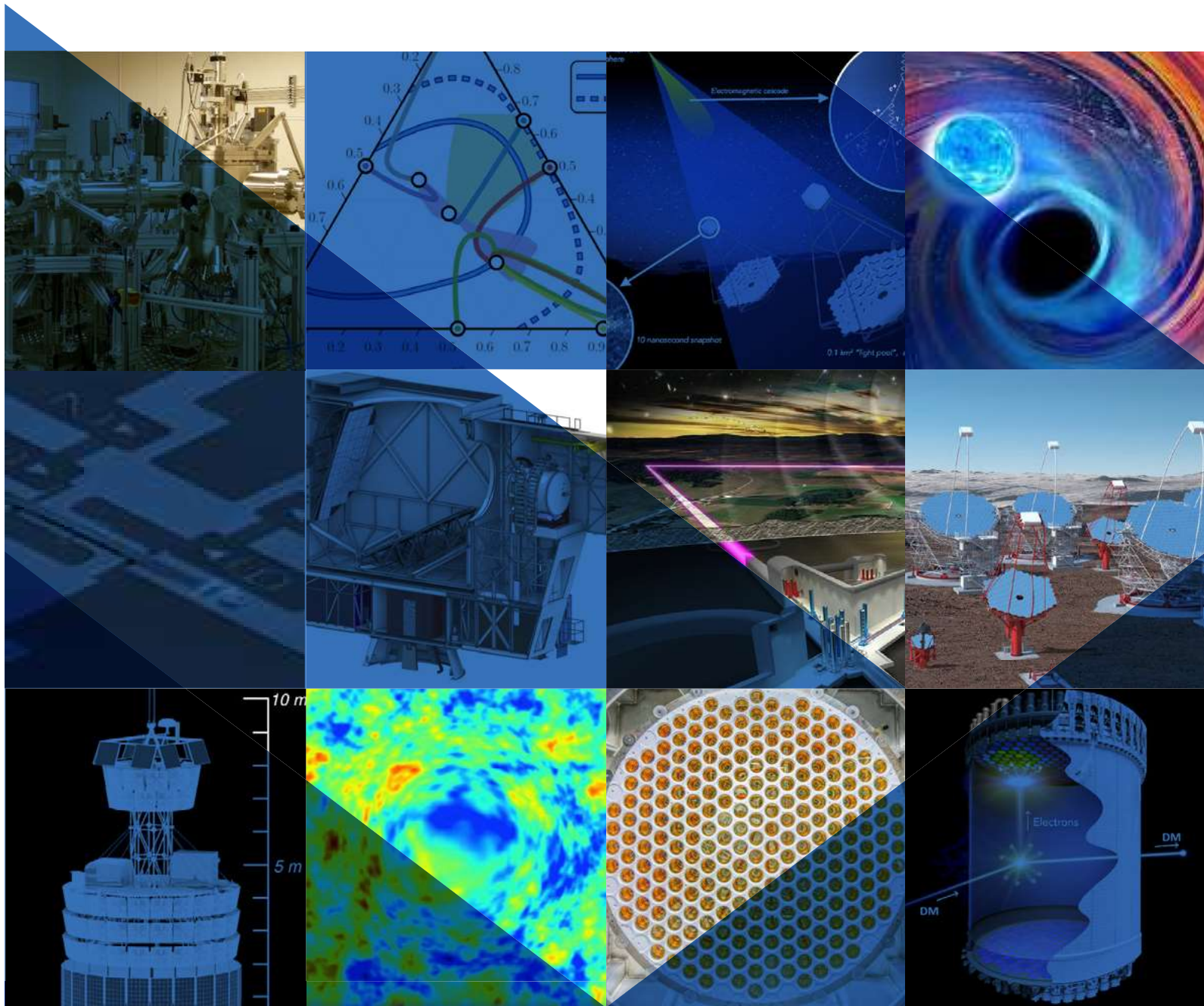


Roadmap for UK Particle Astrophysics 2022

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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 magni-

82 tude compared to current limits. The UK also has involvement in the 20-tonne DarkSide liquid
83 argon experiment. Continued support for LZ and DarkSide remains a high priority. More sensitive
84 future xenon and argon detectors are planned for 2030, and the UK should provide support for
85 at least one future dark matter experiment. Alternative dark matter candidates include wave-like
86 hidden sector dark matter, such as axions. Several projects have been funded by STFC through the
87 Quantum Technologies for Fundamental Physics (QTFP) programme. These include the Quantum
88 Sensors for the Hidden Sector (QSHS), Atom Interferometer Observatory and Network (AION)
89 and Quantum-enhanced Interferometry (QI). It is important that additional funding, beyond the
90 initial QTFP call, is identified to ensure a sustainable programme.

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

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

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

120 **Technology Development, Underpinning Technology, Impact and Infrastructure.**
121 The cross-cutting nature of Particle Astrophysics results in myriad opportunities for technology
122 development in instrumentation, detector technology, analysis techniques and at the theoretical
123 frontier. Research infrastructure is shared with in neighbouring fields such as geophysics, quantum
124 computing, optics and semiconductor research. Particle Astrophysics research has found industrial
125 application in areas including healthcare, security and transportation. There is extensive outreach
126 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

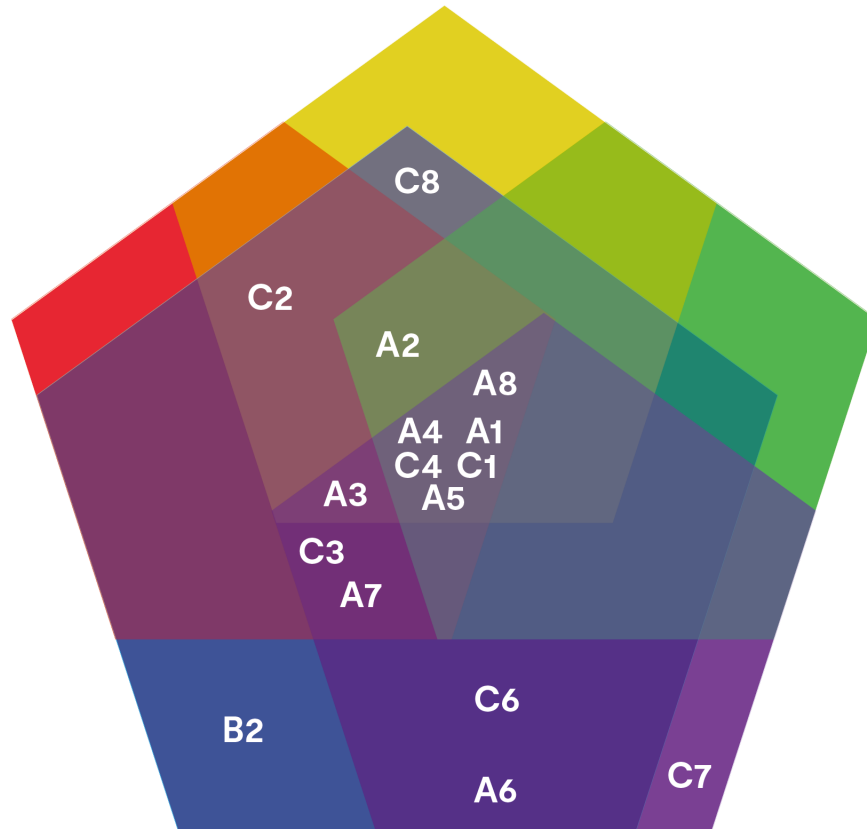
In the past five years, UK scientists have played leading roles in

- 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 telescopes. 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:

- Gravitational waves
- Very High Energy Gamma
- Neutrino
- Direct Dark Matter
- Cosmic Microwave Background



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?

