could be made via a formal partnership with SO or with enhanced versions of SO, although arrangements in this area are still to be determined.

8.1.3 Low-frequency foreground experiments

A limiting factor on the sensitivity of B-mode search experiments is likely to be foreground removal. The expected levels of both synchrotron and dust contamination, which can mimic inflationary B-modes, are greater than the CMB signal for $r = 0.001$ even in the cleanest areas of the sky. All planned CMB B-mode experiments use a wide range of frequencies to combat this problem, but their frequency range is limited by practical considerations – in particular, below 20 GHz bolometers become inefficient and prone to man-made interference from satellites. To solve this problem, the UK has pioneered low-frequency, radiometer-based CMB polarized foreground observations with the 5-GHz C-BASS experiment (with results eagerly awaited by the community), but STFC funding for this area has historically been at a low level. Sensitive future radiometer observations in the 5-20 GHz range would greatly improve the science output from SO, CMB-S4 and LiteBIRD; the technology required has largely been developed for application in the SKA, and the cost is relatively modest compared to the large-scale bolometer experiments. Opportunities exist to collaborate with other countries such as South Africa, Spain and Italy.

Recommendation 8.1. Major UK contributions to the Simons Observatory via SO:UK are the cornerstone of the UK CMB research programme and should be strongly supported. To maximize the scientific impact of UK involvement and leverage current UK strengths, the panel also recommends further funding of scientific exploitation and technical development work for SO.

Recommendation 8.2. The UK should target a leading role in ground-based CMB in the late 2020s and 2030s. Making a significant contribution to CMB-S4, in a way that builds on involvement in Simons Observatory and other current experiments, appears to be the surest route to future UK leadership in this area.

Recommendation 8.3. To complement UK investments in CMB observatories such as Simons Observatory, CMB-S4 and LiteBIRD, the UK should support a low-frequency foregrounds programme that includes the completion of the C-BASS southern survey (interrupted by COVID) and the development of a low-cost 5-20 GHz survey leveraging SKA technology.

8.2 Future Satellite Missions

8.2.1 LiteBIRD

Status. Design phase. Partial funding secured. No direct STFC support.

LiteBIRD is a satellite mission that will hunt for new signatures of cosmic inflation by mapping the large-scale CMB polarization at unprecedented precision over a wide range of frequencies. The primary aim of LiteBIRD is to constrain inflationary gravitational waves precisely enough to rule out (or detect) induced B-modes at a level of $r > 0.0005$, beyond a key threshold that would allow the exclusion of a broad class of large-field inflation models. LiteBIRD's large sky coverage and high-frequency channels, which are valuable for foreground removal, provide complementarity to ground-based efforts. LiteBIRD will also enable a unique high-significance determination of the unknown neutrino mass and will allow detailed studies of cosmic reionization and of the physics of our Galaxy. To achieve these goals, LiteBIRD's design includes 3 telescopes with a total of 3000 superconducting transition edge sensing bolometers, which will make high-sensitivity full-sky CMB observations over 15 frequency bands between 34 and 448 GHz. LiteBIRD will operate for three years at the L2 Lagrange point.

LiteBIRD was recently selected by JAXA as an L-Class (large) satellite mission, scheduled for launch in 2028. The mission envisions significant international contributions, with specific responsibilities and financial contributions still being fully defined. The mid- and high-frequency telescopes are a European responsibility. The UK has participated in the project since the very beginning and, capitalizing on its unique CMB instrumentation and analysis expertise, is well positioned to make significant contributions to the mission. These include provision of several optical components (such as filters, lenses and half-wave plates), thermo-mechanical design and testing, housekeeping electronics, and contribution to the high-frequency detector and focal plane programme. Members from the UK also contribute to analysis within the LiteBIRD Joint Study Groups (JSGs), which focus on low-level analysis work (e.g., systematics characterization, foreground mitigation, and pipeline development). The UK activities are coordinated locally by the LiteBIRD-UK consortium within the wider European framework.

