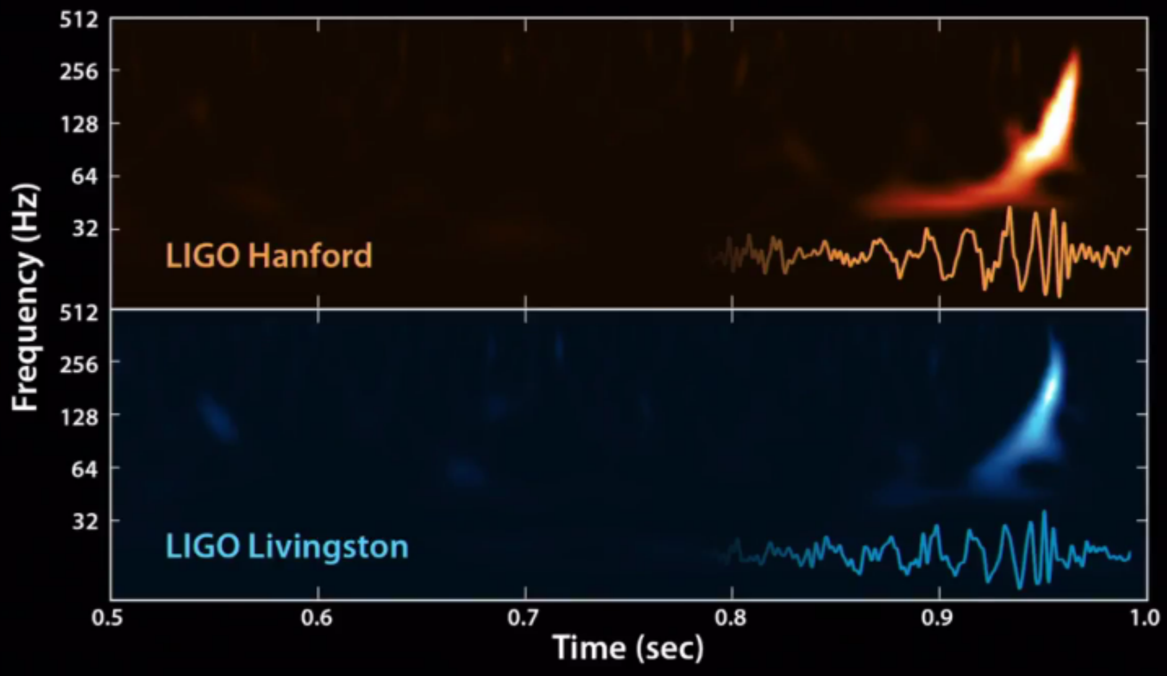
Roadmap for UK Particle Astrophysics

STFC Particle Astrophysics Advisory Panel Report - 2016
Chamkaur Ghag, Ruth Gregory, Julian Osborne, Patrick Sutton, Lee Thompson



The cover image shows the whitened time series and time-frequency images of the gravitational-wave signal GW150914 as measured by the LIGO-Hanford and LIGO-Livingston detectors. The signal is visible for approximately 8 cycles. The increase in frequency and amplitude produces the distinctive "chirp" signature indicative of compact binary coalescence. Detailed analysis reveals the progenitor to have been a merging binary black binary with component masses of $36^{+5}_{-4}\,\mathrm{M}_{\odot}$ and $29^{+4}_{-4}\,\mathrm{M}_{\odot}$ at a distance of $410^{+168}_{-180}\,\mathrm{Mpc}$ [PRL **116** 061102 (2016)].

Executive Summary

This is an exciting time for particle astrophysics (PA). The last few years have witnessed spectacular discoveries, most notably the historic birth of a new era in observational astrophysics, with the first observations of gravitational waves, from binary black hole mergers, reported by the LIGO and Virgo collaborations in 2016 with acknowledged UK leadership. Further, there has been the first observation of PeV-energy neutrinos by IceCube, reported in 2013. Construction has begun on second generation dark matter detectors including LUX-ZEPLIN (LZ), which will probe the WIMP parameter space for masses above a few GeV down to cross-sections near the irreducible neutrino coherent scattering background. The Cherenkov Telescope Array (CTA), the first global observatory for very high-energy photons with sensitivity an order of magnitude better than any previous facility, has entered its pre-construction phase.

Particle astrophysics is by its nature frontier physics, addressing big questions with often exotic detectors, and excites and inspires young people. For example, the gravitational wave discoveries made global front-page news, and were hailed as the discovery of the century and the start of a new and fundamentally novel way to study our Universe. Such ambitious projects require advanced technologies, help to train highly-skilled personnel, and facilitate knowledge exchange with industry. PA is a growing field globally and the UK has a very strong track record. The PAAP has canvassed opinion through a questionnaire, two community consultations, and written comments on our draft report. Here we present recommendations derived from this input: a roadmap for the future of particle astrophysics in the UK over the next decade.

We find that the UK is well positioned to provide an excellent and diverse programme in PA, where the current and planned activities offer world-leading capability to directly address 3 of the 4 top level science challenges in STFC's science roadmap, and we make the case for growth in this area in the longer term. Our proposed roadmap builds on three areas of current STFC investment and UK leadership: **gravitational wave astronomy**, **γ-ray astronomy** and **direct dark matter detection**. The current spend of only $\sim$£3.2M per year supports gravitational wave R&D, operations and exploitation focussed on Advanced LIGO, construction of the LUX-ZEPLIN dark matter detector, and targeted R&D for the γ-ray observatory CTA. **We strongly recommend increasing the funding envelope for UK particle astrophysics. An uplift in support is essential to capitalise on the new opportunities in gravitational waves, γ-ray astronomy, and dark matter, by accommodating both the construction and exploitation phases of the current instruments. An uplift will also enable novel R&D for future detector technology, which is vital to maintaining acknowledged UK leadership in these areas through the next decade.** Particle Astrophysics offers high-impact science, UK leadership and technological innovation and has tremendous scope for increased UK impact if additional resources become available.

1 Particle Astrophysics Science Questions

Scientific questions in Particle Astrophysics can be divided into two broad themes, 'Multi-messenger Astronomy' and 'Fundamental Physics with Cosmic Messengers'. Both of these involve the intersection of astrophysics and particle physics.

1) Multi-messenger Astronomy

Multi-messenger astronomy involves making astrophysical measurements using unconventional messengers, including ultra-high-energy nuclei, very-high-energy γ-rays and neutrinos, and gravitational waves. It encompasses the exploration of extreme and/or otherwise inaccessible environments and phenomena and the origin and role of accelerated particles in astrophysical systems.

1a) What is the nature of compact objects?

What is the nature of black holes? What is the nature of neutron stars? What is the mass function of black holes and neutron stars? How did black holes in galactic nuclei form and evolve? Why are spin frequencies of neutron stars in low-mass X-ray binaries bounded? Are there stable states of matter at densities beyond neutron degeneracy?

1b) What is the physics behind supernovae and gamma-ray bursts?

What is the physical mechanism for core-collapse supernovae and how asymmetric is the gravitational collapse that ensues? What happens when compact objects merge? Are GRB jets driven by neutrinos or magnetically? Is the formation of a highly magnetised neutron star ($B \sim 10^{15}$ G), a magnetar, critical to GRBs and super-luminous supernovae?

1c) What are the origins of ultra-relativistic cosmic particles, and how are they accelerated?

Where are particles accelerated up to 10^{20} eV? What are the dominant sources of relativistic particles in star-forming regions/galaxies? What processes accelerate particles in supernova explosions, pulsar winds and AGN jets?

1d) What role do ultra-relativistic particles play in astrophysical environments?

What is the role of these particles in the evolution of cosmic magnetic fields? In the interstellar medium of galaxies? In star-formation feedback and galaxy evolution? In the interaction between active galactic nuclei and their host galaxies and galaxy clusters?

2) Fundamental Physics with Cosmic Messengers

Cosmic messengers can be used to test fundamental physics under extreme conditions and/or at energies beyond the reach of terrestrial experiments. These include tests of Special and General Relativity and the Standard Model of Particle Physics, and the search for the nature of Dark Matter.

2a) What is the nature of Dark Matter?

What are the mass, interaction cross-section and other properties of the dark matter particles, and what insights to physics beyond the Standard Model will they lead to? How is dark matter distributed in our galaxy and beyond?

2b) What is the nature of Dark Energy?

What is the equation of state of dark energy and does it vary with redshift? What are the consequences for fundamental physics, cosmology, and the nature of space-time and gravitation?

2c) Is General Relativity the correct theory of gravity?

Are the properties of gravitational waves and extreme gravitational environments as predicted by General Relativity? Are modified gravity theories the solution to the dark energy or dark matter puzzles? Is the propagation speed of light constant at ultra-high energies?

2d) What are the properties of neutrinos?
What are the absolute neutrino masses and the precise values of the mixing parameters? Is there CP-violation in the leptonic sector? Is the standard 3-neutrino mixing scenario correct? What is the impact of neutrinos and their properties on the evolution of the Universe and of astrophysical objects?

2e) Are there particles present in the universe which have not yet been detected either directly or indirectly?
Do axion-like particles or topological defects such as magnetic monopoles or cosmic strings exist? How would such discoveries be incorporated into models?

The current and future programme of Particle Astrophysics activities that we recommend is built around a strategy that addresses the above questions, and in doing so addresses the Science Challenges identified by STFC as core to its programme, namely:

A: How did the universe begin and how is it evolving?
C: What are the fundamental constituents and fabric of the universe and how do they interact?
D: How can we explore and understand the extremes of the universe?

In particular, our strategy addresses subquestions A1, A3, A6, C2, C4, C5, and all of the subquestions of D.

2 Observational Strategy

The scientific questions listed above will be addressed using a number of different messengers and approaches. In the following we describe a possible strategy.

