Science and Technology Facilities Council

PARTICLE ASTROPHYSICS PROGRAMME EVALUATION REPORT

JUNE 2019

1. Executive Summary

1.1. Particle astrophysics lies at the fast-moving boundary between particle physics and astronomy, and addresses STFC Science Challenges concerning the nature and evolution of the Universe, the nature of dark matter and the nature of space-time. The science is Nobel prize winning, high profile and exciting.

1.2. The STFC funded Particle Astrophysics (PA) Programme funds projects in three key research areas; gravitational waves, very high energy gamma rays and dark matter. For the most part exploitation is funded by the particle physics and astronomy grant panels, reflecting the strong scientific and technological synergies within the frontier science programme and providing opportunities to support particle astrophysics theory and (limited) neutrino astrophysics research in addition. In this context, the particle astrophysics field is much broader, and consistent with the Particle Astrophysics Advisory Panel (PAAP) roadmap report.

1.3. This review has evaluated the STFC funded PA Programme under three financial scenarios (flat cash, and $\pm$10%). The review includes a consideration of the breadth and balance of the programme, its sustainability, and how that sustainability could be increased by evolving future funding mechanisms.

1.4. We find that although the level of STFC funding is small compared to other areas, research activity is world class and future opportunities are ripe for exploitation. The UK played a leading role in the first detection of gravitational waves and is well positioned to maintain this position with the recently funded A+ upgrade of the aLIGO detectors in the US. The dark matter community has focussed to develop leadership in liquid noble gas experiments, and has the potential to develop world-leading facilities at Boulby laboratory. The technical expertise of the UK CTA community is already sought for the next generation high energy gamma ray facility SGSO.

1.5. Moreover, the strong synergies particle astrophysics has with the rest of the frontier science programme increases science output and science reach. Gravitational wave facilities, neutrino astrophysics experiments and CTA provide crucial inputs to multi-messenger astronomy, for instance, and dark matter and collider experiments combine information to obtain the most stringent limits on this elusive form of matter.

1.6. However, the panel notes that the current position is unsustainable. Flat cash has eroded breadth across the area to the extent that it is no longer possible to reduce support, retain leadership and remain viable. The first Balance of Programme exercise (BoP1) recommended that support for gravitational waves be increased to at least flat cash; this has been achieved by a UKRI uplift only guaranteed until 2020. We note and welcome the success of STFC in funding the A+ upgrade through the UK Research and Innovation (UKRI) Fund for International Collaboration; such an investment, which ensures the medium-term future health of this area, is no longer possible within the core budget.

1.7. The panel finds that in any financial scenario offering less than flat cash and assuming a baselined continuation of the uplift, UK leadership and at least one scientific area will be damaged or lost. In the -10% scenario, without continuation of the uplift, the damage is most severe. In this scenario UK leadership and capability in both high energy gamma ray and dark matter research would be extensively damaged and it is very likely that a complete research area would be lost from the programme, with consequent reputational damage to the UK.

1.8. A 10% increase, assuming a baselined continuation of the uplift, is the minimum amount required to maintain UK visibility and leadership in current projects. Consequently, more than a 10% uplift is required to build breadth back into the programme and to capitalise on the exciting opportunities open to the UK.

1.9. The panel warns that a programme consisting of one project in each science area presents risk for particle astrophysics sustainability and limits ability to tension new opportunities in constrained financial scenarios. This is a particular danger for gravitational wave and direct dark matter detectors. We recommend a review of dark matter to establish a strategy for longer term investment that takes into account future opportunities and maintains UK position. We further recommend that STFC consider how best to support future opportunities in gravitational waves and that funding arrangements between PA and AGP be clarified. More generally, we suggest that a mechanism be developed to tension future development opportunities across the entire frontier science programme, and allow particle astrophysics opportunities to compete with those in other areas, specifically particle physics and astronomy.

1.10. The panel has considered the benefits and disadvantages of reassigning programme areas (development and exploitation) from elsewhere in frontier science to the PA Programme, and of reassigning PA elements to other frontier science areas, to increase the sustainability of the area. We suggest that cosmic microwave background development be added to the PA Programme, based on the complementarity of its science goals with the rest of PA. We recommend that PA exploitation continue through existing grant programmes, and relevant community expertise be included on peer review panels assessing PA proposals to ensure fair treatment of programme priorities.