8.2.2 Future spectral distortion missions

CMB spectral distortion measurements, which can provide a novel test of inflationary predictions and probe several types of new physics, are now widely recognized as an important future probe of early universe physics. Building on the legacy of COBE/FIRAS, several CMB spectrometers are currently being considered, including approaches from the ground, balloon and space. The most prominent space mission concept is PIXIE, but within the ESA Voyage 2050 space program even more ambitious designs could come within reach. One of the clear shortfalls of all existing concepts is the lack of low frequency coverage to tackle the μ-distortion component separation challenge. The UK, with its expertise in low frequency instrumentation and participation in balloon-borne spectrometer projects such as BISOU, has an opportunity to uniquely complement and extend ongoing studies and activities, with the long-term goal of contributing at a leading level to the ESA Voyage 2050 space programme vision.

Recommendation 8.4. The UK should pursue a significant role in the LiteBIRD mission, building on its leading role in experiment and analysis for the Planck satellite. This is the panel's primary recommendation for future satellite missions.

Recommendation 8.5. Technology development for future spectral distortion missions should be encouraged, as investments in this area could have long-term impact.

9 Theory

Theoretical Particle Astrophysics is a crucial part of the programme. It supports the experimental effort by informing the observational or experimental directions that should be pursued and it ensures that experimental results are maximally exploited to gain a deeper understanding of the physical processes at work. The UK has a large and internationally prominent community working on theoretical particle astro-physics. The UK is represented on the EuCAPT steering committee and the 2019 EuCAPT census revealed that the UK has one of the largest Particle Astrophysics-theory communities in Europe, second only to Italy (by number of active institutes).

UK theory activities have strong links with adjacent disciplines such as particle physics, astronomy, cosmology, and more recently, with fields traditionally falling within the EPSRC remit through the QTFP programme. The UK has a long history of leadership in general relativity. Current gravitational-wave theory efforts include both numerical and analytic modelling of GW sources to assess detectability, inform signal analysis strategies and develop the waveform templates that are critical to the success of current GW detectors. Dark matter phenomenologists in the UK work on topics ranging from proposals for novel searches to advance the direct detection programme, dark matter candidates in extensions of the Standard Model, and to the dark matter distribution in the Milky Way and beyond. Strengths of the particle cosmology community include topics in dark energy and modified gravity, inflation and topological defects. The UK also has historical strength in the theory of the CMB, having played a leading role in connecting key open questions to CMB observables such as polarised power spectra, non-Gaussianity and gravitational lensing. Several key advances in the theory of particle acceleration at astrophysical shocks have been made in the UK, and a broad community remain active in high energy astrophysics theory, including cosmic ray production and propagation. The UK hosts a strong theoretical neutrino physics community, studying the phenomenology of neutrino properties, the origin of neutrino mass and mixing and the impact of relic neutrinos on the evolution of the Universe. In VHE Gamma-ray astronomy the UK has strength in several areas of beyond-standard model physics notably indirect DM detection, search for Lorentz Invariance Violation using astrophysical targets, and signatures of Axion-Like Particles (ALPs) in the cluster environments and jets of active galaxies. VHE Gamma-ray astronomy also has importance in cosmology as a probe of the evolution of the extragalactic background light, and by constraining primordial magnetic fields. Finally, the QTFP programme has seeded new theoretical activity in an emerging field that is seeking to develop and apply quantum technologies to open questions within the Particle Astrophysics remit.

To support the long-term health of the Particle Astrophysics programme, the UK must increase its support for theoretical activities. For instance, theoretical and computational development is required now to ensure we have the tools to perform the precision GW astronomy enabled by the next generation GW observatories. Investment in the development of accurate GW models and data science techniques is required now to ensure the UK can fully exploit the CE, ET and LISA data in the future. The R&D activities to support the development of next-generation DM detectors require dedicated theoretical work to better understand and model novel signal and background sources. This is true both for more established technologies employing liquid argon and xenon, as well as for the novel quantum sensors in the QTFP programme. The forthcoming era of VHE Gamma-ray cosmology will have close ties with multi-wavelength and multi-messenger facilities, and should be supported as a key area where the UK holds broad leadership to exploit these synergies. Further UK CMB theory work should be strongly supported to set targets for and maximize the scientific return from upcoming experiments. This should include funding for activities related to

CMB spectral distortions as a probe of particle physics, new dark matter models and interactions, and primordial perturbations; efforts to connect upcoming CMB light relic constraints with bounds on new physics models; the relation of general properties of CMB higher-point-correlators to the symmetries and particle content of the early universe; and the development of new estimators for lensing and scattering effects and their connection with open problems in structure formation.