1a) What is the nature of compact objects?

The detections of gravitational waves (GWs) from the mergers of the binary black hole systems GW150914 and GW151226, announced in February and June 2016 respectively, have already begun to shed light on the properties of these systems and allowed the first tests of General Relativity in the dynamic, strong-field regime. These detections and subsequent analyses are heralding the commencement of gravitational wave astronomy. Further GW measurements of the coalescence of black holes and neutron stars will reveal the mass and spin distributions of these objects, provide a precision probe of strong-field dynamical gravity and help us further understand the evolution of galaxies, giving an independent handle on the nature of dark energy. Furthermore, the tidal distortion of the neutron star leaves an imprint in the GW signal, constraining the equation of state. Similarly, spinning neutron stars in our galaxy emit continuous GWs whose amplitude is determined by the star's ellipticity, while GW emission due to the r-mode instability may be the cause of the apparent bound on spin frequencies of neutron stars in low-mass X-ray binaries. A space-based GW detector will observe mergers of supermassive black-holes and shed light on their growth mechanism, while the intricate GW signal from stellar-mass objects spiralling into such black holes will allow precision mapping of the spacetime geometry around the hole.

In the electromagnetic spectrum, very high angular resolution observations will make possible the detection of strong GR effects on the emission close to the event horizon of Sagittarius $A^\star$, severely constraining the nature of this object. X-ray observations will explore compact objects via time-resolved spectral measurements of emission from accreting material. Pulsar studies in radio, γ-ray and other wavebands will also provide constraints on the nature of these objects.

1b) What is the physics behind supernovae and gamma-ray bursts?

The observation of a GW "chirp" signal from a short gamma-ray burst (GRB) would be conclusive proof that their progenitors are compact-object binaries involving a neutron star. GW-GRB associations would also constrain the short GRB beaming angle. In the collapsar model for long GRBs, GWs could probe for non-axisymmmetric instabilities. Jet formation in GRBs and particle acceleration in the prompt and afterglow phases can be probed by high-energy γ-ray and neutrino observations.

In supernova (SN) explosions, nearly all of the energy is carried by neutrinos which are emitted from the core of the star. Large-volume neutrino observatories will be able reconstruct the time-dependent flux and spectrum of electron, muon, and tau neutrinos with high accuracy, providing critical information on the mechanisms for the SN explosion. GW observations would also probe the inner core of core-collapse SN in our galaxy and throughout the Local Group, and help distinguish the explosion mechanism. The late evolution of the SN into the supernova remnant phase can be effectively probed by combined X-ray, radio and γ-ray measurements.

1c) What are the origins of ultra-relativistic cosmic particles, and how are they accelerated?

To determine the dominant origin of cosmic rays (CRs) in different energy ranges requires a programme of multi-messenger and multi-wavelength observations. The primary tools for the study of the highest energy particles are very large arrays of air-shower CR detectors: capable of "proton astronomy" at energies where magnetic deflections become sufficiently small. Complementary measurements at lower energies, for example TeV emission from UHE-proton initiated cascades, will help to firmly establish the nature of the UHE accelerators. At PeV energies, the combination of Galactic surveys in VHE γ-rays and neutrinos with follow-up pointed observations in the X-ray, radio and other wavebands appears to be the most promising approach for a census of particle acceleration associated with ongoing star-formation in our own Galaxy.

The mechanisms for particle acceleration at relativistic (in AGN jets, pulsar winds and GRBs) and non-relativistic (galaxy cluster mergers/accretion, SNR, colliding stellar winds) shocks remain unclear, with a possible role for magnetic reconnection as well as diffusive shock acceleration. High-resolution observations of nearby objects in (at least) radio, X-ray and TeV γ-ray are required to establish the spatial distribution of particles (of all types) and magnetic fields in these systems. In addition, a larger sample of objects is needed to understand the time-evolution of these systems.

1d) What role do ultra-relativistic particles play in astrophysical environments?

Establishing the role of energetic particles in the interstellar medium, in stellar clusters, starburst galaxies, AGN jets, lobes and bubbles and hence their role in galaxy evolution and in the evolution of cosmic magnetism, requires the mapping of diffuse non-thermal emission associated with all these object classes in multiple wavebands. Next generation γ-ray observatories will have sufficient angular resolution and sensitivity to perform this mapping and unique sensitivity to the ultra-relativistic hadrons which are very difficult to probe using lower energy photons. Synchrotron measurements, in particular in the radio and hard X-ray bands where non-thermal emission often dominates, are however key to these processes, probing magnetic fields and providing higher resolution and access to larger populations. Neutrino and UHE cosmic ray measurements are useful but are likely to be limited by the available statistics and resolution. TeV photons produced by accelerated particles may play an important role in heating of voids, with implications for late-time structure formation. Further observations of TeV blazars are needed to quantify this effect.

2a) What is the nature of Dark Matter?

Dark matter in the form of Weakly Interacting Massive Particles (WIMPs) may be detected directly (via elastic scattering in specialist underground detectors) or indirectly (via their annihilation products, in particular high energy γ-rays, neutrinos and anti-matter). WIMPs may also be produced at particle colliders, such as the LHC. Each of these methods has different uncertainties and backgrounds. Collider production of WIMP-like particles alone would not solve the dark matter problem; it would not demonstrate that these particles are stable over cosmological timescales and are the dark matter in the Universe. It is likely that the convincing discovery of dark matter will require consistent signals from direct and several different indirect experiments. If WIMPs are detected direct and indirect detection experiments will then be able to measure the WIMP properties (mass and interaction cross-sections) and their distribution within the Milky Way galaxy.

Alternatively, dark matter may consist of axions. QCD axions arise out of a standard model extension that solves the strong CP problem, explaining why the CP violating terms in QCD are suppressed by $\sim 10^{10}$ relative to standard model expectations. Experiments sensitive to QCD axions utilize high Q electromagnetic resonators in magnetic fields. Other experiments have constrained axion-like particles, having stronger couplings than QCD axions, either produced in the lab or by the sun. Further experimental dark matter work seeks to explain observations of line features in x-ray satellite data, such as at 3.5 keV, probing possible underlying physics such as sterile neutrinos and decaying WIMPs. Data from micro–calorimeters having greater spatial resolution that can resolve atomic lines, and large datasets from all–sky calorimeters, aim to identify the origin of this intriguing feature.

2b) What is the nature of Dark Energy?

The expansion history of the Universe (measured via supernovae, baryon acoustic oscillations, weak lensing and galaxy cluster counts) and the growth of density perturbations (measured via weak lensing and galaxy cluster counts) provide complementary probes of the physics underlying the current acceleration of the universe. DES, and in the future EUCLID and SKA, will accurately measure the dark energy equation of state, and its time dependence. Furthermore comparing the results of the two different types of probes will test the validity of general relativity on cosmological scales, and whether the acceleration is due to modified gravity.

As the Advanced LIGO detectors head towards design sensitivity over the next four years they will build up the statistics of coalescing black holes. If the host galaxies for these sources are identified, allowing their redshifts to be obtained from electromagnetic observations, initial independent checks of the expansion of the Universe will begin. Future upgrades now planned to Advanced LIGO will deliver measures of the expansion as probed by gravitational signals with increasing accuracy, leading to GW observatories such as the Einstein Telescope (ET) which should observe of the order of 10^5 coalescences of binary neutron stars per year to $z = 2 - 4$ and measure their luminosity distances. When combined with redshifts (via multi-messenger observations of a subset of systems, or directly from tidal deformation in the GW signal), this will yield an independent calibration of the cosmological distance scale using gravity as a probe of the expansion rate and constrain cosmological models. A space-based GW detector, such as eLISA, would extend this type of observation to include much more massive black hole mergers.

2c) Is General Relativity the correct theory of gravity?

GW detectors have given us a completely new view of black holes, which have the strongest gravitational fields in nature. By comparing the detected GW signals to detailed theoretical models we have already placed completely new constraints on deviations from general relativity in the strong-field, high-velocity regime. Further GW observations of neutron star and black hole mergers and ringdowns will allow us to improve these bounds further, and test fundamental predictions of GR such as the area and no-hair theorems. GW observations can also test relativity by searching for polarisation states beyond those predicted by GR, a non-zero graviton mass, and differences in the propagation speeds of light and gravity over cosmological distances. Joint GW/EM observations also offer very stringent tests of the speed of gravity using high spindown pulsars.

General relativity may also break down in the weak-field limit. Modified gravity theories have been proposed as alternatives to dark matter, dark energy, and inflation. Some of these theories could be tested by such PA experiments as LISA Pathfinder, by looking for anomalous tidal stresses if the spacecraft is flown through the L1 Sun-Earth saddle-point.

Effects on the propagation velocity of high energy photons, expected in the framework of Quantum Gravity models, can be tested using γ-ray observatories to find deviations of one part in $> 10^{15}$ at TeV energies, probing linear violations of Lorentz Invariance with characteristic energies well beyond the Planck scale.

2d) What are the properties of neutrinos?

The discovery of neutrino oscillations raises new questions in physics beyond the Standard Model. Large neutrino detectors can be used to study neutrino oscillations in an energy range from MeV to tens of GeV, using solar, atmospheric, supernova, and geo-neutrinos, as well as man-made reactor and accelerator neutrinos. Thanks to the recent measurement of the third mixing angle, these experiments can determine the neutrino mass hierarchy, and have the potential to search for CP-violation, to obtain very precise measurements of the oscillation parameters and to hunt for deviations from the standard 3-neutrino mixing picture.