1.11. The panel concludes that it is essential that PA retain a distinct identity within STFC and it should be maintained as a separate programme area. Finally, we urge STFC to fully support PA exploitation, and uplift the development programme funding by at least 10% to ensure the future health of this vibrant area.

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2. Introduction

2.1. Particle Astrophysics (PA) is the evolving field of research that lies at the point where astronomy, particle physics and cosmology meet. It uses new infrastructures and methods to detect a wide range of cosmic particles including cosmic rays, dark matter, gamma rays, gravitational waves and neutrinos.

2.2. Whilst the STFC funded PA Programme is relatively small, representing 3% of the total frontier science spend in STFC, the PA community is relatively large by comparison and has brought significant success to the UK, as the recent detection of gravitational waves has demonstrated. As with the other frontier science areas, the development, construction and science exploitation of PA instruments leads to ambitious international projects that require advanced technologies, help to train highly-skilled personnel, and facilitate knowledge exchange with industry.

2.3. The purpose of the PA Programme Evaluation (PAPE) was to look at the research portfolio and science strategy to define a balanced programme of excellent science within a realistic financial planning envelope. A specialist panel was convened to consider the quality, effectiveness and impact of the PA Programme. The role of the panel was to look at the current research programme and future opportunities and to make recommendations on how best to achieve an affordable and balanced programme in the future. Programme balance took account of health and breadth, return on past investments and the ability to exploit UK leadership and capability in strategically important areas and engage in future projects. The programme areas are assessed in sections 6-16.

2.4. The PAPE examined the likely impact on the PA Programme of a number of funding scenarios between + 10% / -10%, and considered the future scope and funding structure of the programme. The panel findings are presented in sections 17-21 and 23-34.

2.5. The PAPE also looked at the scope of the programme following feedback from the 2016 Balance of Programmes 1 review (BoP1), which noted that the PA had evolved since the 2013 Programmatic Review. Following the gravitational wave detections, there is an emerging field of gravitational wave astronomy and it is anticipated that groups supported through both the PA Programme and astronomy programme consolidated grants will seek support to exploit this new field of research. The UK has also developed and strengthened leadership within the dark matter and gamma ray astronomy programmes. The BoP1 therefore made the following recommendation:

> "*Recommendation 15: We recommend that STFC review the Particle Astrophysics funding structure and scope with the goal of a smooth transition to a solution that is sustainable in the longer term as the gravitational-wave field – as well as others in the Particle Astrophysics area – grow. This needs to be addressed if the UK is to maintain a competitive world-leading strategy in all the Particle Astrophysics areas in which significant investment has already been made.*

2.6. The panel addressed the recommendation in this review, in section 23.

BACKGROUND

3. Defining the Particle Astrophysics Programme

3.1. PA is a globally recognised and rapidly developing science area e.g. as defined by the APPEC European Astroparticle Physics Strategy (2017-26) and has significant scientific and technical synergies with particle physics and astronomy.

3.2. STFC funding for its PA Programme currently focuses on three science areas: the development and exploitation of ground-based gravitational wave detectors (Advanced LIGO and the A+ upgrade), the development of high energy gamma ray telescopes (the Cherenkov Telescope Array (CTA)), and the development of direct dark matter detectors (LUX-ZEPLIN (LZ)). These areas are identified as high priority by the Particle Astrophysics Advisory Panel (PAAP) Roadmap[1] and of strategic UK priority by the BoP1. Internationally, all three areas are highlighted in the (unprioritised) APPEC roadmap.