Recommendation 9.1. Funding for theoretical activities should be increased to support the long-term health of the Particle Astrophysics programme and to ensure that experimental results can be fully exploited.

Funding for Particle Astrophysics theory comes through the particle physics or astronomy grant panels. In an environment of restricted funding, there is the risk that world-leading Particle Astrophysics research that spans both fields is dismissed with the argument that it should be funded by the other panel and subsequently, is not given due consideration for funding. This is particularly a problem in Particle Astrophysics as there are some projects that will genuinely span both fields so there needs to be a clear process that allows these projects to be funded within the current system. For example, numerical relativity simulations that include the effects of ultra-light dark matter has been considered as too close to particle physics by the astrophysics panel, while particle physics models related to dark energy and inflation has been thought of as too close to the astrophysics panel.

Recommendation 9.2. STFC and the particle and astrophysics panels should acknowledge that not all areas of Particle Astrophysics theory can be neatly classified as either astrophysics or particle physics and that there will be core areas of Particle Astrophysics theory that will necessarily appear to be on the borderline of the panel's remit. Furthermore, we would encourage STFC and the panels to consider mechanisms that could be put in place to prevent world-leading areas of Particle Astrophysics theory from falling between the cracks of the two panels.

The seven projects that were initially funded as part of the (QTFP) programme address the aims of the Particle Astrophysics programme, including the search for dark matter and gravitational waves. All seven projects have a theory component which acts to guide the experimental effort, to provide more precise calculations of observables and to ensure that the experimental data is fully exploited.

Recommendation 9.3. The STFC should ensure that follow-on funding for the theoretical activities in the QTFP area is available. We also recommend that fellowship panels (including Ernest Rutherford, Future Leaders and Stephen Hawking fellowships) recognise that theoretical research in the QTFP area falls within their remit and ensure that they include panel members with the expertise to judge proposals from this area.

10 Technology Development, Underpinning Technologies and Infrastructure Requirements

10.1 Infrastructure Requirements

Infrastructure in the form of state-of-the-art laboratory facilities is essential to ensure the UK maintains its position at the forefront of experimental developments in Particle Astrophysics. This type of investment is typically not provided for on standard or consolidated research grants or indeed on standard capital calls and requires dedicated strategic investment in mid-scale laboratory infrastructure. Particle Astrophysics infrastructure is hosted at the STFC Boulby Underground Laboratory and the Rutherford Appleton Laboratory (RAL), and additionally in University laboratories which have made critical contributions to Particle Astrophysics Experiments.

The STFC Boulby Underground Laboratory has been operating in its existing infrastructure configuration since 2016 when work was completed on upgrading the facility to host particle physics, low background, and multi-disciplinary underground science projects well into the future. The facility works closely with the Particle Physics and Particle Astrophysics communities and currently provides space for various small and medium scale experiments. In addition, the laboratory hosts and runs the Boulby Underground Screening (BUGS) facility which provides world class material characterisation for current and future generation low-background physics experiments through gamma screening as well as surface alpha screening and radon emanation. BUGS is continually developing, and work is ongoing to provide additional facilities both on the surface and underground at Boulby to study material cleanliness. In addition to continuing to host small and medium sized experiments, work is underway to determine the practicalities of hosting a future large scale, next-generation particle and astroparticle physics experiments at Boulby. A recent feasibility study has examined this in some detail and concluded that it would be possible to host such an experiment with new investment and expansion of infrastructure and support staff. Over the next few years, detailed designs will be developed for such a facility and further engagement with the national and international community undertaken to assess need and support. Expansion of facilities is also being considered for hosting the AIT-NEO project, a large water-based US-UK reactor neutrino nuclear non-proliferation R&D project which is currently in conceptual design, feasibility, and planning stage. Beyond Particle Astrophysics applications, the facility continues to host a wide range of pure and applied multi-disciplinary studies spanning the UKRI council's science themes and with substantial international engagement.