Detection of diffuse UHE neutrinos using UHE cosmic ray or dedicated UHE neutrino detectors opens up the possibility of cross-section measurements through the approximately known flux of (GZK) neutrinos from UHE cosmic ray interactions with the CMB. Similarly, comparing the neutrino rate from the Earth direction to the neutrino rate from all other directions can provide a measurement of the effective neutrino-nucleon cross-section at centre of mass energies far greater than those possible in accelerators. High energy neutrino telescopes such as IceCube and KM3NeT are also sensitive to large fluxes of atmospheric neutrinos. Whilst their study is not a primary objective of such detectors, this presents the opportunity to investigate the properties of atmospheric neutrinos, in particular their energy and angular distributions and their flavour content. Above 50 TeV, the measurement of prompt neutrinos from heavy meson decay should be apparent through an observable change in the spectral index and a change in flavour ratios. Instrumenting the cores of neutrino telescopes with densely packed photosensor arrays results in a reduction in the neutrino energy threshold and may make studies of neutrino oscillations and the determination of the mass hierarchy possible.

2e) Are there particles present in the universe which have not yet been detected either directly or indirectly?

Whilst collider-based experiments appear to be the most promising route to the discovery of new particles beyond the hypothetical WIMPs, non-collider PP and PA experiments probe a large and complementary phase space for new particles. Direct Dark Matter detectors are sensitive to weakly-interacting particles in a general sense, with broadband searches providing discovery potential for particles with unexpected properties. Multi-tonne scale instruments will have sensitivity beyond WIMPs to include axions, ALPs, and several other models to complement dedicated axion searches using resonant microwave cavities. Axion searches can also be performed by γ-ray observatories via the detection of reconverted photons from objects with a very high optical depth for primary photons. Topological defects such as cosmic strings may be detectable through high photon fluxes at UHE detectable with cosmic ray observatories. Cosmic strings or superstrings may also be identified directly through gravitational-wave emission, either individually or collectively as a stochastic GW background. Finally, a future large-volume (mega-tonne-scale) multi-purpose neutrino detector would perform a sensitive search for new physics and new particles.

3 Previous reviews and international context

Current PA projects typically require total investments >£10M and international cooperation. The field is growing world-wide and several roadmaps relevant to PA have been developed in recent years. The strategy for PA in Europe is defined by the ASPERA roadmap, first released in 2007 and updated in 2011, with the next update to be released by ApPEC in 2016. The “Magnificent Seven” projects highlighted by ASPERA are the CTA γ-ray observatory, the Einstein Telescope gravitational wave detector, the KM3Net high-energy neutrino telescope, a tonne-scale direct dark matter detector, a megatonne-scale multi-purpose detector (for proton decay, neutrino properties and supernova neutrino detection), a tonne-scale neutrino-mass detector, and the Auger North cosmic ray detector. CTA and KM3Net are on the ESFRI 2016 roadmap, and all are also highlighted in a 2011 report from the Astroparticle Physics International Forum of OECD. UK groups have leading roles in several of these projects, as described in Section 4 below. A working group on physics beyond colliders has been established at CERN to provide input to the European Strategy on Particle Physics for 2018. The emphasis is on experiments which exploit the unique infrastructure available at CERN, with multiple initiatives of relevance to particle astrophysics and dark matter searches in particular.

The ASTRONET roadmap, published in 2008 and updated in 2014, describes the vision for European astronomy over the next 10-20 years. The PA projects CTA and KM3Net are included as the 4th and 5th highest priority ground-based projects for European astronomy, respectively, behind the E-ELT, SKA and the European Solar Telescope. In space, the top-ranked ASTRONET priorities were the IXO X-ray observatory and the LISA gravitational wave telescope (prior to the de-scoping of these missions to Athena and eLISA/NGO, respectively). Subsequently Athena was selected as the ESA L2 mission (launch 2028) and the gravitational-wave universe was selected as the L3 theme (launch 2034). In the US, the comprehensive Astronomy and Astrophysics Decadal Survey (Astro2010) contains LISA at 3rd priority in space and CTA as the 4th ground-based priority.

The 2014 Report of the Particle Physics Project Prioritization Panel (P5) presents a strategy in the US for the next decade and beyond for investments by the Department of Energy’s Office of Science and the National Science Foundation Directorate for Mathematical and Physical Sciences. The report strongly recommended an immediate start and increase in budget for the second generation (‘G2’) dark matter experiments at the tonne scale (Recommendation 19), and subsequently the LZ, Super-CDMS and ADMX-Gen2 experiments were selected for construction. The report also recommended support one or more third-generation (‘G3’) direct detection experiments, guided by the results of the preceding searches, within a globally complementary program and with increased international partnership (Recommendation 20).

The previous PAAP strategy documents in 2009 and 2012 recommended strong UK involvement in γ-ray astronomy, direct-DM detection and GWs, highlighting the need to broaden the UK PA programme. These recommendations were echoed by the IOP review of UK particle astrophysics in 2015, which included a comprehensive survey of the community. The IOP review concluded that UK particle astrophysics is world-class, making major contributions to science, with a high output quality publications, and strong examples of industrial engagement and knowledge transfer. However, the review also noted that the level and breadth of financial support for the community is critically low, and stressed the importance of investment in CTA and dark matter, noting that this *"should not be at the expense of funding for gravitational wave research"*.

4 Current and Future Programme

Below we list the projects and activities that have UK scientific involvement at a significant level.

4.1 Theory

The UK has a large and internationally prominent community working on theoretical particle astrophysics. Particular strengths include general relativity and gravitational wave modelling, dark matter, cosmic ray propagation and acceleration, particle cosmology and neutrinos. These activities support the PA experimental effort and exploit experimental results in order to gain a deeper understanding of particle properties and their impact on the evolution of the Universe and of astrophysical objects, and on the physical processes at work.

The UK has a long history of leadership in general relativity. Current gravitational-wave theory efforts include both numerical and analytic modelling of GW sources to assess detectability, inform signal analysis strategies and develop the waveform templates that are critical to the success of current and future GW detectors; these were demonstrated by the recent detections of binary black hole mergers by LIGO. Dark matter phenomenologists in the UK work on topics ranging from dark matter candidates in extensions of the standard model to the dark matter distribution in the Milky Way and beyond. Strengths of the particle cosmology community include dark energy and modified gravity, inflation and topological defects. Several key advances in the theory of particle acceleration at astrophysical shocks have been made in the UK, and a broad community remain active in high energy astrophysics theory, including cosmic ray production and propagation. Finally, the UK hosts a strong theoretical neutrino physics community, studying the phenomenology of neutrino properties, the origin of neutrino mass and mixing and the impact of relic neutrinos on the evolution of the Universe (e.g. on Big Bang nucleosynthesis, CMB and large scale structure formation).

Much PDRA funding, particularly for particle cosmology, comes from the particle physics theory grant line, which currently supports approximately 3.5 RAs in this area. For comparison, the number of PDRAs per funded member of academic staff (i.e. those receiving some portion of FEC) is 0.17 in particle physics theory, 0.69 in particle physics experiment, and 0.53 in the astronomy grants panel in 2013. This lack of funding for basic research is starving the area of its next generation and presents a genuine risk for the future.

Recommendation: It is essential that the UK strongly supports our excellent theoretical PA community.

Impact of non-participation: long-term decline in the scientific impact of all UK PA activity, as well as loss of leadership in the theory area.

4.2 Gravitational-Wave Astronomy

The first direct detection of gravitational waves announced in 2016 by the LIGO and Virgo Collaborations was a watershed moment in the field. UK scientists made critical contributions to this discovery across a number of areas. These include the design and construction of the complex mirror suspensions that enabled the LIGO detectors to reach their target sensitivity, the development of data analysis techniques for extracting the binary black hole signals from the data, and the creation and implementation of the waveform models used to interpret the detected signals and extract their astrophysical properties. UK scientists also play leading roles in the development of future GW detectors on Earth and in space: upgrading the advanced LIGO and Virgo systems; contributing to the Japanese KAGRA instrument design; contributing to the design and building of third-generation detectors such as the EinsteinTelescope in Europe and the conceptual design of its partner instrument "Cosmic Explorer" in the USA; and contributing to the space-based GW detector eLISA. UK groups have also been major contributors of hardware to Advanced LIGO and to the LISA Pathfinder mission.

4.2.1 Advanced LIGO

Status: In commissioning/operation. STFC supported.

Advanced LIGO is a $175M NSF project consisting of three 4 km laser interferometric GW detectors. Two of these detectors are operational and are located in the United States. Their first science data taking, from Sept 2015 to Jan 2016, yielded the first direct observation of gravitational waves: two unambiguous GW signals were detected from the mergers of black-hole binaries. Extrapolation to design sensitivity (c.2019) indicates that black hole mergers may be detected as frequently as several times per week. The detectors will also be sensitive to the merger of neutron star binaries to a typical distance of ∼200 Mpc, with a best-estimate rate of ∼40 events per year. Other possible sources include pulsars, supernovae, GRBs, cosmic strings, and a stochastic GW background.

Following the announcement of the first detection, the NSF and the Indian government signed an MoU for the transfer of the third LIGO instrument to a new observatory in India, adding a new long baseline to the network in the early 2020s. UK gravitational wave scientists are already developing links between UK and Indian institutes, and the development of stronger linkages over the next 5 years is essential to deliver, install, and commission the hardware for the LIGO-India detector.

The advanced Virgo detector in Italy is close to operation and is expected to join LIGO in observations in spring 2017, while the KAGRA detector is under construction in Japan and is expected to join the network around 2020. In addition, planning has begun for a series of upgrades to the baseline Advanced LIGO design. The A+ upgrade would increase the distance reach by a factor of 1.7 by the early 2020s. LIGO Voyager is a proposed larger upgrade giving a further factor of 2 increase in distance reach by the late 2020s. In the US this programme strategy leads to a possible separate third-generation facility, "Cosmic Explorer", for operation in the 2030s.