- 167 **A:1 What are the laws of physics operating in the early Universe?** Tight constraints on
168 early universe models are provided by measurements of the relic Dark Matter (DM) density,
169 the GW background in the early Universe, and CMB measurements of B-mode polarization
170 and spectral tilt. Searches for DM annihilation and axion-like particles using VHE Gamma
171 signals, as well as searches for cosmic neutrino backgrounds, further constrain the models.
- 172 **A:2. How did the initial structure in the universe form?** Models describing the early struc-
173 ture of the universe are constrained by current observations of the DM spatial distribution,
174 both via direct observation and via indirect detection using VHE Gamma signals. Measure-
175 ments of the CMB and observation of lensing add information about the initial conditions for
176 structure formation and probe structure growth. Searches for sterile and heavy neutrinos fur-
177 ther constrain models that describe the structure formation, while GWs enable observations
178 of supermassive Black Holes (BHs) and their seeds.
- 179 **A:3. How is the universe evolving and what roles do dark matter and dark energy**
180 **play?** While DM experiments provide direct observations of DM and its role in the evolving
181 universe, VHE Gamma observations can provide indirect detection of DM and its spatial
182 distribution, constrain the Hubble constant, and measure the Intergalactic Magnetic Field
183 (IGMF). GW signals show the imprint of DM and the standard sirens they represent can be
184 used as probes of cosmology, and CMB provides cosmological parameter determination and
185 searches for deviations from LCDM.
- 186 **A:4. When and how were the first stars, black holes and galaxies born?** Direct DM
187 observations tightly constrain models of galaxy formation. The star-formation history of
188 the universe can be accessed via measurements of the absorption of gamma rays on the
189 extragalactic background light, and via reionization information from the cosmic microwave
190 background. GW observations of black-hole mergers could give information on the formation
191 of Population III stars and super-massive BHs. Neutrino astronomy contributes via searches
192 for the diffuse supernovae neutrino background, supernovae monitoring and the identification
193 of blazars.
- 194 **A:5. How do stars and galaxies evolve?** VHE Gamma provides understanding of feedback from
195 accelerated particles and their role in the suppression of galaxy formation, while DM is critical
196 for the evolution of galaxies. CMB observations constrain star formation via observations of
197 dusty star forming galaxies and the cosmic infrared background. GWs provide observations
198 of BH (from stellar mass to supermassive) and Neutron Star (NS) populations. Neutrinos
199 observations are used to measure the metallicity of the sun, and in observations of neutrino
200 emission from blazars and supernovae.
- 201 **A:6. How Do Nuclear Reactions Power Astrophysical Processes and Create the Chem-**
202 **ical Elements?** Observations of VHE Gamma probe the highest energy processes in NS
203 mergers. GWs provide for multi-messenger observations and enable measurements comple-
204 mentary to those from electromagnetic observations.
- 205 **A:7. What is the True Nature of Gravity?** GWs probe the strong-field nature of gravity, for
206 example during BH mergers, the polarization content and speed of propagation of gravitaional
207 waves. VHE Gamma observations of active galactic nuclei and Gamma Ray Bursts (GRBs)
208 provide tests of Lorentz Invariance Violation. CMB observations test modifications to gravity
209 via the integrated Sachs-Wolfe effect (ISW) and secondary anisotropies.

- 210 **A:8. What can GWs and high-energy particles from space tell us about the universe?**
 211 GWs provide direct observations of strong gravitational fields, particularly around BH and
 212 NS. CMB observation of B-modes from inflationary GWs probe early-universe physics. VHE
 213 Gamma observations probe Lorentz Invariance Violation from observations of Active Galactic
 214 Nuclei (AGN) and GRBs. Direct DM observations probe high-energy particles from DM
 215 annihilation and neutrino astronomy gives measurements of neutrino flux in the PeV region.
- 216 **B:2. What effects do the Sun and other stars have on their local environment?** Obser-
 217 vations of high energy cosmic rays from supernovae give insight into their feedback into the
 218 local environment influencing star formation.
- 219 **C:1. What are the fundamental particles and fields?** DM candidates are new fundamental
 220 particles, so observation of DM will inevitably lead to discovery of new particles. Neutrino
 221 astronomy performs searches for sterile and heavy neutrinos. The CMB power spectrum is a
 222 sensitive probe of the number of light relic particles or neutrinos, while lensing also measures
 223 neutrino mass. VHE Gamma observations can provide indirect detection of DM; signatures
 224 of axion-like particles in AGN spectra; probes of magnetic fields in cosmic voids; and tests
 225 of Lorentz invariance violation. GW observations probe the fundamental nature of gravity,
 226 including the propagation speed and polarization content of GWs.
- 227 **C:2. What are the fundamental laws and symmetries of physics?** VHE Gamma obser-
 228 vations will constrain or measure Lorentz invariance violation and signatures of Axion-Like
 229 Particles (ALPs) on gamma-ray spectra. Direct DM observations provide tests of symme-
 230 tries in particle physics and CMB observations test for parity violation via polarization angle
 231 rotation, tests for other symmetries via correlation function properties.
- 232 **C:3. What is the nature of space-time?** VHE Gamma provide limits on (or observations of)
 233 Lorentz invariance violation, GW observations determine the polarization content of GWs
 234 and multi-messenger observations allow for measurement of the speed of GW propagation.
 235 CMB observations test modifications to gravity via the ISW and secondary anisotropies.
- 236 **C:4. What is the nature of dark matter and dark energy?** The primary goal of direct
 237 DM experiments is to observe DM interactions with ordinary matter. Neutrino Astronomy
 238 includes searches for sterile and heavy neutrinos, which may be good DM candidates. VHE
 239 Gamma observations are capable of indirect detection of DM and its spatial distribution,
 240 including searches for ALPs via effects on AGN spectra. CMB determines DM density,
 241 constrains DM interactions, mapping of DM distribution via lensing. CMB measurements
 242 and GW standard siren observations constrain dark energy equation of state.
- 243 **C:6. What is the nature of nuclear matter?** GW observations of NS mergers provide measure-
 244 ment of nuclear equation of state at very high densities. VHE Gamma observations provide
 245 measurements of the highest energy processes in neutron-star merger events.
- 246 **C:7. Are there new phases of strongly interacting matter?** GW observations will probe
 247 possible phase transitions to exotic matter phases, like de-confined quarks, during binary
 248 mergers.
- 249 **C:8. Why is there more matter than antimatter?** Direct DM measurements can be used
 250 for tests of Charge-Parity (CP)-violation in dark sector, while VHE Gamma provides mea-
 251 surement of the electron/positron spectrum as well as evidence for cosmic matter-antimatter
 252 annihilation.