3.3. Funding for the PA Programme currently supports:

- **Ground-based gravitational waves programme –** consortium grant support for commissioning, characterisation and operation of the Advanced LIGO detectors and their upgrades, developing technologies and advanced interferometry techniques for upgrades and towards future generations of detector, and performing searches, modelling and simulation studies. This builds on previous STFC investment in Advanced LIGO, which led to the first detection of gravitational waves in 2015.
- **Advanced LIGO operations** – on-site support at the LIGO sites, including operation of UK provided hardware; and computational infrastructure and data storage.
- **Development projects:**
  - **LZ:** Construction until September 2019. UK funding was approved in April 2015 with the global project expected to complete by the Early Finish CD-4 date of April 2020.
  - **CTA:** Pre-production until December 2019. The CTA project is in a pre-construction phase (PCP) and international partners are finalising the technical design and the international legal entity to allow construction to begin. Building on a three year R&D phase, STFC is funding UK participation in the pre-construction phase, focusing on developing prototype cameras for the Small Size Telescopes and will decide on future participation in CTA construction and operation during 2019.
- **Other –** ad hoc research grant support and international subscriptions, for example, UK contribution to CTA Observatory GmbH operating costs.

3.4. **Exploitation:** Unlike the particle physics, nuclear physics and astronomy programmes, the PA Programme does not have a consolidated grant to support its exploitation. Exploitation is supported through other programmes as follows:

- Gravitational waves: Exploitation of Advanced LIGO is split between the operations grant and consortium grant in the PA Programme. Gravitational waves exploitation (and R&D) is also supported through the astronomy programme, with new groups now being established.

[1] The PAAP submission to this programme evaluation retained the prioritisation.

- Very High Energy (VHE) gamma ray astronomy: the development programme (CTA) is currently supported through the PA Programme and science exploitation is supported through the astronomy programme.
- Dark matter research: the development programme (LZ) is currently supported through the PA Programme and exploitation of both Xe and Ar experiments are supported through the particle physics programme.
- Support for PA theory is through both particle physics theory and astronomy consolidated grants.

3.5. The PAAP Roadmap identifies the scope of the PA community's research activities. This extends beyond the currently funded PA Programme areas and for this review the panel defined the PA programme consistent with the PAAP roadmap to include the areas of high-energy neutrino astronomy and cosmic ray detectors. The panel considered it important that STFC continue to recognise PA as a separate science area of research for strategic investment both to respond to new developments in this growing field and to engage and collaborate with its international funding partners effectively.

3.6. The panel notes areas of significant overlap, for example Cosmic Microwave Background (CMB) that is part of the astronomy programme, and accelerator based experiments that are part of the particle physics programme, such as the long baseline neutrino experiments DUNE and Hyper-K that have sensitivity to extragalactic supernova neutrinos, and neutrinoless double beta decay (NDBD) experiments like SNO+ and SuperNEMO.

3.7. The STFC's Boulby Underground Laboratory now hosts projects covering a wide range of scientific disciplines. Foremost among these are its world-class facilities for the support of rare event physics searches, such as NDBD or dark matter. Opportunities exist to build further upon this success, for example by establishing a national centre for the development of low background clean technology i.e. TERAS (TEchnologies for RAre event Searches).

3.8. High performance computing (HPC) underpins particle astrophysics theory, gravitational waves and CMB. Gravitational wave collaborators have access to a unique facility (the Raven cluster at Cardiff), while theory and CMB make extensive use of DIRAC in common with particle physics theory. High throughput computing underpins dark matter exploitation and will enable CTA data analysis. LZ computing needs are met by GRIDPP, and it is expected that CTA will align with a similar model.

4. Size of the particle astrophysics community

4.1. PA is an evolving field of research and there are active research groups in over 20 universities and the STFC RAL national laboratory. Support for the PA community comes from different science areas within STFC, and this makes it difficult to precisely gauge the community size and overall funding.

4.2. ResearchFish is intended to provide a way for researchers to log the outputs, outcomes and impacts that have been generated through STFC's research funding. The panel noted differing and inconsistent levels of engagement by PIs and research groups, giving them little confidence in the data generated by this system.

4.3. The following 2018 data indicate the breadth of the research area and list the annual FTEs:

4.4. Within the **STFC-funded PA programme,** the Gravitational Waves consortium requested support for 5.8 academic FTE (2.8 FTE awarded) and 17 PDRA FTE (11.6 awarded) across five institutes; the CTA pre-construction phase project 2.1 FTE (1.1 FTE awarded) and 6.1 FTE PDRA (3 FTE PDRA awarded); and the LZ project 3.9 FTE academic staff (0.2 FTE awarded) and 8 FTE PDRA (3.75 FTE awarded) plus additional support in STFC laboratories.