Radon emanation has emerged as the most important background that limits the science capability in leading DM experiments such as LZ. Facilities that provide high sensitivity radon emanation assay are rare, with only a handful across the world. None of these, however, can assess radon emanation at cryogenic temperatures. The Cold Radon Emanation Facility (CREF), which is being constructed at RAL, will become the world's first facility that measures the cryogenic emanation of radon when it becomes operational in 2022. This facility is essential for progress towards the next generation DM experiments where the radon emanation problem will be even more severe.

10.2 Technologies

The PRD funding route provided a valuable means for technology development at the single project level, and has been sorely missed. Though UK expertise is broad and highly developed in a wide range of technologies relating to Particle Astrophysics, UK funding levels do not allow these skills to be exploited across all the possible opportunities. In addition to PRD, an effective and cost efficient mechanism could be to provide funding for long-term technology development in areas applicable to a larger number of the upcoming projects. This would represent a different model for STFC, not solely relying on lower-level PRD-type funding, which would itself be valuable to reinstate, but also larger, technology-focussed grants which could fund centres of excellence comprising either single or a distributed network of institutes. This would exploit the efficiencies of scale and risk reductions to be gained in investment in technology development for applications in several Particle Astrophysics project areas, or which would have impact outside Particle Astrophysics (e.g. particle/nuclear/astronomy).

Recommendation 10.1. Renew funding for the existing PRD scheme alongside a new mode of larger scale technology programmes which would assemble expertise to develop high impact technologies with application across multiple projects and fields.

10.2.1 Sensors

Photo-sensors are commonly required in Particle Astrophysics experiments, with detectors often comprising very large arrays of sensors. For example, the CTA SST array will utilise 76k silicon photo-multipliers (SiPMs). Typical performance requirements include fast timing, high sensitivity, photon-counting, and low background rates. New experiments are gradually replacing the conventional vacuum photo-multiplier tubes with SiPMs. While the UK has not previously led SiPM development, there are areas where UK expertise could be employed to advantage. For example, next generation rare event search experiments requiring VUV sensitivity could leverage existing UK industrial expertise in back side illumination to develop new SiPM technology removing requirements for wavelength shifting materials, improving sensitivity and reducing costs.

10.2.2 Electronics

Large arrays of high-speed photo-sensors comprising a typical DM and IACT experiments are instrumented using high density electronics with very large channel counts. These commonly utilise ASICs and FPGAs on high density PCBs, with typical requirements for very high speed, nanosecond timing, low noise, and low cost per channel. There are often large synergies between Particle Astrophysics (and other Particle Physics) experiments and the idea of a UK design and fabrication facilities for the development and manufacture of such electronics and serving all STFC communities was raised in the previous Particle Astrophysics road-map.

Recommendation 10.2. Given the near-certainty of increased complexity, channel count and miniaturisation of future Particle Astrophysics experiments, the concept of one or a small number of focused UK design and fabrication facilities, serving all STFC communities for electronics design and construction, should be considered.

Alongside larger scale funding for technologies, better funding and fellowships for experimentalists and instrument specialists are equally as important. Higher historic funding levels have placed the UK in a situation where we are currently surfing on a wave of earlier technology development, and now we are rapidly being overtaken by those who have invested in this area, both in people and infrastucture.

Recommendation 10.3. UK expertise in particle astrophysics instrumentation should be enhanced by extending funding opportunities and fellowships for experimentalists and instrument specialists. This is necessary in order to maintain the UK's international competitiveness.