2.3 International Context and other reviews

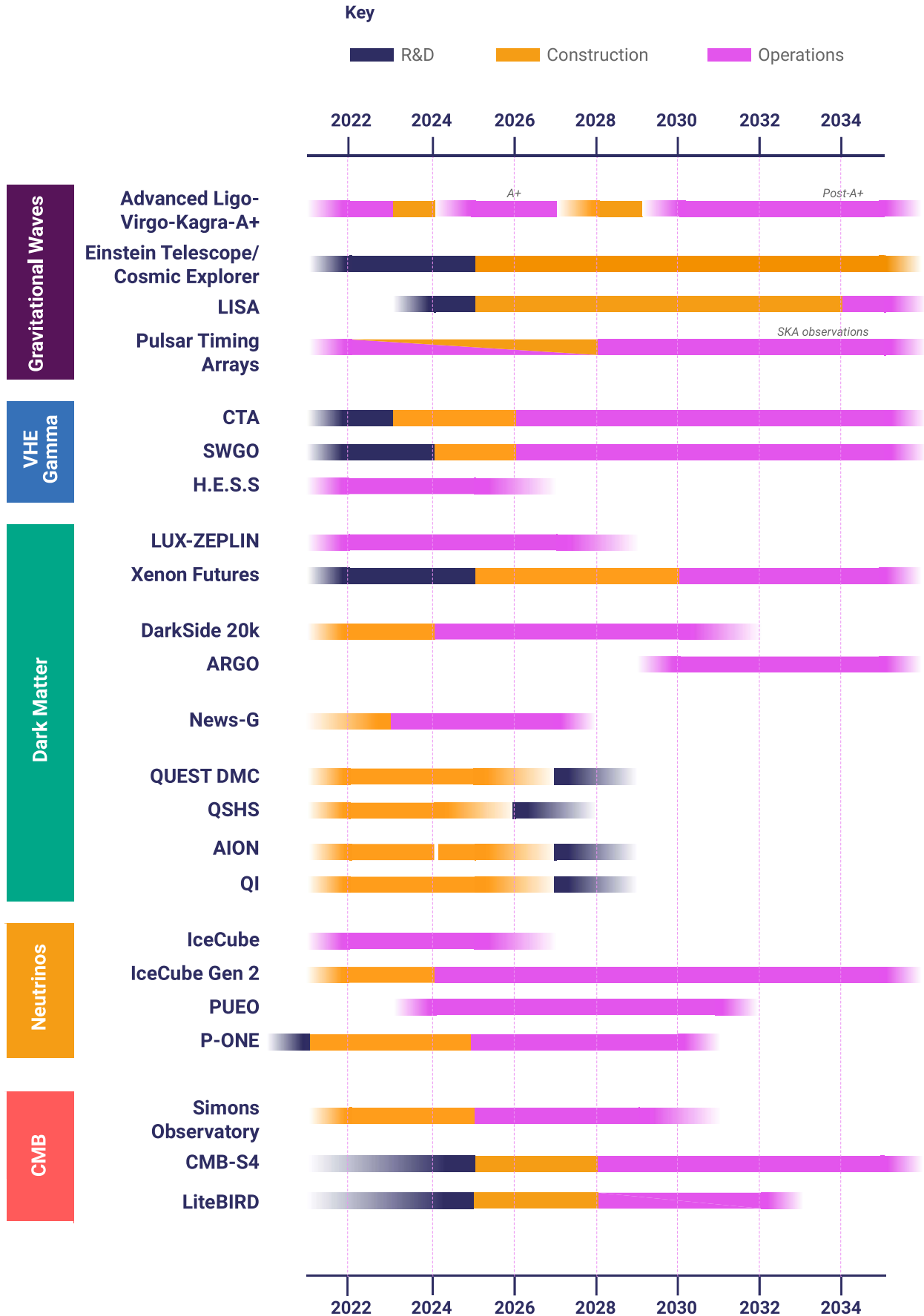
The majority of Particle Astrophysics research in the UK is undertaken in large, international collaborations. UK particle astrophysics is tightly integrated with European, US and global efforts, and the priorities laid out in this Roadmap are entirely consistent with those in the Astroparticle Physics 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



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.

¹Cosmic 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.

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

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

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

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

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

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

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

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

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

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

411 **Recommendation 3.7.** Cooperation between agencies supporting space missions should be fos-
412 tered through cross-representation on relevant committees. Additionally, the funding mechanisms
413 and processes underlying the dual-key approach should be made more transparent via monitoring
414 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,

457 observational and operational working groups within the LIGO Scientific Collaboration. The fourth
458 observing run is scheduled to commence in late 2022, at which time the global network is expected
459 to observe several gravitational wave transients per week.

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

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

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

479 4.2 Next generation GW observatories

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

490 4.2.1 Einstein Telescope

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

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

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

500 **4.2.2 Cosmic Explorer (CE)**

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

502 CE is a concept for two ‘L’-shaped GW observatories, likely to be located in the US, one with
503 40 km arms and the other with 20 km, that are designed to greatly deepen and clarify our ability
504 to study the cosmos using GWs. The CE Horizon Study [15] lays out the detailed scientific goals
505 and technical design of the CE detectors. The timeline foresees site selection and construction
506 beginning later this decade, followed by commissioning and a first observing run around 2035.

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

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

532 **Recommendation 4.2.** Investment in next-generation GW observatories is vital to maintain
533 the UK’s existing leadership in the field. In the short-term, this requires dedicated investment
534 in next generation technology development and computational and modelling work required for
535 precision GW astronomy. Longer term, the UK must provide a large-scale contribution to full
536 project infrastructure costs to ensure continued priority access to gravitational wave data, and UK
537 leadership in scientific exploitation. STFC should submit a bid to the UKRI Infrastructure Fund
538 to support next generation GW Observatories.

539 **4.3 LISA**

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

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

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

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

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

574 4.4 Pulsar Timing Arrays

575 **Status.** Operating. Not supported by STFC.

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

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

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

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

608 **Recommendation 4.4.** The UK should maintain its involvement with EPTA and IPTA. STFC
609 should seek to provide a modest investment to PTAs as this could represent a significant stake for
610 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 (SWGGO). 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 Schwarzschild-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

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

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

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

668 5.2 Southern Wide-field Gamma-ray Observatory

669 **Status.** Planned. Not currently supported by STFC.

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

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

680 The SWGO Collaboration was founded in July 2019 by a group of about 40 institutions from
681 9 countries (including the UK) as an international R&D Project to develop what would be the
682 first extensive air-shower array for γ -ray astronomy in the Southern Hemisphere providing unique
683 access to the Galactic Centre. It will be highly complementary to CTA and to neutrino telescopes
684 such as KM3Net and IceCube.

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

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

695 5.3 High-Energy Stereoscopic System

696 **Status.** Running. Not supported by STFC.

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

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

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

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

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

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

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

770 6.1.1 LUX-ZEPLIN

771 **Status.** Operating. Construction and exploitation supported by STFC.

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

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

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

790 6.1.2 Liquid Xenon Rare Event Observatory (XENON FUTURES)

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

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

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

807 The project is supported in UK until 2024 with 10 UK institutions participating. It is expected
808 that it will be followed by a 2-year Pre-Construction Project and this will lead to a capital-intensive
809 4-year Construction Project planned to start in 2025. Data-taking would take place for around 10
810 years until late 2030s. A site for the experiment has not been chosen yet and the Boulby mine
811 could be a possible host.

812 6.1.3 DarkSide

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

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

819 The DarkSide-UK project leverages the UK’s world-leading silicon detector integration capabil-
820 ity to grow UK leadership in production of large silicon photo-multiplier (SiPM) arrays for future
821 liquid noble dark matter experiments and the DUNE module of opportunity. Substantial knowl-
822 edge exchange with the DarkSide collaboration allows R&D to be kick-started on the SiPM module
823 (PDM) from the state-of-the-art. The R&D includes a production process for PDMs with low
824 radioactivity and VUV sensitivity, and integration of electronics including 3D integration strate-
825 gies. The PDMs will be characterised in a cryogenic platform at liquid nitrogen temperature and
826 installed at the DarkSide experiment to be used for dark matter searches. The UK has responsi-
827 bility for delivery of 2,500 PDMs for the instrumentation of the DarkSide-20k experiment (25%
828 of the total). The project was approved by STFC Science Board in 2020 with 14 collaborating
829 institutions in the UK. DarkSide has secured major capital funding in Italy, the USA, Canada,
830 Poland, Spain, France, Russia, and a capital funding bid in China is in progress. DarkSide-20k
831 commissioning is planned for 2024 with data-taking through to 2030.

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

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

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

841 6.1.4 DarkSphere

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

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

852 6.1.5 QUEST-DMC

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

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

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

864 6.2 Direct Searches for wave-like hidden sector dark matter

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

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

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

886 6.2.1 Quantum Sensors for the Hidden Sector

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

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

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

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

901 **6.2.2 AION**

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

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

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

918 **6.2.3 Quantum-enhanced Interferometry**

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

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

929 **Recommendation 6.4.** STFC should continue to support hidden sector direct dark matter re-
930 search and grow the new research community in this area through further funding calls beyond the
931 initial QTFP call, to sustain this research in the longer term. This funding must be made available
932 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

976 after the end of the current R&D experiments (e.g. after 2025). No large-scale future experiment
977 is currently approved.