4.5. In the most recent three year cycle of the **Astronomy Consolidated Grants** Panel (2015 – 2017), 741 academics were requested overall of which 35 FTE were identified by STFC as PA with 24 FTE being awarded. 617 PDRA FTE was requested overall, with 35 PDRA FTE identified as PA and 18 FTE funded.

4.6. In the 2016 **Particle Physics Theory Consolidated Grant** round, seven science areas (of 45) were identified by the panel as PA. 102 academic FTE[2] was requested overall, of which 17 academic FTE considered PA was requested with 3 funded. Overall, 71 PDRA FTE was requested, with 12 PDRA FTE considered PA requested and 6 FTE funded.

4.7. In the 2015 **Particle Physics Experiment Consolidated Grant** round 118 academic FTE was requested overall of which 5 FTE was identified by the panel as PA, and 5 FTE awarded. 153 PDRA FTE was requested overall, of which 8.5 PDRA FTE was considered PA and 6 FTE awarded. It should be noted that the particle physics does not identify dark matter/neutrino astronomy specifically, instead separating non-accelerator and neutrino physics. In a broader definition of PA to include all neutrino and non-accelerator research, 32 academic FTE could be considered PA and 29 FTE awarded, and 37 PDRA FTE requested with 19 FTE awarded.

4.8. The panel considered the gender balance of the area. In June 2018, there were 19 grants on Siebel that were listed as PA. There are 2 female PI positions and 3 female CoI positions. Of these five positions, two are covered by the same female academic. There are 17 male PI positions and 27 male CoI positions. The panel considered the gender balance to be poor at this level.

4.9. **Fellowships**: In 2018 STFC were funding 66 **Ernest Rutherford Fellowships (ERF)**, of which nine fellows are listed as PA and cosmology. Seven of these are for theory, indicating the UK strength in this area. Potential fellows select which panel they wish their application to be considered by and STFC can refer these to another panel if necessary, but this is rare.

4.10. **Studentships**: In June 2018, STFC funded 910 studentships of which the panel thought 26 related to PA and 33 to Particle Theory. Studentship allocations are made to astronomy, particle physics experiment, particle physics theory and nuclear physics. PA is not identified separately, however, departments have the flexibility to allocate the studentships as they wish. Data on the studentship allocation from the university may not be provided or is not always accurate.

4.11. **Computing**: In addition to accessing computing support through GridPP (primarily for dark matter), the PA community also uses HPC machines including DiRAC. In the 2016 call of the DiRAC Resource Allocation Committee there were 20 applications for time on DiRAC; three were for cosmology and all were funded. In the 2017 call 27 applications were funded, eight of which were classed as cosmology and one as PA.

[2] Academic FTE: one academic is a three year position spending 60% of their time on research.

The application process does not allow proposals to be identified with a particular research theme such as PA; instead, applicants are allowed to request whether they wish to be considered by either the Astronomy and Cosmology Panel or the Particle Physics and Nuclear Theory Panel. CTA computing is supported by IRIS with 570 CPUs and 228 TB disk allocated in the 2019 round.

5. Particle Astrophysics Programme funding

5.1. The funding planned for the future STFC-funded programme is outlined below:

PA Programme	18/19	19/20	20/21	21/22	22/23	23/24	24/25	25/26
Ground-based GW – committed Ground-Based GW Consortium (exploitation, R&D)	2.625	2.185	0.800					
Ground-based GW – uncommitted Ground-Based GW Consortium (exploitation, R&D)			1.300	2.200	2.200	2.200	2.200	2.200
PA Development – committed CTA + LZ	0.700	0.700	0.100					
PA Development – uncommitted New Projects	0.175	0.615	1.300	1.300	1.300	1.300	1.300	1.300
Other – committed	0.025							
Other – uncommitted Joint calls (MPI etc.)	0.075	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Total (Capital + Resource)	**3.600**	**3.600**	**3.600**	**3.600**	**3.600**	**3.600**	**3.600**	**3.600**

Table 1: Future funding lines planned for the STFC-funded PA Programme (excluding additional uplift awarded to STFC by UKRI in FY2018/19 and FY 2019/20)

5.2. The 2013 Programmatic Review (PR 2013) reduced support for gravitational waves from 2019/20 to open up a development line for the STFC-funded PA Programme. However, given the scientific developments in this area, the BoP1 recommended (Recommendation 14) that STFC award additional funding to maintain the current gravitational wave consortium grant at flat cash.