Approximately 100 UK researchers are involved in Advanced LIGO, at the Universities of Glasgow, Cardiff, Birmingham, Southampton, Sheffield, Strathclyde, Cambridge, Edinburgh, West of Scotland, and King's College London. UK scientists occupy a large fraction of leadership roles in the LIGO

Scientific Collaboration, including co-chairs of 2 of the 4 international GW search groups. UK development of mechanical and optical technology for Advanced LIGO gained the UK partnership in this major project and ensured data access for UK scientists. STFC support also leverages funds from the EU, the European Research Council, the Royal Society, the Royal Society of Edinburgh, the Scottish Funding Council, and The Max Planck Society.

Recommendation: It is essential that the UK supports Advanced LIGO operations/exploitation as the highest priority activity in GWs. R&D towards enhancements to the baseline Advanced LIGO design should also be supported.

Impact of non-participation: loss of high-profile UK leadership and influence in an entirely new observational field, failure to capitalise on significant past investment and UK expertise.

Milestones: Second science operations from 2016. Design sensitivity c.2019. A+ operation c.2022.

4.2.2 Einstein Telescope (ET)

Status: Planned, Conceptual Design Study completed. Not currently supported by STFC.

The Einstein Telescope is a proposed third-generation GW observatory in Europe and is one of ASPERA's "Magnificent Seven" research infrastructures. Conceived of as a set of underground interferometers whose arms form an equilateral triangle, ET will have 10 times the distance reach of Advanced LIGO across a broad frequency band, and be sensitive to GW frequencies as low as $\sim$1 Hz. This will constitute a facility with infrastructure capable of delivering science over several decades. With initial gravitational wave signals having been detected by Advanced LIGO, the anticipated science return from ET has been confirmed as a major step forward in precision gravitational wave astrophysics. The ET design gives an instrument capable of detecting of order 10^5 compact binary coalescences per year: neutron star binaries to z $\sim$ 2-4, stellar mass black hole binaries to z $\sim$ 8-20, and intermediate mass black holes (up to $10^4 M_\odot$) to z $\sim$ 5-15. The wealth of high signal-to-noise observations will permit precision studies of compact objects and tests of extended gravity theories and extra dimensions (such as braneworld scenarios), provide vital clues to how black holes in galactic nuclei formed via observation of their intermediate-mass "seeds", probe core-collapse supernovae, magnetars, and GRBs, and measure the dark energy equation-of-state, dark matter and dark energy density parameters. The UK has a strong presence in ET gained through the recognised strengths of our groups across hardware design and astrophysical capabilities: the 2011 design study included 62 UK authors from 7 institutions (Glasgow, Cardiff, Birmingham, Southampton, Cambridge, Sheffield, and the Royal Observatory); and UK scientists lead 2 of the 4 scientific working groups.

Recommendation: It is essential that the UK should support R&D for future GW detectors, working towards participation in and capital contribution to ET.

Impact of non-participation: long-term loss of UK leadership in a key science area at the birth of a new field, failure to capitalise on significant past and current investment and UK expertise.

Milestones: Construction begins 2023. First science operations c.2030.

4.2.3 GEO600 / GEO-HF

Status: Running. STFC supported.

GEO600/GEO-HF is a 600 m long GW interferometer near Hannover jointly constructed and run by Germany and the UK. GEO has a history of demonstrating innovative technological advances, including monolithic suspensions, dual recycling, electro-static actuators, adaptive thermal compensation, and the use of squeezed states of light to reduce noise in a large interferometer below the standard quantum limit. GEO also acts as an "eye" on the sky while Advanced LIGO and Advanced Virgo are offline for commissioning. Due to this dual functionality, GEO provides a unique place to test new techniques and ideas for future upgrades of LIGO and Virgo, and for ET R&D. Current STFC support funds operations and exploitation.

Recommendation: Support exploitation of GEO at current levels as a research infrastructure for R&D towards enhancements to Advanced LIGO and ET.

Impact of non-participation: loss of a unique research infrastructure and UK expertise.

4.2.4 eLISA/LISA

Status: GW theme selected for ESA L3 mission. LISA Pathfinder operating; UKSA supported.

In 2013 the "gravitational-wave universe" was selected as the science theme for ESA's L3 mission, to launch in 2034. A major part of the preparation for L3 is the LISA Pathfinder technology demonstration mission. LISA Pathfinder launched in Dec 2015, and has shown that the proof-mass technology is not only viable but already reaches the original LISA requirement. Groups at Glasgow, Birmingham, and Imperial College were major contributors of flight hardware for this mission, positioning the UK well for a prominent role in an eventual LISA/eLISA mission and its associated science return. Following the Pathfinder success, in 2016 an ESA advisory team recommended that the approach adopted for L3 should be a laser interferometer mission and called for an advanced schedule that could allow a launch in 2029. The community is currently refocussing on the original proposed LISA observatory, which will consist of three identical spacecraft orbiting the Sun in a triangular configuration to form a high-precision interferometer. The expectation is that the actual L3 mission will comprise the full 3-arm, 6-link system that provides the maximum science return. LISA's science goals include a survey of compact stellar-mass binaries in the Galaxy, tracing the formation and merger history of massive black holes out to $z \sim 20$, acting as an early warning system for black hole mergers occurring at higher frequency in the band of future ground detectors, exploring stellar populations and dynamics in galactic nuclei, testing General Relativity, and probing new physics and cosmology. Birmingham, Cardiff, Cambridge, Edinburgh and Southampton have also contributed to the development of data analysis techniques and the study of potential sources of gravitational waves detectable by LISA.

Recommendation: LISA should be strongly supported by UKSA, with early commitment to subsystem provision and to the associated technology development required.

Milestones: Planned call for mission concepts for L3 in 2016. LISA Pathfinder mission completion expected at the end of May 2017. L3 launch in the range 2029 – 2034.

4.3 γ-ray Astronomy

Astronomy at photon energies above ~100 keV is key to a wide range of scientific investigations, focussing on non-thermal processes. These include 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. Space-based systems have the advantage of continuous operations, while ground-based facilities achieve huge effective area by using the atmosphere as a calorimeter, measuring the Cherenkov light from very high-energy gamma-ray interactions. Currently operational are HAWC, HESS, MAGIC and VERITAS on the ground, and Integral, Agile, Fermi, Swift BAT, Calet and the IPN in orbit. In the next few years, the eagerly awaited Cherenkov Telescope Array will bring unprecedented sensitivity, imaging, band-pass and response capability to the world scientific community. The UK played a founding role in ground-based gamma-ray astronomy, and is now participating in HESS and CTA.

4.3.1 CTA

Status: Pre-Construction Phase starts in 2017. STFC Supported.

The Cherenkov Telescope Array will be the first open observatory in the 30 GeV to 300 TeV bandpass. It will have more than an order of magnitude more sensitivity than any other VHE gamma-ray system, a factor of five better angular resolution, and with sites in the north and south, it will offer full sky coverage. Consisting of 8 large (23m), 40 medium (12m) and 70 small-sized telescopes (4m), it will be sited at on the island of La Palma and at the ESO Paranal grounds in Chile. Listed as an ESFRI (2016) project with a capital value of €400M, and recommended in the 2015 IoP Astroparticle Physics Review; CTA is now reaching the end of its pre-construction phase and in 2017 will begin pre-production and advance deployment; science observations will ramp up from this phase, with the full observatory running in 2023. Over 1500 scientists from 33 countries have contributed to CTA. Construction is the responsibility of the CTA council (members France, Germany, Italy, Japan, Czech Republic, Spain, Switzerland, UK; associate members The Netherlands, South Africa, Sweden; anticipated members Austria, Australia); it will be operated by the CTA Observatory. CTA has passed a number of significant milestones recently, including a very complete TDR, the definition of consortium key science projects, the manufacture of prototype small and medium-size telescopes and ground-breaking for the manufacture of a prototype large size telescope on La Palma, the first air-shower detection with a two-mirror telescope using a UK-designed and built camera, the site decisions, and the decisions on the locations of the CTA HQ in Bologna and the data centre in Berlin. Matching the expected funding profile, the project has adopted a staged implementation plan that allows exciting science capability to be delivered on schedule; initial arrays in the north and south will be large subsets of the final layouts. In the UK, the Universities of Liverpool, Leicester, Durham and Oxford are funded to 2017 by STFC primarily for the development of the novel Si photomultiplier-based camera for the small-sized telescopes. The UK leads the GCT consortium, which plans to provide half of the CTA SSTs; and also provides the GCT camera lead. Ambitions for a significant UK input to CTA data analysis activities, potentially the national science return, are presently underfunded.

Recommendation: UK participation in CTA construction and exploitation are essential given its high scientific return.

Impact of non-participation: Loss of significant on-going leadership in the realisation of a global observatory in a science area initially established by the UK.

Milestones: MOU for construction and operation 2016. Pre-production phase and first science 2018. Full observatory operations 2023.

4.3.2 HESS

Status: Running. Not supported by STFC.

The HESS experiment consists of four 12 m telescopes and one 28 m telescope observing together in Namibia. The project is a 170-scientist collaboration between institutes in Germany, France, the UK, Namibia and eight other countries. The University of Leicester is the only current UK member. First operational in 2003, the world's largest air-shower telescope was added to HESS in 2012, extending its sensitivity to much lower energies. HESS has resulted in 13 publications with more than 200 citations, and was the recipient of the AAS Rossi Prize in 2010. HESS is sensitive to 30 GeV to 100 TeV gamma-rays.