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

992 **7.1.1 IceCube/IceCube-Gen2**

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

994 IceCube is an international experiment using the optical Cherenkov technique at the South Pole that
995 has reached a mature stage of its exploitation and has 300 collaborators. It is the largest running
996 neutrino experiment and is world-leading around the PeV energy scale. IceCube is a flagship
997 experiment in neutrino and multimessenger astronomy thanks to the discovery of very high energy
998 cosmic neutrinos and the detection of the first likely source of high-energy neutrinos, a blazar that
999 was also observed with gamma rays and lower energy photons. IceCube recently reported the
1000 detection of a cascade of high-energy particles (a particle shower) consistent with being created at
1001 the Glashow resonance by the interaction of a very high-energy astrophysical antineutrino. IceCube
1002 is also a multipurpose research facility with outstanding precision measurements in neutrino physics
1003 and exceptional contributions to cosmic ray physics, dark matter searches, and glaciology. The
1004 first stage of the IceCube-Gen2 (2030s fully instrumented), called IceCube-Upgrade, is funded to
1005 install seven new strings (2024 operation start). By roughly doubling the instrumentation already
1006 deployed, the telescope will achieve a tenfold increase in volume to about 10 cubic kilometers,
1007 aiming at an order of magnitude increase in neutrino detection rates. IceCube-Gen2 will provide
1008 an unprecedented view of the high-energy universe.

1009 **7.1.2 ANITA/PUEO**

1010 **Status.** Running. Not supported by STFC except for CG.

1011 ANITA/PUEO is a balloon experiment using the radio Cherenkov technique in Antarctica that is
1012 both proving the feasibility of the technique and providing world-leading results above the EeV
1013 energy scale. PUEO has improved sensitivity compared to ANITA and is an approved NASA
1014 mission with a flight scheduled for December 2024. ANITA/PUEO has 30 collaborators, mostly
1015 in the US with some involvement in the UK and Asia.

1016 **7.1.3 Pacific Ocean Neutrino Explorer**

1017 **Status.** Proto-collaboration. Test string construction 2021. Securing funding for the installation
1018 of the first 10 strings for P-ONE.

1019 P-ONE is a new initiative for the staged construction of a multi-cubic-kilometre neutrino telescope
1020 in the deep Pacific Ocean underwater infrastructure of Ocean Networks Canada. P-ONE is estab-
1021 lishing a formal collaboration and so far includes 40 scientists from Canada, Germany, and the
1022 UK. Two pathfinder missions have published water-quality and deployment results. The project is
1023 supported by Ocean Network Canada (ONC). At present, a global effort is underway to explore the
1024 sky at the highest energies in order to reveal the most powerful cosmic accelerators. The contribut-
1025 ing parties are the neutrino telescopes ANTARES (12 strings) in operation since 2008, KM3NeT
1026 under construction in the Mediterranean, the Gigaton Volume Detector (GVD) under construction
1027 at Lake Baikal, Russia, IceCube-Gen2 at the South Pole, and the new initiative P-ONE. If they
1028 were combined and used as a single distributed planetary instrument, it would cover almost the
1029 entire sky and the detection probability would improve by up to two orders of magnitude with
1030 respect to the one IceCube has today.

1031 **Recommendation 7.1.** UHEN represents a concerted effort by members of the community to
1032 support one large-scale future neutrino astronomy experiment, as was recommended in the 2016
1033 Particle Astrophysics roadmap and by the STFC Science Board. We recommend that the consor-
1034 tium continues to grow and broaden its support within the UK community. We also recommend
1035 that STFC supports this effort through appropriate funding, both for the near-term experiments
1036 that require travel and computing funding in order to maintain a community of trained early-career
1037 scientists, and PPRP funding to enable the UK to play a significant role in a longer-term large-scale
1038 experiment.

1039 **7.2 Quantum Technologies for Neutrino Mass**

1040 **Status.** Early R&D. Supported by STFC.

1041 A laboratory measurement of the absolute neutrino mass is one of the most important experimental
1042 challenges that remains in particle physics. Current leading techniques employed in the KATRIN
1043 experiment cannot probe neutrino mass scales below 200 meV. Reaching better sensitivities is moti-
1044 vated by the two mass scales: one corresponding to the inverted mass ordering ($m_\nu > 50$ meV) and
1045 the other to normal mass ordering ($m_\nu > 9$ meV). The overarching goal of the Quantum Technolo-
1046 gies for Neutrino Mass (QTNM) project is to use recent breakthroughs in quantum technologies
1047 to carry out an experiment capable of a guaranteed measurement of neutrino mass even in the
1048 worst case scenario of $m_\nu \sim \mathcal{O}(10)$ meV. To do this QTNM will employ a novel technology known
1049 as Cyclotron Radiation Emission Spectroscopy to carry out a study of unprecedented accurate of
1050 the energy spectrum of electrons emitted in Tritium beta decay around the end-point. In addition,
1051 this technique will yield unique sensitivity to the existence of sterile neutrinos by studying lower
1052 energy parts of the beta spectrum.

1053 QTNM is considered to be primarily in the PP remit. The intention is to host the experiment
1054 on UK soil, and the UK holds leading roles in the project. As such, we would welcome its inclusion
1055 as part of the Particle Physics roadmap.

1056 8 Cosmic Microwave Background

1057 The success of the Planck satellite, with UK leadership in key areas, has led to major advances in
1058 CMB cosmology. However, the CMB still contains a wealth of unexploited information. Over the
1059 next decade, CMB experiments will map the microwave sky to new precision in polarization and on
1060 small angular scales in order to pursue several key scientific goals. Searches for large-scale B-mode
1061 polarization signals from inflationary gravitational waves will provide new insights into the early
1062 universe, constraining physics at energy scales a trillion times higher than at the Large Hadron
1063 Collider. Experiments are seeking to improve current B-mode constraints, parameterized by the
1064 tensor-to-scalar ratio r , by more than an order of magnitude to $\sigma(r) \sim 10^{-3}$; such measurements
1065 will allow us to exclude a broad class of large-field inflation models – or will provide a revolutionary
1066 first detection of gravitational waves from the early universe. Using high-precision small-scale
1067 power spectra, CMB surveys will greatly advance the search for new light relic particles that
1068 are undetectable in current laboratory experiments. Upcoming experiments will soon approach
1069 thresholds where they will have some sensitivity even to particles that decoupled at the earliest
1070 times (well before the quark-hadron phase transition), providing new insights into beyond-the-
1071 standard-model physics. Surveys will also employ the CMB as a “backlight” to precisely map
1072 the distribution of mass and baryons across our Universe through lensing and scattering effects.
1073 This will unlock powerful new measurements of the neutrino mass and constrain dark energy
1074 phenomenology. Further into the future, satellites performing spectral distortion measurements
1075 can test inflationary predictions in a novel small-scale regime and search for energy injection by
1076 new physics.

1077 CMB measurements will not only constrain fundamental physics, but will also serve as a power-
1078 ful probe of astrophysics: upcoming surveys will precisely determine the properties of gas around
1079 and within galaxies and clusters, constrain star formation at high redshifts via emission from dusty
1080 star-forming galaxies, and provide new insights into reionization as well as radio sources and tran-
1081 sients.

1082 CMB research can thus address several STFC Science Challenge Questions, including: search-
1083 ing for primordial gravitational waves (A:8) to constrain inflation and the early universe (A:1);
1084 constraining the Universe’s particle and field content (C:1) by seeking signatures of new light relic
1085 particles; probing initial conditions and structure formation (A:2) with power spectra and lensing;
1086 constraining non-standard dark energy and dark matter properties and testing the standard cos-
1087 mological model and Einstein gravity (A:3, C:3, C:4); providing insights into star formation and
1088 reionization (A:4, A:5).

1089 8.1 Ground-based CMB Experiments

1090 8.1.1 Simons Observatory

1091 **Status.** Construction underway. Some STFC support for exploitation. Plans for major UK in-
1092 volvement via SO:UK are advanced and under final review.