5.3. STFC secured additional resource funding from UKRI for its core programme for the remainder of this CSR (FY 2018-19 and 2019-20) to help maintain international commitments and reinstate some R&D and innovation activity. Within the PA Programme this includes up to £0.5M a year to help restore the volume of gravitational waves research.

5.4. No funding is available to support neutrino astronomy and CMB research beyond limited support through the consolidated grant.

5.5. The PA community receives further support through STFC's studentship and fellowship schemes and by non-STFC funds. Within the UK, funders include the Leverhulme and Ogden Trusts, the Royal Society, EPSRC and charities. European funding includes H2020 schemes; training networks, EC funded design studies and ERC grants. Although the total funding is difficult to capture, three known ERC grants, a few Marie Curie fellows and an international training network gave an estimated contribution of

~£900k/year at the time of BoP1[3]. The gravitational wave community estimate leveraged non-STFC support of £8.8M[4] and the dark matter community estimate non-STFC support at the level of £3.5M.

5.6. The **Global Challenges Research Fund (GCRF)** and **Industrial Strategy Challenge Fund (ISCF)** were launched by government in 2015/16 to support cutting edge research in solving societal and industrial challenges in developing countries (GCRF) and in the UK by linking with industry (ISCF). The PA community are active in pursuing these sources of funding and Annex 1 lists currently funded awards and future applications identified by the community pro-forma returns to this exercise.

5.7. The **Newton Fund**, launched in 2014, now has a total UK investment of £735 million, with partner countries providing matching resources within the fund. 25 proposals falling within STFC science remits have been funded. In PA this includes one for multi-wavelength research projects involving CTA and the Square Kilometre Array (SKA) in the southern Africa SKA partner countries, and one for capacity building in India for the siting of the 3rd aLIGO detector in the Hingoli District, Maharashtra.

5.8. Overall, the panel observed that obtaining quantitative data on the size and funding of the PA community was problematic. PA statistics are recorded differently across STFC and few schemes identify PA as a research area, so the panel and STFC used its own knowledge to identify PA research activity. ResearchFish data proved unreliable, mainly because identification of an area as PA relied on individual PI input which was neither consistent nor accurate.

Recommendation 1: STFC should ensure that PA research activity is identified consistently across STFC programme areas and funding mechanisms, to enable accurate data on the scale and impact of PA to be monitored.

SCIENCE PRIORITIES

6. Assessment

6.1. The panel considered each of the science areas identified in the PAAP roadmap as well as CMB research. Each science area is described and evaluated and priorities assigned, but the ordering of the science areas is not significant. The panel considered the key science drivers of each area, the international context, how the science area has evolved since the last review, overlaps and synergies with other frontier science areas, and whether there are particular issues to address or where there are critical decision points.

6.2. The panel invited projects and running experiments to submit proforma to enable the panel to assess their relative research priorities. The assessment criteria was based on that previously used in the PR2013, namely ‘**a**’ rankings for projects and ‘**g**’ rankings for science exploitation experiments. In addition a new ‘**i**’ ranking was introduced to cover evaluation of impact for the economy and society. The ranking definitions are listed in Annex 3 of the Programme Evaluation document. Projects submitted through the 2018 ‘Developing a World Class Research Programme’ (also referred to as ‘priority projects’) exercise, were also noted.

6.3. Projects were initially ranked on the basis of science excellence, taking account of synergies, economic and societal impact and leadership. The panel also assessed the

[3] 2016 Balance of Programmes report, paragraph 127.
[4] Gravitational Wave consortium input to the programme evaluation.

impact of the programme. Ratings were based on the score of the highest quality piece of impact within each area and a broad assessment of the range of impact activity, i.e. volume measures of impact were not considered. The panel regard the impact ratings as indicative of activity rather than an absolute measure, and caution that they be treated accordingly.