10.3 Computing and Data Science

Particle Astrophysics research requires large-scale, high-performance and high-throughput computing resources due to the very large observational and experimental data-sets, and to the multi-scale, multi-dimensional and non-linear domains to be explored in building model simulations. At present, the community's needs are well met by the existing hardware provision, notably through the STFC Distributed Research utilising Advanced Computing (DiRAC) and IRIS facilities and supplemented by a dedicated UK Gravitational Wave computing resource. This has required significant community effort in proposing and supporting the recent upgrade to DiRAC 3 and the establishment of the IRIS consortium. Moving forward, it is critical that computing requirements are established early, during the planning stages for new experiments, and that computing costs should be captured and incorporated into long-term plans and budgets.

Recommendation 10.4. Large-scale computing for simulations and data analysis is critical for all areas of Particle Astrophysics. STFC must ensure that appropriate computing resources are made available to enable full exploitation of observational and experimental data.

Computational techniques are evolving rapidly, with machine learning and Artificial Intelligence becoming commonplace across Particle Astrophysics analyses. This evolution requires continual engagement with computing providers to ensure the ensures that the community's needs are met. At present, Particle Astrophysics experiments are well-represented on the IRIS management board, and modellers have a voice on the DiRAC board. The rapid development of computational techniques necessitates both training for existing researchers and provision of dedicated computing specialists. STFC initiatives, such as the Data Intensive Centre for Doctoral Training (CDT), have provided specialist training for a large number of PhD students. It is important that similar training is available to PDRAs and more senior staff.

Since the past roadmap, there has been a significant development in the UK of a community of Research Software Engineers (RSEs) [1]. In 2020 STFC awarded its first RSE Fellowship. RSEs are vital across Particle Astrophysics research, however, at present there is insufficient support for such positions. Additionally, there is no well established career path for RSEswithin academia. Adequate funding for expert computing staff is essential to ensure efficient usage of computing resources and to facilitate the use of cutting-edge computational techniques in both simulations and data interpretation.

Recommendation 10.5. STFC should provide a greater level of support for specialist computing staff, particularly RSEs, within Particle Astrophysics. Continued, long-term support, such as through RSE Fellowships, is vital to retain the computing specialists required to ensure the success of Particle Astrophysics experiments and observations.

11 Impact

11.1 Applications, innovation and industrial engagement

Research in all areas of particle astrophysics requires development of experimental methods which push existing techniques to, and beyond their current limits. It isunsurprising that these methods find applications outside of their direct research areas. For instance, single-photon detection, geodesy with compact atom interferometers, enhanced magnetometry, sub-quantum limited amplification. These have applications in minimally invasive imaging solutions for healthcare, security and defence applications, monitoring systems for energy, transportation, and infrastructure.

Gravitational wave experimental techniques have found applications in silicate bonding techniques to create improved high power laser systems, low noise MEMs devices for monitoring of sub-surface magma flow relevant to volcanic eruptions. The development of "nanokicking" started as a collaboration between gravitational physicists and biologists. The first clinical trials of surgical bone graft, grown from a patients own stem cells, will be conducted in 2022/23 as a demonstration of healing critical size defects and has the potential to transform surgical procedures. Coating technologies, and wider material developments, are absolutely critical for addressing industrial challenges, such as laser performance and laser damage threshold in the UK photonics industry. GW-inpired interferometry has been incorporated in the GRACE-FO Earth-observation gravity mission, which has major implications for climate studies.

Further development of novel resonators, sensors and amplifiers will have applications outside the field, as well as advancing the search for wave-like dark matter. Timing and NIR photon detection efficiency improvements have application in light interferometry and ranging (LIDAR, used in autonomous navigation). Detectors with improved UV sensitivity have application to photolithography in the semiconductor industry. Other applications include muon imaging of voids, neutron detectors for moisture detection in soils and development of materials for next generation fission and fusion reactors based on activation studies for rare event search experiments. QTFP funded research feeds back into the development of quantum information processing such as novel quantum computing architectures and systems. A hidden sector facility would enable a range of measurements and form a technology test bed for devices operating at the quantum limit.

Oceanic infrastructure plays an important role in neutrino astronomy. The nascent P-ONE experiment utilises the infrastructure of Ocean Networks Canada that monitors the west and east coasts of Canada and the Arctic to continuously gather data in real-time for scientific research that helps communities, governments and industry make informed decisions about our future.