1093 Advances in the CMB field in the next 5-10 years will be driven by ground-based experiments at
1094 the two sites with the best atmospheric conditions: the Simons Observatory (SO) in Chile and the
1095 South Pole Observatory at the pole. Broad UK community involvement has coalesced around the
1096 SO and indeed UK researchers already hold several leadership roles within the SO collaboration.

1097 The SO is a US-led CMB observatory which is currently under construction for deployment in
1098 the Atacama Desert in northern Chile. SO has several primary scientific objectives. Using B-mode
1099 polarization, SO will search for inflationary gravitational wave signals with a target of $\sigma(r) \approx 0.003$.
1100 SO will also seek new light relic particles, providing bounds nearly four times tighter than Planck.
1101 More broadly, SO will obtain new constraints on neutrino masses, astrophysics, dark energy, and
1102 dark matter with high precision analyses of CMB secondary anisotropies.

1103 The SO telescopes are divided into one high-resolution 6m Large Aperture Telescope and an
1104 array of three 0.5m Small Aperture Telescopes focused on measuring large scales. With 60000
1105 superconducting transition edge sensing bolometers, SO will map the CMB sky in six frequency
1106 bands ranging from 27-280 GHz. The telescopes are currently under construction at Vertex in
1107 Germany, and the receivers are currently under construction at various SO institutions in the US
1108 and around the world. A phased deployment of hardware to Chile is set to begin in 2022, with
1109 full operations scheduled to begin in 2024. SO will then start its nominal 5-year survey, with an
1110 expected completion date of 2029. The analysis of the SO data is expected to extend several years
1111 beyond that end-of-survey date.

1112 The construction and deployment of the SO telescopes & receivers is funded by the Simons
1113 Foundation (at \$72.5M). The foundation has additionally committed $\approx 50\%$ (\$20M) of the funding
1114 SO needs for its operations and data analysis phase. SO is actively seeking the remaining $\approx 50\%$.

1115 The SO:UK project is a £10M proposal from a consortium of UK CMB scientists to make
1116 a major UK contribution to SO, including both data pipeline and hardware contributions. The
1117 project is of central importance to the UK CMB research programme in the near future. SO:UK
1118 has previously been assessed by Science Board and PPRP and is currently in a STFC-funded Phase
1119 A study. The anticipated UK contributions are the following: i) provision of a UK Data Centre,
1120 responsible for delivering the Science-Ready Data Products for SO; ii) construction of a KIDs high-
1121 frequency (220/280 GHz) optics tube for the SO Large Aperture Telescope, demonstrating key UK
1122 technical expertise; and iii) major contributions to algorithm development for SO data pipelines. A
1123 more ambitious hardware contribution is also being considered. UK scientists currently hold several
1124 leadership roles in the SO Analysis Working Groups and the Theory and Analysis Committee;
1125 as first SO observations approach, increased funding for exploitation via AGP is important for
1126 preserving the UK's leading role in this area.

1127 **8.1.2 CMB-S4**

1128 **Status.** Reference design completed. Recommended for U.S. agency funding. No direct STFC
1129 support.

1130 CMB-S4 is an ambitious, near-future ground-based CMB experiment, which is envisioned as a
1131 successor to current ground-based efforts such as the Atacama Cosmology Telescope, South Pole
1132 Telescope, BICEP/Keck, SO, and the South Pole Observatory. By deploying an order of magni-
1133 tude more detectors than current-generation experiments, CMB-S4 will improve CMB polarization
1134 measurements significantly, reaching several key targets in fundamental physics and astrophysics.
1135 CMB-S4 goals include: probing inflationary gravitational wave B-modes precisely enough to either
1136 set an upper limit of $r < 0.001$ at 95% C.L., ruling out large classes of inflation models, or detect
1137 this primordial signal; searching for light relic particles with some sensitivity even to particles that
1138 decoupled well before the quark-hadron phase transition; detecting tens of thousands of galaxy
1139 clusters and mapping mass and baryons over more than half of the sky at high precision. CMB-S4

1140 also has several astrophysical science goals in areas such as transient and source science.

1141 To achieve these goals the S4 project will deploy telescope arrays to both sites with the best
1142 atmospheric conditions, the South Pole and the Atacama Desert in Chile. The telescopes will rely
1143 on a total of 500,000 detectors and will observe at up to 9 frequencies between 20 and 270 GHz.
1144 An array of small aperture telescopes will be deployed at the South Pole to integrate down to great
1145 depth over 3% of the sky; this will be complemented by the South Pole large aperture telescope,
1146 which will focus on cleaning the polarization from lensing noise on the same area. An array of large
1147 aperture telescopes will also be deployed to Chile and will undertake a wide survey over 60% of the
1148 sky that will enable constraints on light relics as well as cluster and mass mapping. First light may
1149 be as early as 2027, while full CMB-S4 science observations are expected to begin towards the end
1150 of this decade. A seven-year survey is planned.

1151 CMB-S4 is intended to be a joint US DOE and NSF project. It has been recommended as
1152 a priority for DOE funding by the 2014 Particle Physics Project Prioritization Panel (P5); NSF
1153 funding is also expected following CMB-S4's endorsement by the recent US astronomy and astro-
1154 physics decadal survey (CMB-S4 was ranked the joint second priority for new large ground-based
1155 facilities).

1156 In-kind contributions to the CMB-S4 project from international partners are explicitly anti-
1157 cipated and welcomed, which should provide opportunities for significant UK involvement. Although
1158 UK participation is currently restricted to collaboration membership as well as a small number of
1159 leadership positions, broader UK contributions could build on UK leadership in current experiments
1160 such as SO and in dedicated low-frequency telescopes such as C-BASS. Possible UK contributions
1161 could include optical components, a data centre and/or a dedicated, advanced low-frequency in-
1162 strument; contributions could be made via a formal partnership with SO or with enhanced versions
1163 of SO, although arrangements in this area are still to be determined.

1164 8.1.3 Low-frequency foreground experiments

1165 A limiting factor on the sensitivity of B-mode search experiments is likely to be foreground removal.
1166 The expected levels of both synchrotron and dust contamination, which can mimic inflationary B-
1167 modes, are greater than the CMB signal for $r = 0.001$ even in the cleanest areas of the sky. All
1168 planned CMB B-mode experiments use a wide range of frequencies to combat this problem, but
1169 their frequency range is limited by practical considerations – in particular, below 20 GHz bolometers
1170 become inefficient and prone to man-made interference from satellites. To solve this problem, the
1171 UK has pioneered low-frequency, radiometer-based CMB polarized foreground observations with
1172 the 5-GHz C-BASS experiment (with results eagerly awaited by the community), but STFC funding
1173 for this area has historically been at a low level. Sensitive future radiometer observations in the
1174 5-20 GHz range would greatly improve the science output from SO, CMB-S4 and LiteBIRD; the
1175 technology required has largely been developed for application in the SKA, and the cost is relatively
1176 modest compared to the large-scale bolometer experiments. Opportunities exist to collaborate with
1177 other countries such as South Africa, Spain and Italy.

1178 **Recommendation 8.1.** Major UK contributions to the Simons Observatory via SO:UK are the
1179 cornerstone of the UK CMB research programme and should be strongly supported. To maxi-
1180 mize the scientific impact of UK involvement and leverage current UK strengths, the panel also
1181 recommends further funding of scientific exploitation and technical development work for SO.

1182 **Recommendation 8.2.** The UK should target a leading role in ground-based CMB in the late
1183 2020s and 2030s. Making a significant contribution to CMB-S4, in a way that builds on involvement
1184 in Simons Observatory and other current experiments, appears to be the surest route to future UK
1185 leadership in this area.

1186 **Recommendation 8.3.** To complement UK investments in CMB observatories such as Simons
1187 Observatory, CMB-S4 and LiteBIRD, the UK should support a low-frequency foregrounds pro-
1188 gramme that includes the completion of the C-BASS southern survey (interrupted by COVID) and
1189 the development of a low-cost 5-20 GHz survey leveraging SKA technology.