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

4.4 Direct Dark Matter Detection

The UK is a renowned leader in direct dark matter detection, operating experiments over several decades that have advanced about 5 orders of magnitude in sensitivity. The UK pioneered the use of noble liquid time projection chambers with xenon targets, the technology that has dominated the field for several years now. The xenon based LUX experiment has set the world-leading constraints on WIMP-nucleons interactions. The LUX project is not supported by STFC, but groups at Edinburgh, Imperial, and UCL are active members of the collaboration and play significant roles. Groups at RHUL and Sussex are involved in the DEAP-3600 experiment, commissioning a single phase liquid argon detector at SNOLab, Canada. Sheffield are collaborators on the ADMX axion search, working on design and delivery of novel resonators aimed at increasing the search rate of the window of possible axion masses between $1\,\mu$eV and $1\,$meV. ADMX is the only experiment to have achieved sensitivity to QCD axions, and has been funded as one of three Second Generation (G2) dark matter experiments in the U.S. alongside SuperCDMS and LZ.

Following the recommendations of the Dark Matter Sub-Group of Science Board in 2012, the DMUK consortium was formed to consolidate UK effort and select a single future tonne scale experiment with significant UK involvement and leadership. The community selected the LUX-ZEPLIN (LZ) experiment in 2013. LZ brought together the LUX project in the US with the UK-led ZEPLIN programme that completed operations at the Boulby Underground Laboratory in 2012. STFC funds have been awarded in 2015 for a 3-year construction phase of the experiment. The UK also remains active in the development of directional capability through the DRIFT and DMTPC experiments and has begun R&D towards Third Generation (G3) experiments, both relatively low cost activities with broad community support. The DMUK will continue to play an important role in aiding strategic coordination to ensure investment is safeguarded and the UK remains in a good position to react to future requirements informed by experimental findings.

The recent emergence of collider-based generic Dark Matter searches, and the need for interpretation and comparison with the results from direct-detection and astroparticle communities, has led to considerable cross-pollination between the fields. Driven in a large part by UK scientists, direct-detection experiments are updating and improving theoretical models and also the statistical tools and interpretations underpinning results. The outcome has been the development of a mutually beneficial dialogue between groups and significant synergy between these complementary and uniquely sensitive approaches to searching for Dark Matter.

4.4.1 LUX-ZEPLIN (LZ)

Status: Under Construction. STFC supported.

LZ is a ∼\$75M DOE-led project with 190 researchers from 32 universities and national laboratories in the US, UK, Portugal, S. Korea, and Russia. LZ will feature a 7 tonne liquid xenon time projection chamber operating at the Sanford Underground Research Facility (SURF), in South Dakota, USA. The primary scientific objective of LZ is to discover and study WIMP dark matter with >GeV masses, achieving a spin-independent cross-section sensitivity below $3\times10^{-48}\,\mathrm{cm}^2$ for intermediate mass WIMPs with 1,000 live days of exposure. The project was approved in the US as part of a joint NSF and DOE selection process as one of three G2 experiments in 2014, and approved for construction both in the US and UK in 2015. Over 40 UK researchers are involved in LZ, bringing together most of the UK experimental community, at Edinburgh, Imperial, Liverpool, Oxford, Sheffield, STFC RAL, STFC Daresbury, and UCL. UK scientists occupy significant leadership roles in the LZ construction project, with co-leadership of 3 of the 11 Work Packages, and major contributions across nearly all areas. The UK holds responsibilities for delivery of the LZ titanium cryostat, a fraction of the phototubes, low-background assays for material selection and background modelling, one of two project Data Centres, internal sensors, and contributions to calibration systems.

Recommendation: It is essential that the UK supports LZ operations/exploitation as the highest priority in Dark Matter.

Impact of non-participation: loss of UK leadership in a key science area, failure to capitalise on significant past investment and UK expertise.

Milestones: Construction 2015-2019, Commissioning 2019-2020, Exploitation 2020+.

4.4.2 Third-Generation R&D

Status: Planned. Partially supported by STFC.

R&D towards appropriate technologies for construction of 'third generation' (G3) experiments is an area where the UK is well placed for immediate impact. The P5 report in the U.S. recommends support for a G3 experiment under all funding scenarios, with choice of technology contingent upon results from the G2 experiments presently under construction. Similarly, ApPEC recommends maintenance of a rich program for dark matter that includes R&D, towards a global strategy for the ultimate noble-liquid detectors by 2019 (Recommendation 5). LZ will probe close to the irreducible neutrino background and in case of a discovery, a liquid-xenon G3 experiment will likely be built somewhere around the world. The U.S. Department of Energy have begun planning for G3 R&D through their Cosmic Frontier programme. Discovery of physics beyond the standard model at the TeV scale from the LHC may accelerate the G3 process. Lessons learnt from LUX and designs of LZ, both now concluded, and from DEAP-3600 and XENON1T, both undergoing commissioning, indicate areas of R&D that require further work. These areas include engineering issues related to up-scaling (e.g., electrode grids); identification and mitigation of non-fiducialisable backgrounds; noble liquid technology and characteristics; and optical and electrical properties of materials (e.g., PTFE). Many of these activities would enhance existing G2 experiments too. Previous R&D in the UK was highly successful, and helped to embed the UK within the LZ project with technical development, sensitivity studies, and advancement of the design leading to the conceptual design and accurate cost range. UK expertise in low background techniques and background model development is applicable to any G3 experiment irrespective of the chosen technology. Development of gamma-spectroscopy instrumentation at the new STFC Boulby Underground Laboratory, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) techniques for high throughput assays, and development of enhanced radon emanation measurements will be required for G3. The UK benefits from significant existing infrastructure with these techniques, that collectively deliver internationally unique capability.

Recommendation: We recommend support of R&D to continue to capitalise on successful consolidation of UK expertise and significant previous investment, facilitating UK leadership at G3 at the appropriate timescale.

Impact of non-participation: loss of UK leadership in a key science area, failure to capitalise on significant current and past investment and UK expertise.

Milestones: R&D 2017/18+.

4.4.3 Axion Dark Matter Experiment (ADMX)

Status: Under Construction. Project not currently supported by STFC.

ADMX is a ∼\$5M DOE-led project with 30 researchers from 10 universities and national laboratories in the U.S, and a single UK group at Sheffield. ADMX consists of a 220 litre high Q copper resonant cavity cooled to 100mK and instrumented with quantum limited RF signal amplification, threaded by a static 8T magnetic field. Halo axions are induced to convert to real photons with virtual photons provided by the magnetic field conserving momentum in a Primakov–like process. The photons deposit energy in a suitable cavity mode, which is detected by ultra–low–noise electronics. This generation 2, DOE funded dark matter experiment is now cold and taking first data at unprecedented sensitivity, which is projected to probe an initial axion mass range up to 8 micro-eV in the first year of running.

Recommendation: Axions are well-motivated dark matter candidates, and a balanced UK program should include a component in this area. We support axion research through the PRD line.

4.4.4 Directional detector R&D

Status: Ongoing. Not currently supported by STFC.

Directional detectors can confirm the Galactic origin of any potential dark matter signal, and also probe the WIMP velocity distribution. These searches are coordinated internationally through the CYGNUS consortium, currently with a UK chair, and an agreement to progress to a single larger international directional effort has been achieved. Emulsion technologies and gaseous targets in time projection chambers, as operated by the DMTPC and DRIFT-II projects, are being explored. DMTPC, based in the U.S. has UK leadership through RHUL, and DRIFT-II, operated at Boulby, has had significant UK involvement since inception through Sheffield and Edinburgh. These experiments are presently developing their low-mass sensitivity and performing feasibility assessments for scaling-up target masses.

Recommendation: We recommend consolidation of UK effort with appropriate project management and technical coordination, and that support for R&D continues to be considered via the PRD line.

Milestones: R&D 2016+.

4.5 Neutrino Astronomy

The observation of high energy and ultra-high energy neutrinos provides crucial information on astrophysical sources and the acceleration mechanisms taking place in those sources. High energy neutrinos may also act as a signature of WIMP annihilation in cosmic gravitational traps such as the centre of the Sun and Galaxy. The search for high energy and ultra-high energy neutrinos necessitates detectors with huge effective volumes such that man-made volumes of detection media are not feasible; instead, naturally-occurring bodies of suitable media including water, ice and salt, are instrumented. Phenomena employed and considered include the detection of optical Cherenkov light, radio Cherenkov waves (the "Askaryan effect") and acoustic detection. IceCube has observed the first high-energy astrophysical neutrinos, is now working to determine the sources of these neutrinos. UK involvement in neutrino astronomy is very limited due to the lack of STFC support. Experiments with previous or current UK involvement, but no current STFC support, are ANTARES, ACORNE, ANITA and IceCube.

In its recent review of PA the IOP concluded that the UK could develop a coherent and successful effort in this area, with a recommendation that the UK community of scientists involved in astroparticle neutrino physics should develop a more strategic approach to the topic. We concur with this recommendation.

4.5.1 km^3-scale optical Cherenkov detectors

Status: Operational / under construction / planned. Not currently supported by STFC.

IceCube, a km^3 detector in the South Polar ice announced the first observation of astrophysical high energy (HE) neutrinos in late 2013. IceCube-Gen2 is now being planned to extend IceCube's sensitivity to both high energy (larger coverage) and low energy (denser instrumentation) neutrinos, to improve measurements of both astrophysical (including supernova) and atmospheric neutrinos. The HE extension aims to instrument $10\,\text{km}^3$ of clear glacial ice at the South which will result in sensitivity to new physics such as Lorentz invariance violation or decoherence induced by quantum gravity as well as continuing the study of VHE cosmic neutrinos in a multi-messenger programme, studying correlations of cosmic neutrinos with observations of X-ray, gamma-ray, and potential gravitational wave sources. The low energy (LE) extension, called PINGU, will instrument a large effective volume for detecting GeV-scale neutrinos. Its chief goal is to determine the neutrino mass hierarchy with at least 3σ significance as well as observing tau-neutrino appearance and measuring the neutrino mixing parameters (θ_{23}, δm^2_{31}) with high sensitivity. PINGU can extend the search for solar WIMP dark matter into the region currently favoured by some direct dark matter experiments and will improve sensitivity to galactic supernova neutrino bursts and enable it to extract the neutrino energy spectral shape. Oxford has made significant theoretical contributions to IceCube since 2004. In 2013, Manchester and QMUL joined the IceCube-Gen2 collaboration, with a lack of funding preventing them taking up full membership of IceCube. Current UK activities are focused on oscillation analyses, atmospheric neutrino flux uncertainties and the development of the physics case for PINGU (the UK provides one of the leads of the PINGU analysis working group).