UK industry is playing a significant role in optics and electronics development and manufacture for IACT, and in particular for CTA. Optical components are being developed and manufactured by UK industry. Industry-based expertise and technologies include large camera windows with multi-layer coatings to provide tuned window transmittance and reflectance properties to match camera requirements and sensor performance. The modular custom, multi-channel combined digitizer and trigger electronics for CTA, which digitize at 1 GSa/s are manufactured, assembled, and tested within UK industry, which also has expertise in the development and manufacture of wavelength-shifting materials with application to water Cherenkov detectors, as used in HyperK and SWGO.

In the theory community, efforts to improve the efficiency of numerical general relativity simulations have benefitted from engagement with industrial partners. For example, the GRCHOMBO open-source code was successfully ported to Intel Xeon Phi MIC processors with direct participation from Intel: an Intel engineer was seconded to the development group. More recently, GRCHOMBO is being updated to support modern GPU architectures using the Intel oneAPI DPC++ compilers, with input from industry stakeholders including Intel and the HPC-library developers AMReX. Data analysis techniques developed to address particle astrophysics challenges have been used in areas from medical science to finance and climate change. For example, techniques developed in gravitational wave analyses have been used to improve quality control in ophthalmic devices.

11.2 Outreach and Public Engagement

Outreach and public engagement activities are an integral part of all areas of Particle Astrophysics research. Examples of successful activities include:

A planetarium show called “Exploring the High Energy Universe” has been written and produced in-house by the Armagh Observatory and Planetarium. The show introduces the viewer to the multi-wavelength sky, illustrates two examples of extreme phenomena in the cosmos, brings in the range of telescopes astronomers use to study them, and ends by introducing gamma ray telescopes and finishing with the CTA as the next generation facility for exploring the high energy universe. The show has been written for Digistar planetaria, which are widely available through the world, and will be shared and made freely available using the Digistar Cloud.

The Prototype Outreach Cherenkov Imaging Telescope (POCIT) is a 1 m^2 class optical telescope being developed as an outreach tool to explain the concept of CTA and bring real-time particle astrophysics observations to the public at events such as stargazing live. Based around components from the CTA SST telescope, several POCIT may be sited at publically accessible observatories such as the Armagh Observatory, and the National Space Centre. The technology might also be of interest for future expansions of CTA and SWGO.

Major LIGO results papers are accompanied by a science summary, a short, non-technical article written to accompany the publication. These have proven to be an effective tool for communicating the ambition, excitement and research impact of LIGO’s scientific program to a wide audience. The science summaries are published in 21 languages and have increased public understanding and awareness of gravitational waves, directly assisting journalists in communicating to the public.

The Remote^3 programme is hosted by the Boulby Underground Laboratory. The project aims to deliver much-needed STEM outreach to some of the most remote areas of Scotland. The Remote^3 project is aimed at Key Stage 3 students, age 10-14, in 10 Scottish high schools. Over a 14-week peroid, teams of 4-6 students in each school design, build and program a miniature Mars Rover. This rover is then sent to the Boulby Underground Laboratory to explore the STFC Mars Yard located 1.1 km underground. In 2020-21, Boulby engaged nearly 3,000 people directly, plus thousands more watching recordings. Over 50% of those were in the crucial 8-14 year old category, which research has shown [11] as a key age group to target, in terms of influencing future career decisions.

International Dark Matter Day was launched in 2017. Highlights include a joint UK/China event in 2019, broadcast to over 44,000 viewers internationally, providing an excellent mutual learning opportunity of science and culture and establishing future collaborative opportunities. This was followed up by a presentation to the UK embassy and consulates to China in 2020.

Recommendation 11.1. Outreach and public engagement are essential for broader societal appreciation of science and attracting the next generation of talented researchers, regardless of background. Particle Astrophysics research is particularly suitable for outreach, as it focuses on some of the most extreme environments in the universe and most profound open questions in science. Outreach activities from the Particle Astrophysics community should be strongly supported.