1190 8.2 Future Satellite Missions

1191 8.2.1 LiteBIRD

1192 **Status.** Design phase. Partial funding secured. No direct STFC support.

1193 LiteBIRD is a satellite mission that will hunt for new signatures of cosmic inflation by mapping
1194 the large-scale CMB polarization at unprecedented precision over a wide range of frequencies. The
1195 primary aim of LiteBIRD is to constrain inflationary gravitational waves precisely enough to rule
1196 out (or detect) induced B-modes at a level of $r > 0.0005$, beyond a key threshold that would allow
1197 the exclusion of a broad class of large-field inflation models. LiteBIRD’s large sky coverage and
1198 high-frequency channels, which are valuable for foreground removal, provide complementarity to
1199 ground-based efforts. LiteBIRD will also enable a unique high-significance determination of the
1200 unknown neutrino mass and will allow detailed studies of cosmic reionization and of the physics of
1201 our Galaxy. To achieve these goals, LiteBIRD’s design includes 3 telescopes with a total of 3000
1202 superconducting transition edge sensing bolometers, which will make high-sensitivity full-sky CMB
1203 observations over 15 frequency bands between 34 and 448 GHz. LiteBIRD will operate for three
1204 years at the L2 Lagrange point.

1205 LiteBIRD was recently selected by JAXA as an L-Class (large) satellite mission, scheduled for
1206 launch in 2028. The mission envisions significant international contributions, with specific responsi-
1207 bilities and financial contributions still being fully defined. The mid- and high-frequency telescopes
1208 are a European responsibility. The UK has participated in the project since the very beginning
1209 and, capitalizing on its unique CMB instrumentation and analysis expertise, is well positioned to
1210 make significant contributions to the mission. These include provision of several optical components
1211 (such as filters, lenses and half-wave plates), thermo-mechanical design and testing, housekeeping
1212 electronics, and contribution to the high-frequency detector and focal plane programme. Members
1213 from the UK also contribute to analysis within the LiteBIRD Joint Study Groups (JSGs), which
1214 focus on low-level analysis work (e.g., systematics characterization, foreground mitigation, and
1215 pipeline development). The UK activities are coordinated locally by the LiteBIRD-UK consortium
1216 within the wider European framework.

1217 8.2.2 Future spectral distortion missions

1218 CMB spectral distortion measurements, which can provide a novel test of inflationary predictions
1219 and probe several types of new physics, are now widely recognized as an important future probe of
1220 early universe physics. Building on the legacy of COBE/FIRAS, several CMB spectrometers are
1221 currently being considered, including approaches from the ground, balloon and space. The most

1222 prominent space mission concept is PIXIE, but within the ESA Voyage 2050 space program even
1223 more ambitious designs could come within reach. One of the clear shortfalls of all existing concepts
1224 is the lack of low frequency coverage to tackle the μ -distortion component separation challenge.
1225 The UK, with its expertise in low frequency instrumentation and participation in balloon-borne
1226 spectrometer projects such as BISOU, has an opportunity to uniquely complement and extend
1227 ongoing studies and activities, with the long-term goal of contributing at a leading level to the ESA
1228 Voyage 2050 space programme vision.

1229 **Recommendation 8.4.** The UK should pursue a significant role in the LiteBIRD mission, building
1230 on its leading role in experiment and analysis for the Planck satellite. This is the panel's primary
1231 recommendation for future satellite missions.

1232 **Recommendation 8.5.** Technology development for future spectral distortion missions should be
1233 encouraged, as investments in this area could have long-term impact.

9 Theory

1235 Theoretical Particle Astrophysics is a crucial part of the programme. It supports the experimental
1236 effort by informing the observational or experimental directions that should be pursued and it
1237 ensures that experimental results are maximally exploited to gain a deeper understanding of the
1238 physical processes at work. The UK has a large and internationally prominent community working
1239 on theoretical particle astro-physics. The UK is represented on the EuCAPT steering committee
1240 and the 2019 EuCAPT census revealed that the UK has one of the largest Particle Astrophysics-
1241 theory communities in Europe, second only to Italy (by number of active institutes).

1242 UK theory activities have strong links with adjacent disciplines such as particle physics, as-
1243 tronomy, cosmology, and more recently, with fields traditionally falling within the EPSRC remit
1244 through the QTFP programme. The UK has a long history of leadership in general relativity. Cur-
1245 rent gravitational-wave theory efforts include both numerical and analytic modelling of GW sources
1246 to assess detectability, inform signal analysis strategies and develop the waveform templates that
1247 are critical to the success of current GW detectors. Dark matter phenomenologists in the UK work
1248 on topics ranging from proposals for novel searches to advance the direct detection programme,
1249 dark matter candidates in extensions of the Standard Model, and to the dark matter distribution in
1250 the Milky Way and beyond. Strengths of the particle cosmology community include topics in dark
1251 energy and modified gravity, inflation and topological defects. The UK also has historical strength
1252 in the theory of the CMB, having played a leading role in connecting key open questions to CMB
1253 observables such as polarised power spectra, non-Gaussianity and gravitational lensing. Several key
1254 advances in the theory of particle acceleration at astrophysical shocks have been made in the UK,
1255 and a broad community remain active in high energy astrophysics theory, including cosmic ray pro-
1256 duction and propagation. The UK hosts a strong theoretical neutrino physics community, studying
1257 the phenomenology of neutrino properties, the origin of neutrino mass and mixing and the impact
1258 of relic neutrinos on the evolution of the Universe. In VHE Gamma-ray astronomy the UK has
1259 strength in several areas of beyond-standard model physics notably indirect DM detection, search
1260 for Lorentz Invariance Violation using astrophysical targets, and signatures of Axion-Like Particles
1261 (ALPs) in the cluster environments and jets of active galaxies. VHE Gamma-ray astronomy also
1262 has importance in cosmology as a probe of the evolution of the extragalactic background light,
1263 and by constraining primordial magnetic fields. Finally, the QTFP programme has seeded new
1264 theoretical activity in an emerging field that is seeking to develop and apply quantum technologies
1265 to open questions within the Particle Astrophysics remit.

1266 To support the long-term health of the Particle Astrophysics programme, the UK must increase
1267 its support for theoretical activities. For instance, theoretical and computational development is
1268 required now to ensure we have the tools to perform the precision GW astronomy enabled by the
1269 next generation GW observatories. Investment in the development of accurate GW models and data
1270 science techniques is required now to ensure the UK can fully exploit the CE, ET and LISA data
1271 in the future. The R&D activities to support the development of next-generation DM detectors
1272 require dedicated theoretical work to better understand and model novel signal and background
1273 sources. This is true both for more established technologies employing liquid argon and xenon,
1274 as well as for the novel quantum sensors in the QTFP programme. The forthcoming era of VHE
1275 Gamma-ray cosmology will have close ties with multi-wavelength and multi-messenger facilities, and
1276 should be supported as a key area where the UK holds broad leadership to exploit these synergies.
1277 Further UK CMB theory work should be strongly supported to set targets for and maximize the
1278 scientific return from upcoming experiments. This should include funding for activities related to

1279 CMB spectral distortions as a probe of particle physics, new dark matter models and interactions,
1280 and primordial perturbations; efforts to connect upcoming CMB light relic constraints with bounds
1281 on new physics models; the relation of general properties of CMB higher-point-correlators to the
1282 symmetries and particle content of the early universe; and the development of new estimators for
1283 lensing and scattering effects and their connection with open problems in structure formation.

1284 **Recommendation 9.1.** Funding for theoretical activities should be increased to support the long-
1285 term health of the Particle Astrophysics programme and to ensure that experimental results can
1286 be fully exploited.