7. Gravitational Waves

7.1. Gravitational Waves (GW) research is a rapidly developing branch of observational astronomy based on gravitational, rather than electromagnetic, radiation. The field addresses STFC science drivers “A. How did the Universe begin and how is it evolving?”, by studying gravity and matter in extreme conditions, placing constraints on a potential stochastic background, and providing a non-electromagnetic measurement of the Hubble constant, and “C. What are the basic constituents of matter and how do they interact?” by testing the nature of space-time in extreme astrophysical environments with compact objects, using standard sirens to help infer the nature of dark matter and dark energy, and using neutron star inspirals to study nuclear matter at extreme densities, and the nuclear equation of state.

7.2. Currently, gravitational waves are detected by laser interferometers. Facilities include Advanced LIGO (aLIGO) (Hanford, WA and Livingston, LA in the US), Advanced Virgo (Italy) and GEO-HF (Germany).

7.3. The UK has developed an internationally leading role in the area. The UK designed and supplied key instrumentation, notably the monolithic silica suspension, that allowed aLIGO to achieve the unprecedented levels of low frequency sensitivity necessary to detect gravitational waves: an achievement recognised by the 2017 Nobel Prize in Physics. UK consortium members hold a number of key positions within the international LIGO Scientific Collaboration and lead major aspects of the modelling and data analysis, including the development and leadership of the analysis pipeline that identified the first signals and the waveform models used in their astrophysical interpretation.

7.4. The ground-based gravitational wave activities and aLIGO operations were reviewed by the panel and received the highest rankings; **a5 – mature, i5** for the ground-based GW activities and **g3 – mature, i5** for exploitation via aLIGO operations.

7.5. The field is growing with new groups joining and new faculty positions opening. Currently around 30 faculty and 15 PDRAs work in the area. The panel noted that the expansion of a new field in multi-messenger astronomy, where joint observations of gravitational waves can be made with electromagnetic counterparts, is also likely to attract scientists from other areas of astrophysics in the coming years.

7.6. The aLIGO Upgrade (A+) **(a5 – developing, i4)** represents the medium-term future GW opportunity. This will maximise the discovery potential of the existing facilities by almost doubling their observational range and increasing the rate of observation of the black hole systems and deepening the sensitivity of the detectors. The US NSF requested the UK to be the lead international partner in the $US30 million A+ project on the basis of our scientific and technical leadership. Funding has been secured from the UKRI Fund for International Collaboration for a four-year project beginning early 2019.

7.7. Planning for longer-term opportunities has recently accelerated. Next-generation facilities are planned in Europe (the Einstein Telescope) and the US (‘Cosmic

Explorer'). The UK sits on the steering board of the Einstein Telescope consortium and plays a leading role in its activities. The Einstein Telescope consortium is currently preparing a proposal to the 2020 update of the ESFRI roadmap.

7.8. Although beyond the remit of this report, the UK space-based gravitational wave effort has advanced significantly following the impressive success of the LISA Pathfinder mission which fully demonstrated key technologies for the forthcoming LISA observatory. Phase A studies for LISA are currently progressing well and the UKSA is already investing significant resources in support of their commitment to provide the main optical interferometer flight hardware for LISA. The nominal launch date for LISA remains 2034.

7.9. The Einstein Telescope, "UK AION for the exploration of Ultra-Light Dark Matter and Mid Frequency Gravitational Waves" and "Gravitational-wave optical transient observatory: GOTO" were submitted as projects in the 2018 Developing a World Class Research Base exercise. The panel considered and commented on the submissions.

7.10. The Einstein Telescope (timescale: 2030+) will have 10 times the distance reach of Advanced LIGO across a broad frequency band, and have sensitivity to GW frequencies as low as ~1 Hz. The panel noted that R&D undertaken now will be important to lay the foundation for instruments required in the next 15-20 years. The panel considers the UK to be well positioned to play a leading role, and it is vital that sufficient support is given to maintain and exploit this position. The panel note that investment would increase UK and STFC influence even further at a critical time in the field, when it is rapidly expanding and being highly prioritised in international scientific programmes. This is a maturing project with a detailed design study already undertaken under an FP7 EU programme. Investment (Italy, Netherlands) has already being provided to support site infrastructure studies and prototype facilities.