A Contributions to the roadmap

We received significant input to the roadmap from members of the UK Particle Astrophysics Community. This input comprises

- Initial input at the Particle Astrophysics Town hall in January 2021
- 101 individual submissions to a roadmap questionnaire in May 2021
- 19 experimental submissions of a roadmap proforma in May 2021. Experiments which submitted proformas are:
  - Atom Interferometer Observatory and Network (AION)
  - Advanced LIGO (aLIGO)
  - Cosmic Explorer (CE)
  - Einstein Telescope (ET)
  - LUX-ZEPLIN (LZ)
  - Quantum-enhanced Interferometry (QI)
  - Quantum Technologies for Neutrino Mass (QTNM)
  - QUEST-DMC
  - Simons Observatory (SO)
  - Xenon Futures
  - Cherenkov Telescope Array (CTA)
  - Dark Side
  - UK High-Energy Neutrino (UHEN)
  - Dark Sphere
  - Quantum Sensors for the Hidden Sector (QSHS)
  - Laser Interferometer Space Antenna (LISA)
  - Pulsar Timing Array (PTA)
  - Southern Wide-field Gamma-ray Observatory (SWGO)
  - Cherenkov Telescope Array (CTA) Galactic Plane Survey
- Attendance at a Roadmap focused PA town hall in July 2021
- Individual feedback on the draft roadmap, provided in November 2021 both via written submission and at PAAP "office hours"

We thank Ailsa Johnstone and Karen Clifford from STFC, and Alex Murphy, the Particle Astrophysics representative on Science Board, for their advice and feedback throughout the preparation of this Roadmap. We thank the STFC design team for producing the graphics included in the Roadmap.

Acronyms

A+ Advanced LIGO plus.

AGN Active Galactic Nuclei.

AGP Astronomy Grants Panel.

AION Atom Interferometer Observatory and Network.

aLIGO Advanced LIGO.

ALP Axion-Like Particle.

APPEC Astroparticle Physics European Consortium.

BH Black Hole.

BUGS Boulby Underground Screening.

CDT Centre for Doctoral Training.

CE Cosmic Explorer.

CMB Cosmic Microwave Background.

CP Charge-Parity.

CREF Cold Radon Emanation Facility.

CTA Cherenkov Telescope Array.

DiRAC Distributed Research utilising Advanced Computing.

DM Dark Matter.

EPSRC Engineering and Physical Sciences Research Council.

EPTA European Pulsar Timing Array.

ESA European Space Agency.

ET Einstein Telescope.

EuCAPT European Consortium for Astroparticle Theory.

GRB Gamma Ray Burst.

GW Gravitational Wave.

H.E.S.S. High-Energy Stereoscopic System.

IACT imaging air Cherenkov telescope.

IGMF Intergalactic Magnetic Field.

IPTA International Pulsar Timing Array.

ISW integrated Sachs-Wolfe effect.

LCDM Lambda Cold Dark Matter.

LEAP Large European Array for Pulsars.

LISA Laser Interferometer Space Antenna.

LZ LUX-ZEPLIN.

NS Neutron Star.

P-ONE Pacific Ocean Neutrino Explorer.

PPGP Particle Physics Grants Panel.

PPRP Projects Peer Review Panel.

PRD Project Research and Development.

PTA Pulsar Timing Array.

QCD Quantum Chromodynamics.

QI Quantum-enhanced Interferometry.

QSHS Quantum Sensors for the Hidden Sector.

QTFP Quantum Technologies for Fundamental Physics.

QTNM Quantum Technologies for Neutrino Mass.

RAL Rutherford Appleton Laboratory.

RSE Research Software Engineer.

SiPM silicon photo-multiplier.

SKA Square Kilometre Array.

SO Simons Observatory.

STFC Science and Technology Facilities Council.

SWGO Southern Wide-field Gamma-ray Observatory.

UHEN UK High-Energy Neutrino.

UKRI UK Research and Innovation.

UKSA United Kingdom Space Agency.

VHE Gamma Very High Energy Gamma Ray.

WIMP Weakly Interacting Massive Particle.

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