1287 Funding for Particle Astrophysics theory comes through the particle physics or astronomy grant
1288 panels. In an environment of restricted funding, there is the risk that world-leading Particle Astro-
1289 physics research that spans both fields is dismissed with the argument that it should be funded by
1290 the other panel and subsequently, is not given due consideration for funding. This is particularly a
1291 problem in Particle Astrophysics as there are some projects that will genuinely span both fields so
1292 there needs to be a clear process that allows these projects to be funded within the current system.
1293 For example, numerical relativity simulations that include the effects of ultra-light dark matter has
1294 been considered as too close to particle physics by the astrophysics panel, while particle physics
1295 models related to dark energy and inflation has been thought of as too close to the astrophysics
1296 panel.

1297 **Recommendation 9.2.** STFC and the particle and astrophysics panels should acknowledge that
1298 not all areas of Particle Astrophysics theory can be neatly classified as either astrophysics or particle
1299 physics and that there will be core areas of Particle Astrophysics theory that will necessarily appear
1300 to be on the borderline of the panel's remit. Furthermore, we would encourage STFC and the
1301 panels to consider mechanisms that could be put in place to prevent world-leading areas of Particle
1302 Astrophysics theory from falling between the cracks of the two panels.

1303 The seven projects that were initially funded as part of the (QTFP) programme address the
1304 aims of the Particle Astrophysics programme, including the search for dark matter and gravitational
1305 waves. All seven projects have a theory component which acts to guide the experimental effort, to
1306 provide more precise calculations of observables and to ensure that the experimental data is fully
1307 exploited.

1308 **Recommendation 9.3.** The STFC should ensure that follow-on funding for the theoretical activ-
1309 ities in the QTFP area is available. We also recommend that fellowship panels (including Ernest
1310 Rutherford, Future Leaders and Stephen Hawking fellowships) recognise that theoretical research
1311 in the QTFP area falls within their remit and ensure that they include panel members with the
1312 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

1355 to be exploited across all the possible opportunities. In addition to PRD, an effective and cost
1356 efficient mechanism could be to provide funding for long-term technology development in areas
1357 applicable to a larger number of the upcoming projects. This would represent a different model for
1358 STFC, not solely relying on lower-level PRD-type funding, which would itself be valuable to rein-
1359 state, but also larger, technology-focussed grants which could fund centres of excellence comprising
1360 either single or a distributed network of institutes. This would exploit the efficiencies of scale and
1361 risk reductions to be gained in investment in technology development for applications in several
1362 Particle Astrophysics project areas, or which would have impact outside Particle Astrophysics (e.g.
1363 particle/nuclear/astronomy).

1364 **Recommendation 10.1.** Renew funding for the existing PRD scheme alongside a new mode
1365 of larger scale technology programmes which would assemble expertise to develop high impact
1366 technologies with application across multiple projects and fields.

1367 **10.2.1 Sensors**

1368 Photo-sensors are commonly required in Particle Astrophysics experiments, with detectors often
1369 comprising very large arrays of sensors. For example, the CTA SST array will utilise 76k silicon
1370 photo-multipliers (SiPMs). Typical performance requirements include fast timing, high sensitivity,
1371 photon-counting, and low background rates. New experiments are gradually replacing the conven-
1372 tional vacuum photo-multiplier tubes with SiPMs. While the UK has not previously led SiPM
1373 development, there are areas where UK expertise could be employed to advantage. For example,
1374 next generation rare event search experiments requiring VUV sensitivity could leverage existing
1375 UK industrial expertise in back side illumination to develop new SiPM technology removing re-
1376 quirements for wavelength shifting materials, improving sensitivity and reducing costs.

1377 **10.2.2 Electronics**

1378 Large arrays of high-speed photo-sensors comprising a typical DM and IACT experiments are
1379 instrumented using high density electronics with very large channel counts. These commonly
1380 utilise ASICs and FPGAs on high density PCBs, with typical requirements for very high speed,
1381 nanosecond timing, low noise, and low cost per channel. There are often large synergies between
1382 Particle Astrophysics (and other Particle Physics) experiments and the idea of a UK design and
1383 fabrication facilities for the development and manufacture of such electronics and serving all STFC
1384 communities was raised in the previous Particle Astrophysics road-map.

1385 **Recommendation 10.2.** Given the near-certainty of increased complexity, channel count and
1386 miniaturisation of future Particle Astrophysics experiments, the concept of one or a small number
1387 of focused UK design and fabrication facilities, serving all STFC communities for electronics design
1388 and construction, should be considered.

1389 Alongside larger scale funding for technologies, better funding and fellowships for experimental-
1390 ists and instrument specialists are equally as important. Higher historic funding levels have placed
1391 the UK in a situation where we are currently surfing on a wave of earlier technology development,
1392 and now we are rapidly being overtaken by those who have invested in this area, both in people
1393 and infrastructure.

1394 **Recommendation 10.3.** UK expertise in particle astrophysics instrumentation should be en-
1395 hanced by extending funding opportunities and fellowships for experimentalists and instrument
1396 specialists. This is necessary in order to maintain the UK’s international competitiveness.

1397 **10.3 Computing and Data Science**

1398 Particle Astrophysics research requires large-scale, high-performance and high-throughput comput-
1399 ing resources due to the very large observational and experimental data-sets, and to the multi-scale,
1400 multi-dimensional and non-linear domains to be explored in building model simulations. At present,
1401 the community’s needs are well met by the existing hardware provision, notably through the STFC
1402 Distributed Research utilising Advanced Computing (DiRAC) and IRIS facilities and supplemented
1403 by a dedicated UK Gravitational Wave computing resource. This has required significant commu-
1404 nity effort in proposing and supporting the recent upgrade to DiRAC 3 and the establishment of the
1405 IRIS consortium. Moving forward, it is critical that computing requirements are established early,
1406 during the planning stages for new experiments, and that computing costs should be captured and
1407 incorporated into long-term plans and budgets.

1408 **Recommendation 10.4.** Large-scale computing for simulations and data analysis is critical for
1409 all areas of Particle Astrophysics. STFC must ensure that appropriate computing resources are
1410 made available to enable full exploitation of observational and experimental data.

1411 Computational techniques are evolving rapidly, with machine learning and Artificial Intelligence
1412 becoming commonplace across Particle Astrophysics analyses. This evolution requires continual
1413 engagement with computing providers to ensure the ensures that the community’s needs are met. At
1414 present, Particle Astrophysics experiments are well-represented on the IRIS management board, and
1415 modellers have a voice on the DiRAC board. The rapid development of computational techniques
1416 necessitates both training for existing researchers and provision of dedicated computing specialists.
1417 STFC initiatives, such as the Data Intensive Centre for Doctoral Training (CDT), have provided
1418 specialist training for a large number of PhD students. It is important that similar training is
1419 available to PDRAs and more senior staff.

1420 Since the past roadmap, there has been a significant development in the UK of a community
1421 of Research Software Engineers (RSEs) [1]. In 2020 STFC awarded its first RSE Fellowship. RSEs
1422 are vital across Particle Astrophysics research, however, at present there is insufficient support for
1423 such positions. Additionally, there is no well established career path for RSEs within academia.
1424 Adequate funding for expert computing staff is essential to ensure efficient usage of computing
1425 resources and to facilitate the use of cutting-edge computational techniques in both simulations
1426 and data interpretation.

1427 **Recommendation 10.5.** STFC should provide a greater level of support for specialist computing
1428 staff, particularly RSEs, within Particle Astrophysics. Continued, long-term support, such as
1429 through RSE Fellowships, is vital to retain the computing specialists required to ensure the success
1430 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 is unsurprising 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 patient’s 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-inspired 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

1475 is being updated to support modern GPU architectures using the Intel oneAPI DPC++ compilers,
1476 with input from industry stakeholders including Intel and the HPC-library developers AMReX.
1477 Data analysis techniques developed to address particle astrophysics challenges have been used in
1478 areas from medical science to finance and climate change. For example, techniques developed in
1479 gravitational wave analyses have been used to improve quality control in ophthalmic devices.