KM3NeT is a HE neutrino distributed research infrastructure under construction in the Mediterranean Sea, and was added to the ESFRI roadmap in 2016. KM3NeT will have separate HE and LE Cherenkov observatories built in parallel in separate locations. The HE neutrino observatory, ARCA, a multiple km^3 PMT array sensitive to TeV to PeV energy neutrinos will be located in Italy and plans to be built in 3 construction phases. ARCA's science programme concentrates on determining the sources of HE astrophysical neutrinos in a multi-messenger approach. The LE counterpart, ORCA, will be built in the French Mediterranean and focusses on determining the neutrino mass hierarchy and CP-violating phase as well as providing sensitivity to low-mass WIMPs caught in gravitational traps in the Sun and Galactic Centre. Current KM3NeT participation in the UK is now limited to Sheffield who have contributed to calibration (having designed the optical beacons for ANTARES) and to WIMP annihilation studies.

Recommendation: The PAAP supports the statements made in the IOP review of Astroparticle Physics that the UK community should seek to support a single project. The PAAP would support such an activity's inclusion in the PAAP roadmap.

4.5.2 Short and long baseline neutrino oscillation experiments

Status: Design and prototype construction underway, STFC supported via PP programme.

Next generation long baseline neutrino oscillation experiments such as DUNE (liquid argon) and HyperK (water Cherenkov) and short baseline experiments such as MicroBooNE (liquid argon) have a primary physics goal of improving our knowledge of the parameters in the PMNS neutrino mixing matrix. However their large target masses coupled with excellent particle identification results in a broad scientific programme which includes a number of particle astrophysics topics including observing neutrinos from magnetars, PWN, GRB and AGN, supernova neutrino bursts, supernova relic neutrinos, solar flares, solar neutrinos, and indirect dark matter detection. All three collaborations have significant UK involvement.

Recommendation: we consider DUNE, HyperK and MicroBooNE to be primarily PP instruments with significant PA capabilities. As such we welcome their inclusion as part of the PPAP roadmap.

4.5.3 Neutrinoless double beta decay experiments

Status: Under construction, STFC supported.

Neutrinoless double beta decay experiments seek to establish the Majorana nature of the neutrino. SNO+ is an underground kilo-tonne scale liquid scintillator detector located in SNOLAB, Canada which will search for neutrinoless double beta decay of $^{130}\mathrm{Te}$, by loading the scintillator with natural tellurium. SuperNEMO is a underground experiment situated in MODANE which will use a tracking and calorimetry technique to search for neutrinoless double beta decays in up to 100 kg of isotopes including $^{82}\mathrm{Se}$. SNO+ also has a programme of other measurements including the study of solar neutrinos and sensitivity to nearby supernovae. Both collaborations have significant UK leadership and involvement.

Recommendation: we consider SNO+ and SuperNEMO to be primarily PP instruments with significant PA capabilities. As such we welcome their inclusion as part of the PPAP roadmap.

4.5.4 ANITA/ARA

Status: Ongoing. Not currently supported by STFC.

ANITA and ARA are two projects with UK interest that will detect radio Askaryan emission and radio geosynchrotron emission to study UHE neutrinos and cosmic rays. The ANITA-III flew in the austral summer 2014/15 and analysis of the data is underway. The ANITA-IV mission was approved by NASA for 2017/18 and promises to result in the most sensitive search for UHE neutrinos above 10^{19} eV. ARA plans to deploy a large number of antennae to detect the faint radio emission from high energy neutrinos interacting in the Antarctic ice cap. To date 3 antennae stations have been deployed at the South Pole and a further 3 constructed. The UCL group has a significant involvement in the data-acquisition and analysis software development efforts in both projects.

Recommendation: Radio-based UHE neutrino detectors, whilst providing important science, should not form part of the prioritised Roadmap for STFC support due to the modest scale of the UK involvement,

4.6 Cosmic Ray Detectors

The UK has a long history of association with cosmic rays, from the pioneering work in air Cherenkov detection in the 1950s to the design and operation of the Haverah Park water Cherenkov experiment in North Yorkshire from 1967 to 1987. More recently, with STFC support, UK scientists were instrumental in the original concept, design, operation and early exploitation of the Pierre Auger Observatory (PAO) a hybrid detector comprising 1600 water Cherenkov tanks and nitrogen fluorescence telescopes. To date, the PAO collaboration have reported on a number of key scientific questions including the steepening of the energy spectrum above 4×10^{19} eV, the origin of the highest energy cosmic rays and their composition, and the interaction cross-section of protons at extremely high energies. UK funded involvement in PAO has now ceased.

LOFAR is a low-frequency radio interferometer with its core in the Netherlands and additional stations in other countries, including a UK station at the Chilbolton Observatory in Hampshire. As part of its broad scientific programme, the core of LOFAR has been used to measure radio emission from UHE cascades initiated by cosmic rays in the Earth's atmosphere, verifying models of the nature of the radio emission and determining properties of the cascades, which provide information about the composition of the original cosmic ray, with precision similar to other techniques. The low-frequency component of the Square Kilometre Array (SKA), a similar instrument which will be constructed in Western Australia but headquartered at Jodrell Bank Observatory, will have a denser, larger core than LOFAR's, allowing it to detect larger numbers of cosmic rays with greater precision, and with the potential to also detect UHE cosmic rays or neutrinos interacting in the lunar regolith. The VHE gamma-ray observatory CTA will characterise the supernova remnants thought to be responsible for cosmic ray production, and will search for 'PeVatrons', the young SNRs expected to be the accelerators of the very highest energy cosmic rays.

Recommendation: At this stage, dedicated cosmic ray detection experiments, whilst very successfully pursued by the UK in the past, should not form part of the prioritised Roadmap for STFC support, due to the modest size of the active community in the UK.

4.7 Complementary non-PA instruments

A wide range of non-PA instrumentation is helpful to address our science questions, with certain instruments particularly worthy of note.

SKA stands out as a critical piece of astronomical instrumentation to fully exploit next generation PA instruments. Currently operating radio detectors with UK involvement such as LOFAR and e-MERLIN (and the European EVN and global VLBI networks of which it is a part) are supported as powerful tools for jet and particle acceleration physics. Radio-based timing of millisecond pulsars will also open the GW spectrum at nanoHertz frequencies via pulsar timing arrays.

The importance of wide-field X-ray and low- to medium-energy γ-ray observations for PA is becoming increasing clear. These instruments will provide alerts for transients to PA instruments and help to identify transients detected with PA instruments. Swift and Fermi (arguably a PA-focussed instrument itself) are most widely considered to be important for PA, with the future Athena and SVOM missions as promising complementary instruments with strong UK involvement. In addition, the XIPE X-ray polarimetry mission is a candidate for the M4 launch in 2025, with some UK participation. A large part of its science case is fundamental physics, including QED in strong magnetic fields and strong-field relativity.

Optical/NIR follow-up of PA-detected transients is also considered to be vital for the community. One particularly important example is following up the EM counterparts of gravitational wave emission from binary neutron star mergers. These are prime candidates for detection by the global network of ground-based interferometers over the next decade - beginning from early 2017 with Advanced LIGO and Advanced Virgo. Given the relatively poor sky localisation (tens to hundreds of square degrees) achievable with the GW interferometers, upcoming facilities such as LSST that are wide, fast and deep may be crucial for detecting the optical/NIR emission from the so- called 'kilonovae' associated with these mergers - particularly as relativistic beaming may prevent observation of the prompt x-ray and gamma-ray emission from the majority of sources. Smaller aperture dedicated facilities such as GOTO and/or other fast-response instruments such as the Liverpool Telescope may also have a crucial role, and redshift measurements for EM counterparts of these, and other, transient events will be vital to their full interpretation. Relevant facilities include ESO and La Palma.

Continued strong UK involvement in a broad programme of collider and non-collider PP is equally important to the health of PA in the UK. The phase spaces explored for new physics are very different for PP and PA instruments and as such a combined PP+PA approach maximises the chances for important new discoveries. The effort to develop generic collider-based Dark Matter searches at a time with new high-energy data from the LHC is perhaps the newest and most rapidly-evolving areas of constructive cross-pollination.

4.8 Computing

Particle Astrophysics research requires large-scale high-performance computing resources due to the very large datasets it produces, and to the multi-scale, multi-dimensional and non-linear domains to be explored in building model simulations. High-performance and high-throughput computing are required for both PA theory and data analysis. PA observatories will produce very substantial datasets that require sophisticated and efficient data reduction procedures. The CTA archive growth is expected to be $\sim$25 PB/year; accurate data interpretation requires extensive Monte-Carlo simulations of the gamma-ray particle shower interactions in the atmosphere. The analysis of gravitational wave observations (∼100 TB/year for Advanced LIGO) relies heavily on filtering the data streams against banks of theoretically predicted waveform templates, both for signal detection and source characterisation.

Theoretical PA activities also have intense compute requirements; simulations of highly non-linear systems in GR, multi-scale physics at shocks, and (astro-)particle phenomenology studies are needed. Computational methods play a central role in particle cosmology due to the highly non-linear and out-of-equilibrium effects being studied. The dynamics of inflationary re/pre-heating, cosmic-defect evolution and phase transitions have a direct impact upon observables such as the baryon asymmetry, gravitational waves and non-Gaussianity. Theoretically predicted waveform templates for sources such as compact binary coalescences and collapsars are required for the analysis and interpretation of gravitational wave observations. Accurate quantitative predictions can only be made via large-scale numerical simulations using high-performance computing.