7.11. UK AION would enable the search for axions, search for new fundamental interactions and provide a small-scale prototype for detecting gravitational waves. The panel noted this uses an alternative technology (atomic interferometry) to space-based laser interferometers, which could probe low frequency GW's in the sub 1Hz band, although a full noise analysis has not been presented to date. AION technology could be strategically important within quantum sensing/quantum technologies, and has strong synergies with dark matter search technologies. The panel noted the technology is at an early stage but prototype systems to verify technology are of high importance.

7.12. GOTO is an astronomy facility providing twenty-four hour GW follow up for transients, enabling multi messenger astronomy and full exploitation of the science potential of the programme. The panel recommend that GOTO is best pursued within astronomy, owing to the importance of the multi messenger area, but note it has strong synergy with GW follow-up.

7.13. In summary, **the panel attributed the success of the GW field to the stable, long-term core funding awarded through the STFC's PA programme**. This has enabled the UK community to develop a critical mass in areas such as data analysis and instrumentation, resulting in international leadership of aLIGO suspensions, flagship data analysis searches and strong involvement with the A+ upgrade and leadership in critical areas of future R&D. The panel ranked the area as the highest priority within the PA programme.

7.14. The panel thought it was essential that the UK supports the ground-based GW programme, for which additional UKRI funds have been secured to the end of FY19/20.

The panel note that the UK has leadership in a rapidly expanding and competitive scientific field. Further investment is essential to maintain this position and contribute fully to next-generation projects.

8. VHE gamma ray

8.1. The field of VHE gamma-ray astronomy has reached maturity with the present generation of ground-based Imaging Air Cherenkov Telescope (IACT) experiments and the imminent construction of the first global open observatory for the science area, CTA. The telescopes detect the Cherenkov radiation emitted by particle air showers that are created when VHE gamma-rays from astrophysical sources enter the Earth's atmosphere. Science drivers include studying the astrophysics of sources (e.g. active galaxies and transients) at lower photon energies, particle acceleration and beyond-standard-model physics such as dark matter at high photon energies and tests of axions and Lorentz invariance violation throughout the photon energy spectrum.

8.2. Current VHE gamma ray facilities include three existing IACT experiments (MAGIC on La Palma, VERITAS in Arizona, and the High Energy Stereoscopic System (H.E.S.S.), in Namibia). H.E.S.S. received the Descartes Prize of the European Commission, the Bruno Rossi Prize of the American Astronomical Society, and has been named one of the 10 most influential observatories world-wide by publications and impact[5]. The UK has a history of leadership in H.E.S.S., enabled by previous PPARC and STFC funding. H.E.S.S. is now outside the PA funded programme, but UK activities continue with support from new institutional funds and the GCRF.

8.3. CTA will have a sensitivity an order of magnitude larger than the present generation of experiments. CTA has recently become an ESFRI Landmark, indicating that start of construction is imminent.

8.4. Besides the science drivers above, CTA will provide optical follow-up for alerts generated by LSST and other astrophysics, GW and neutrino astrophysics facilities. The array's ability to repoint telescopes on approximately a minute's timescale allows follow-up of gamma ray bursts, galactic transients, x-ray, optical and radio transients, black hole or neutron star mergers and blazars. The full potential of CTA's science reach is achieved by exploiting this strong synergy across the astrophysics and particle astrophysics programmes.

8.5. Operationally CTA comprises the CTA Observatory (CTAO), the international body which will operate the observatory sites; and the CTA Consortium (CTAC), the international scientific collaboration which is developing the telescopes and instrumentation and organising the CTA Key Science Projects (KSPs). Initially, CTAO observing time will be devoted to the CTAC Key Science projects. In the long term 10% of CTAO time will be available via ESO. Membership of CTAC is dependent, by MoU, on significant contribution to design & construction of the CTA telescopes and scientific analysis.

8.6. Within the UK 56 researchers (faculty, PDRAs and students, from 12 institutes) are members of the CTAC. PA project funding supports the prototyping and pre-construction of CTA. Four institutes – Durham, Leicester, Liverpool and Oxford – and 6 faculty, 8 PDRAs and 7 students are involved in the pre-construction phase of CTA.