1480 11.2 Outreach and Public Engagement

1481 Outreach and public engagement activities are an integral part of all areas of Particle Astrophysics
1482 research. Examples of successful activities include:

1483 A planetarium show called “Exploring the High Energy Universe” has been written and pro-
1484 duced in-house by the Armagh Observatory and Planetarium. The show introduces the viewer to
1485 the multi-wavelength sky, illustrates two examples of extreme phenomena in the cosmos, brings
1486 in the range of telescopes astronomers use to study them, and ends by introducing gamma ray
1487 telescopes and finishing with the CTA as the next generation facility for exploring the high energy
1488 universe. The show has been written for Digistar planetaria, which are widely available through
1489 the world, and will be shared and made freely available using the Digistar Cloud.

1490 The Prototype Outreach Cherenkov Imaging Telescope (POCIT) is a 1 m² class optical telescope
1491 being developed as an outreach tool to explain the concept of CTA and bring real-time particle
1492 astrophysics observations to the public at events such as stargazing live. Based around components
1493 from the CTA SST telescope, several POCIT may be sited at publically accessible observatories
1494 such as the Armagh Observatory, and the National Space Centre. The technology might also be of
1495 interest for future expansions of CTA and SWGO.

1496 Major LIGO results papers are accompanied by a science summary, a short, non-technical article
1497 written to accompany the publication. These have proven to be an effective tool for communicating
1498 the ambition, excitement and research impact of LIGO’s scientific program to a wide audience.
1499 The science summaries are published in 21 languages and have increased public understanding and
1500 awareness of gravitational waves, directly assisting journalists in communicating to the public.

1501 The Remote³ programme is hosted by the Boulby Underground Laboratory. The project aims
1502 to deliver much-needed STEM outreach to some of the most remote areas of Scotland. The Remote³
1503 project is aimed at Key Stage 3 students, age 10-14, in 10 Scottish high schools. Over a 14-week
1504 period, teams of 4-6 students in each school design, build and program a miniature Mars Rover. This
1505 rover is then sent to the Boulby Underground Laboratory to explore the STFC Mars Yard located
1506 1.1 km underground. In 2020-21, Boulby engaged nearly 3,000 people directly, plus thousands more
1507 watching recordings. Over 50% of those were in the crucial 8-14 year old category, which research
1508 has shown [11] as a key age group to target, in terms of influencing future career decisions.

1509 International Dark Matter Day was launched in 2017. Highlights include a joint UK/China event
1510 in 2019, broadcast to over 44,000 viewers internationally, providing an excellent mutual learning
1511 opportunity of science and culture and establishing future collaborative opportunities. This was
1512 followed up by a presentation to the UK embassy and consulates to China in 2020.

1513 **Recommendation 11.1.** Outreach and public engagement are essential for broader societal ap-
1514 preciation of science and attracting the next generation of talented researchers, regardless of back-
1515 ground. Particle Astrophysics research is particularly suitable for outreach, as it focuses on some
1516 of the most extreme environments in the universe and most profound open questions in science.
1517 Outreach activities from the Particle Astrophysics community should be strongly supported.

1518 **A Contributions to the roadmap**

1519 We received significant input to the roadmap from members of the UK Particle Astrophysics Com-
1520 munity. This input comprises

- 1521 • Initial input at the Particle Astrophysics Town hall in January 2021
- 1522 • 101 individual submissions to a roadmap questionnaire in May 2021
- 1523 • 19 experimental submissions of a roadmap proforma in May 2021. Experiments which sub-
1524 mitted proformas are:
 - 1525 – Atom Interferometer Observatory and Network (AION)
 - 1526 – Advanced LIGO (aLIGO)
 - 1527 – Cosmic Explorer (CE)
 - 1528 – Einstein Telescope (ET)
 - 1529 – LUX-ZEPLIN (LZ)
 - 1530 – Quantum-enhanced Interferometry (QI)
 - 1531 – Quantum Technologies for Neutrino Mass (QTNM)
 - 1532 – QUEST-DMC
 - 1533 – Simons Observatory (SO)
 - 1534 – Xenon Futures
 - 1535 – Cherenkov Telescope Array (CTA)
 - 1536 – Dark Side
 - 1537 – UK High-Energy Neutrino (UHEN)
 - 1538 – Dark Sphere
 - 1539 – Quantum Sensors for the Hidden Sector (QSHS)
 - 1540 – Laser Interferometer Space Antenna (LISA)
 - 1541 – Pulsar Timing Array (PTA)
 - 1542 – Southern Wide-field Gamma-ray Observatory (SWG0)
 - 1543 – Cherenkov Telescope Array (CTA) Galactic Plane Survey
- 1544 • Attendance at a Roadmap focused PA town hall in July 2021
- 1545 • Individual feedback on the draft roadmap, provided in November 2021 both via written
1546 submission and at PAAP “office hours”

1547 We thank Ailsa Johnstone and Karen Clifford from STFC, and Alex Murphy, the Particle Astro-
1548 physics representative on Science Board, for their advice and feedback throughout the preparation
1549 of this Roadmap. We thank the STFC design team for producing the graphics included in the
1550 Roadmap.

1551 **Acronyms**

1552 **A+** Advanced LIGO plus.

1553 **AGN** Active Galactic Nuclei.

1554 **AGP** Astronomy Grants Panel.

1555 **AION** Atom Interferometer Observatory and Network.

1556 **aLIGO** Advanced LIGO.

1557 **ALP** Axion-Like Particle.

1558 **APPEC** Astroparticle Physics European Consortium.

1559 **BH** Black Hole.

1560 **BUGS** Boulby Underground Screening.

1561 **CDT** Centre for Doctoral Training.

1562 **CE** Cosmic Explorer.

1563 **CMB** Cosmic Microwave Background.

1564 **CP** Charge-Parity.

1565 **CREF** Cold Radon Emanation Facility.

1566 **CTA** Cherenkov Telescope Array.

1567 **DiRAC** Distributed Research utilising Advanced Computing.

1568 **DM** Dark Matter.

1569 **EPSRC** Engineering and Physical Sciences Research Council.

1570 **EPTA** European Pulsar Timing Array.

1571 **ESA** European Space Agency.

1572 **ET** Einstein Telescope.

1573 **EuCAPT** European Consortium for Astroparticle Theory.

1574 **GRB** Gamma Ray Burst.

1575 **GW** Gravitational Wave.

1576 **H.E.S.S.** High-Energy Stereoscopic System.

1577 **IACT** imaging air Cherenkov telescope.

1578 **IGMF** Intergalactic Magnetic Field.

1579 **IPTA** International Pulsar Timing Array.

1580 **ISW** integrated Sachs-Wolfe effect.

1581 **ΛCDM** Lambda Cold Dark Matter.

1582 **LEAP** Large European Array for Pulsars.

1583 **LISA** Laser Interferometer Space Antenna.

1584 **LZ** LUX-ZEPLIN.

1585 **NS** Neutron Star.

1586 **P-ONE** Pacific Ocean Neutrino Explorer.

1587 **PPGP** Particle Physics Grants Panel.

1588 **PPRP** Projects Peer Review Panel.

1589 **PRD** Project Research and Development.

1590 **PTA** Pulsar Timing Array.

1591 **QCD** Quantum Chromodynamics.

1592 **QI** Quantum-enhanced Interferometry.

1593 **QSHS** Quantum Sensors for the Hidden Sector.

1594 **QTFP** Quantum Technologies for Fundamental Physics.

1595 **QTNM** Quantum Technologies for Neutrino Mass.

1596 **RAL** Rutherford Appleton Laboratory.

1597 **RSE** Research Software Engineer.

1598 **SiPM** silicon photo-multiplier.

1599 **SKA** Square Kilometre Array.

1600 **SO** Simons Observatory.

1601 **STFC** Science and Technology Facilities Council.

1602 **SWG0** Southern Wide-field Gamma-ray Observatory.

- 1603 **UHEN** UK High-Energy Neutrino.
- 1604 **UKRI** UK Research and Innovation.
- 1605 **UKSA** United Kingdom Space Agency.
- 1606 **VHE Gamma** Very High Energy Gamma Ray.
- 1607 **WIMP** Weakly Interacting Massive Particle.

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