Current computing for PA is split between dedicated facilities, clusters developed for theoretical astrophysics and particle physics computing (GridPP). Facilities such as DiRAC may provide capability for PA theory, but additional resources will be required to perform PA data reduction. The anticipated DiRAC 2.5 would provide a cost-efficient extension of capability for ∼3 years; the much larger DiRAC 3, which depends on central Government capital and Research Council operations costs, would include a data-intensive component optimized for the analysis of the future PB-level datasets, and could provide important capability via a competitive time allocation process.

Large PA projects typically need dedicated computing facilities, or dedicated time on existing facilities. LZ's UK data centre, built on the hardware and software resources of GridPP, has generated and analysed more than 50 TB of simulated background (in 350,000 core hours) to inform the LZ detector design. After commissioning in 2020, the running experiment will similarly rely on UK e-infrastructure to search for and interpret a handful of dark-matter interactions in ∼1 PB of raw event data per year. CTA bulk data processing is anticipated at 4 first-level dedicated centres. To 2021 a data centre with a UK-specific component would require several thousand cores, ∼200 TB of fast storage, a few PB of Direct Attached Storage, and a tens of PB tape facility. Computing needs for GW analysis will increase over the coming years as Advanced LIGO sensitivity improves and other detectors come online. The UK share is equivalent to 5,000 dedicated cores by 2017-18, and 10,000 cores by the early 2020s. Long-term data storage will require approximately 100 TB per year.

Recommendation: The PAAP supports the recommendations of the STFC Computing Strategic Review 2015. We note in particular the importance of general access of the PA community (including the theory community) to required resources, and the need for clear procedures to access those resources. It is also essential that the UK strongly supports the computing resources needed for the exploitation of funded projects.

Impact of non-participation: loss of UK leadership in data analysis and numerical simulations. Failure to properly exploit investments in new PA facilities.

5 Programme Balance

Responses to our consultations have reflected a desire for scientific breadth in the PA programme, with the need to cover all scientifically relevant activities with current or strong potential for UK leadership. Respondents were, however, generally happy with the current balance between different types of activity within the programme. The presence of substantial activity in each of R&D, construction, operations, exploitation and sustained support for theory should be maintained in the future programme. We note in particular the need to exploit projects that the UK has funded.

We stress that it is also important that small experiments which offer genuine discovery potential for minimal investment can continue to be supported at some level even in times of constrained funding. These small experiments not only provide exceptional PhD training and outreach potential, but they also provide a cost effective means of retaining breadth in the UK particle astrophysics program.

The training of a new generation of scientists has emerged as a very relevant aspect for the future of the field. To this aim, maintaining the current or an enhanced level of funding devoted to studentships and fellowships is deemed important by the community. In particular, the extraordinary competitive pressure for research fellowships means that the recent decrease in the number of available fellowships has been strongly felt.

6 Technologies and Infrastructure

Responses to the 2012 community consultation question "What are the technology needs for each key priority?" featured a number of areas where it was felt that technological advances are necessary in order for the field of particle astrophysics to proceed in the next decade. It is clear that, as projects become larger, there are certain cost-drivers that ultimately dictate the overall cost envelope of a project, e.g. price per channel of sensor, price per channel of readout electronics, etc. Whilst many of the technologies highlighted in the responses were specific to a particular area, e.g. gravitational waves, γ-ray telescopes, etc., there were some which were common across the field. In addition to computing (discussed in Section 4.8), here are two examples that cross the boundaries between disciplines:

- **Fast electronics** (∼nanosecond timescale) was one such area, with a low cost per channel being a common requirement, as well as high speed and low noise. Some responses commented on specific technologies here, including FPGA and ASIC and high-density PCBs which led the panel to consider whether there is a need for a central UK design and fabrication facility serving all of the STFC communities (PP, PA and AP). However, currently work in this area is largely in the form of university/industry partnerships, with design work led by skilled engineering staff in universities. The viability of this model in the long-term, and the impact of university-based PA development, depends on retention of key engineering positions.
- **Photosensors** featured in many responses. Here the wish-list is long and includes low background, fast sampling rate, sensitivity to low light levels, high bandwidth and, particularly in the case of lower-gain devices such as SiPMTs, low-cost per unit channel pre-amplifiers to sit downstream of the sensors. UK industry is competitive in parts of the photosensor market and university/industrial partnerships for photosensor development are being explored.

More application-specific responses focussed on the need for improved mirror coatings and, in particular, mirror suspensions, in the gravitational wave community. Similarly, the use of improved photosensors in low-cost, high-speed, large-area photon cameras was flagged by the high energy γ-ray community. Finally, the dark matter community outlined the challenges in development of large-scale low radiation level detectors, either single liquid or dual-phase noble targets, with key technological needs including improved cryogenics, calibration, purification, and low-background assay and characterisations.

Development of infrastructure towards world-class low-background facilities has begun at the STFC Boulby Underground Laboratory and at UK institutes. Investment in Boulby over the last 2 years includes a £1.7 M grant to build a new underground inter-disciplinary facility, allowing Boulby to continue to be an asset to UK science and particle astrophysics in particular. The facility will be completed in 2016 and already includes a dedicated low-background counting area to house gamma spectroscopy instrumentation managed through the DMUK for G2 construction as well as supporting other rare-event searches, particularly neutrino and neutrinoless double beta decay experiments. Further development in the gamma screening capability at Boulby to parts-per-trillion U/Th sensitivity will establish readiness and facilitate leadership for G3 dark matter and next generation neutrinoless double beta decay instruments. Boulby is also well placed for radon plate-out, surface contamination and particulate control studies that present non-fiducialisable backgrounds of increasing importance as radiogenic contributions from fixed contaminants are mitigated through material assays. The value of these capabilities extends well beyond pure PA applications; efforts by STFC and other Research Councils to capitalise further on this unique laboratory are encouraged.

7 Impact

7.1 Knowledge Exchange and Economic Impact

Particle astrophysics combines academic questions in fundamental physics, astrophysics, and cosmology with practical research in data analysis, engineering, and materials science. This has led to a diverse and extensive range of knowledge exchange projects which have benefited UK industry and academia. Recent examples include:

- Methods developed for modelling muon transport through rock to evaluate cosmogenic background in dark matter and neutrino experiments by Sheffield are now successfully applied in muon tomography and muon radiography work, such as modelling sensitivity of monitoring carbon storage with muons and detecting illicit nuclear materials using cosmic rays. Sheffield are working with Premier Oil PLC on carbon storage monitoring. With funding in part by STFC via the Futures Challenges Concept scheme and a PhD studentship, Sheffield are evaluating a small prototype borehole detector at Boulby within a specially drilled test mock borehole. This work was supported by the Department of Energy & Climate Change.

- The discovery of "nanokicking", a nanoscale technique for mechanically controlling stem cell differentiation, has arisen directly from experimental techniques developed within the gravitational wave community. Stem cell bioreactors, co-developed and patented by UWS/Glasgow, have uniquely demonstrated the ability to generate bone cells, in 3D culture, without the requirement for growth factors or complex engineering solutions. This research paves the way for improved techniques both within cell engineering and various aspects of regenerative medicine (e.g. bone graft repair), in addition to providing a therapeutic testbed for the study of osteoporosis and severe spinal injuries (e.g. through established links with the Queen Elizabeth National Spinal Injuries Unit, Glasgow). Spin-out opportunities are currently being pursued through an RSE Enterprise Fellowship (STFC/BBSRC).

- The development of the ultra-low-noise suspensions used in Advanced LIGO has led to the development of novel low-frequency MEMS-based devices suitable for borehole gravity surveying and environmental monitoring. These MEMS devices, with a mass less than 100 g and size $<3\,\mathrm{cm}^3$, have already been shown to have a sensitivity at a similar level to much more bulky (>100 kg) and expensive absolute gravimeters.

- Collaborative development of CTA mirror technology is on-going with Glyndwr Innovations in St Asaph and Thin Film Metals in Basingstoke (supported by a mini-IPS). Also under development (with the Engineering department at Oxford) is a neural net gamma/hadron separator with a long-term goal of making a very fast hardware image classifier for problems that need fairly simple decisions done at high speed.

- The design and construction of new ultra-low background castles for the Boulby gamma spectroscopy detectors is being carried out with Lead Shield Engineering Ltd. Knowledge exchange and industrial partnership has lead to these designs now produced as standard for Lead Shield customers, including AWE.

- Research in gravitational wave data analysis has been utilised to improve the quality assurance procedures for the Optos production of ultra-widefield retinal imaging devices. A ‘generic’ image quality test was developed and applied, as well as algorithms to identify specific image artefacts resulting from production issues. The project is in its final phase and initial testing has shown that the implementation of our algorithms will improve quality assurance of Optos products.

- Oscillation tracking methods developed for gravitational wave data analysis have found potential industrial applications, leading to a patent application from the University of Sheffield. One initial target application is control of electric motors, where the work leads to a completely new control scheme for permanent magnet motors with demonstrablybetter performance than existing vector control, especially at low rotation rates, due to the noise removing characteristics of the novel algorithm. Additional applications being explored include mobile communications and microwave test and measurement.

- Scientists at Leicester have worked with EASL to developed an improved assembly process for printed circuit boards for the CTA CHEC-S (small-scale telescope cameras). This includes designing a new jig to support the large, delicate boards during soldering, and a technique to remove flux solder pastes which are normally left on the circuit boards.

- RAL expertise in designing cryostats for noble liquid detectors can be extended to other particle physics activities within the STFC remit, notably neutrino LAr TPCs. In particular, the LZ pressure vessel is being designed to ASME Section 8 code to operate in the US, and this required TD staff to become familiar with this code as well as with the corresponding British Standard. This involves cryogenic pressure vessel testing and certification, as well as seismic analysis, which apply to many such projects. In addition, advanced welding techniques must be pursued to preserve low radioactivity, along with the development of an approved system of welding. New links with UK industry have been forged and others strengthened in this area (TWI, Titanium Techniques, Portobello, various metal suppliers).

PA provides unique training opportunities which are well-suited to the needs of UK industry. End-to-end experience from hardware development to modelling and interpretation work is possible in the framework of a UK PA PhD and serves as excellent preparation for work in technology-based SMEs.

The combination of detailed numerical calculations and analytic work is also a common feature of PA PhD and PDRA work, and the addition of strong communication and presentation skills makes these individuals attractive to commerce and industry. Former PDRAs and PhD students are employed in a wide range of positions including finance, consultancy, industrial R&D, software engineering and teaching. Creative university-based engineers trained on PA projects, who later go into industry, also have significant impact.

7.2 Outreach

Particle astrophysics encompasses a range of topics which interest and excite the public – including gravitational waves, black holes, dark energy, dark matter and neutrinos – and researchers are involved in a wide variety of highly successful outreach activities, engaging via newspapers, television, radio, social media, science festivals and exhibitions.

An outstanding example is the announcement in Feb 2016 of the first direct detection of GWs by LIGO, which was reported on 961 newspaper front pages around the world. UK-based LIGO scientists were interviewed or featured in all major national UK newspapers as well as on BBC television and radio, Sky News, Time magazine, CNN, and national radio stations in the US, Russia, China and Australia – with several early career researchers based in the UK also gaining national awards and huge media coverage in their home countries. The global LIGO social media campaign, which was coordinated by UK scientists, garnered more than 70 million aggregate impressions on twitter and the @LIGO twitter feed had increased its followers approximately tenfold within 72 hours of the announcement. The University of Glasgow's detection video received over 2 million views and their communications team won two national media awards for their coverage of the detection announcement.

UK scientists also coordinated the LIGO exhibition at the 2016 USA Science and Engineering Festival, attended by more than 200,000 people, and gave the keynote address at the accompanying X-STEM conference, attended by 8000 high school students. The LIGO discovery and the UK leadership role within it also feature in a special Science Cafë at the 2016 Royal Society Summer Exhibition, the Hay Festival, the Edinburgh Book Festival, TEDx CERN, the Cheltenham Science Festival and the Jodrell Bank Blue Dot Festival. Further, the 2016 BBC Proms included in a special performance of "Gravitational Waves" – a piece by Iris ter Schiphorst – accompanied by a special invited pre-Proms talk commissioned by the National Youth Orchestra of Great Britain.

The CTA explanation room at the BBC StarGazing Live event in 2014 was visited by 4,000 people, and a CTA fold-out leaflet was produced in large quantities and multiple languages. With its interesting location and diverse science programme Boulby is a great resource for eduction and outreach. Ongoing outreach activities include public talks, representation at science fairs, enabling live-links to underground for public Q&A and occasional underground visits. Boulby has a strong social media presence and the facility and its science has also been the focus of many local and national media pieces including (recently) BBC One show, Country File, and BBC Radio 4 Today Programme. Other outreach examples include: the Cosmic 100 exhibit at the Royal Society Summer Science Exhibition 2012, which attracted 11,000 visitors; and Space Time Quest, a gravitational-wave computer game, which has been downloaded more than 10,000 times and is available in English, Spanish, Dutch and Chinese.

8 Proposed Roadmap

Particle astrophysics has seen significant advances since the previous version of this roadmap. These include the first observation of gravitational waves from binary black hole mergers, by Advanced LIGO, with its subsequent opening of a new field of astrophysics, and the first observation of PeV-energy neutrinos, by IceCube. Construction has begun on the second generation dark matter detector LUX-ZEPLIN and the high-energy neutrino experiment KM3NeT, and CTA has entered the pre-construction phase. The coming years will see exciting science from these projects, including the observation of tens to hundreds of binary black hole mergers, the potential direct detection of WIMPs, and the expected discovery of a thousand or more new high-energy gamma-ray sources.

The UK has particularly large and influential communities in three particle astrophysics areas: **gravitational wave astronomy**, **γ-ray astronomy**, and **direct dark matter detection** (as already identified in the 2009 and 2012 PAAP reports). Maintaining this breadth in the experimental programme is vital for the long-term health of particle astrophysics in the UK. Moreover, continued investment in these areas will position the UK to play leading roles in the exciting science to come over the next decade. Figure 1 shows the expected evolution of projects with significant UK involvement.

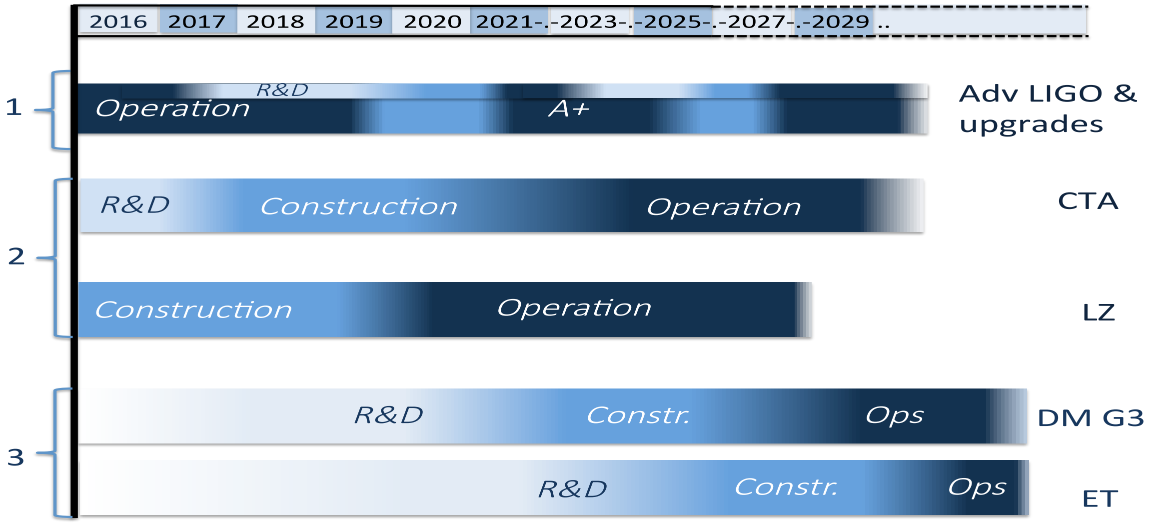


Figure 1: Anticipated roadmap for UK particle astrophysics, showing the global R&D, construction/installation, and operations phases of each project. Numbers on the left indicate the prioritisation bands.

With these considerations in mind, we propose the following prioritisation for UK particle astrophysics. Projects within a given band are considered as equal priority:

1. **Advanced LIGO:** exploitation to profit from major UK investment and leadership in this new field of astronomy, and development and implementation of initial upgrades to the system

2. **LUX-ZEPLIN:** exploitation, building on current investment and substantial UK expertise and leadership

CTA: construction and exploitation, building on current investment and substantial UK expertise and leadership

3. **Einstein Telescope:** support of R&D for future GW detectors, to facilitate future UK participation in ET
G3 Dark Matter: support of R&D to facilitate UK participation in a future G3 experiment.

This prioritisation combines guaranteed science over both the short and long term (e.g. GWs and γ rays) with high-risk/high-reward science (e.g. WIMPs). It also strikes a balance between basic R&D, experiment construction and exploitation. We stress that it is essential to fully support the exploitation phase of projects that have been funded by the UK in order to maximise the return on investment. It is also vital to maintain the health of other activities and infrastructure that support these large projects, including the theoretical work and data analysis and computing infrastructure that underpin all particle astrophysics experiments.

Full support of the recommended activities will require expansion in the currently foreseen level of funding over the next few years. **We strongly recommend increasing the funding across particle astrophysics.** Specifically, we recommend: **increasing the funding for gravitational wave research, based both on its proven track record of delivery and future potential; fully supporting the exploitation of LZ; and funding the CTA construction phase at a significant level**. We note also that the envisioned spend for CTA construction will begin in 2018, as UK spending for LZ construction draws to a close. As a consequence, the LZ and CTA construction phases are not tensioned against one another from a funding standpoint (as might have been inferred from Figure 1). However, to seize the exciting opportunities present in GWs and DM and to maintain ongoing leadership these areas will require investment in R&D for next generation instruments on the same timescale. **A moderate expansion of the current budget envelope would ensure strong UK positions in all three areas (GWs, DM, and γ-ray astronomy) into the next decade, and a healthy and balanced PA programme.**

There is also potential for significant UK impact in high-energy neutrino astronomy. The PAAP supports the statements made in the IOP review of Astroparticle Physics that the UK community should seek to coalesce around a single project, and we would support such an project's inclusion in a future PAAP roadmap. We note for comparison the success of the UK DM community since 2012, and the leading roles it plays in LUX-ZEPLIN.

For space-based instrumentation we highlight the importance of eLISA/LISA, and a future wide field X-ray/soft γ-ray telescope to the particle astrophysics community. We welcome the ongoing UKSA community consultation on LISA; we recommend that LISA be strongly supported by UKSA, and note the need to avoid tensioning UK involvement in space-based GWs against support for ground-based GW science.

There are a number of excellent projects with significant UK involvement that are not included in this prioritised roadmap. The PAAP continues to recommend that funding be permitted to be allocated to generic R&D for future projects as a vital component of a balanced programme in particle astrophysics. Finally, we reiterate the importance of supporting small experiments that offer genuine discovery potential for minimal investment. Such experiments help to retain breadth in the UK particle astrophysics program and also offer exceptional PhD training.