[5] Nature, 2009, doi:10.1038/news.2009.81.

8.7. The UK has significant leadership in CTA construction, concentrated mostly in the development of the small-sized telescope (SST). CTA will deploy seventy SSTs. The UK provided the original optical design for the dual-mirror SST concept, and the front-end electronics readout/digitization/ triggering “TARGET” modules which are currently under consideration as the core technology for the SST camera. The UK provides the Spokesperson and Deputy Instrument Scientist for the Gamma Cherenkov Telescope SST project.

8.8. The panel considered CTA to be of fundamental interest to astrophysics, closely aligned to STFC’s science challenges and an important component of multi-messenger astronomy. CTA will have unique capabilities when the Fermi mission ends; for example, it will be the only gamma-ray experiment with sufficient angular resolution to allow prompt optical follow-up.

8.9. The panel noted the high priority given to CTA in the BoP1 exercise and the PAAP roadmap, and the substantial investment made by the UK to date. The investment guarantees access to CTA data for a much larger body of interested scientists. UK interests in CTA include study of particle acceleration mechanisms, WIMP and axionic dark matter, and evolution of structure in the Universe. The panel recognised that the wider UK community is world-leading in many aspects of the astrophysics to be studied by CTA, such as very-high-energy cosmic rays and multi-wavelength astrophysics of pulsars, supernova remnants and AGN.

8.10. However, the potential of this facility may not be fully appreciated within the astronomy community. The panel believe it is important that astronomy assess their community level of interest in CTA, so that opportunities for growth can be understood and a priority for exploitation funding established within AGP.

Recommendation 2: The astronomy community should assess their level of interest in CTA, so that opportunities for growth can be understood and a priority for exploitation funding established.

8.11. The panel ranked CTA as **a4 – developing, i4.** The panel agreed that the UK’s existing investment should be secured by supporting the construction phase of CTA. A decision on the construction phase needs to be taken by late 2019/early 2020.

8.12. Future opportunities in VHE gamma rays were considered as part of the 2018 Developing a World Class Research Base exercise. The next VHE gamma-ray project is expected to be the Southern Gamma-ray Survey Observatory (SGSO). The panel considered the submission.

8.13. The global VHE community is in the early stages of defining SGSO. The facility, a high-altitude water-Cherenkov observatory aimed at photon energies greater than 10 TeV, will be complementary to CTA. The UK have been invited to collaborate on the basis of their expertise and technical excellence. The panel noted that participation in SGSO would allow further return on investment in CTA technologies for the UK on timescales after CTA construction.

9. Dark matter

9.1. Dark matter research is a core theme of particle astrophysics. Direct searches for dark matter aim to confirm the existence of, and then characterise, the non-baryonic material that dominates the matter content of the Universe. Observation of dark matter would be a scientific breakthrough of great importance, and have huge implications across frontier science from particle physics to astronomy.

9.2. The area has strong synergies with particle physics. Dark matter searches at colliders complement those performed within PA and future experiments may have sensitivity to NDBD as well as dark matter. Dark matter experiments also have sensitivity to galactic supernova and solar neutrinos, allowing some measure of neutrino astrophysics.

9.3. The UK has a particularly strong history and track record in dark matter, leading and contributing to numerous world-leading results and innovations with a range of scintillator, semiconductor and gas based detectors.

9.4. The PA Programme supports one project, LZ (two-phase liquid-xenon, ~50 scientists from nine institutions), which is under construction at the Homestake mine in the US. The LZ science reach is expected to be world-leading, although there is fierce international competition. Exploitation (2020-2025) will be supported by the particle physics consolidated grant **(g3 – developing, i5)**. LZ was also assessed by the Particle Physics evaluation Panel.

9.5. Other dark matter search experiments with UK involvement are: DEAP3600 at SNOLAB (single phase liquid argon, 13+ scientists from RHUL, Sussex, STFC-RAL), DRIFT/CYGNUS at Boulby mine (direction sensitive, nine scientists from Sheffield, STFC-Boulby), DM-TPC (directional) and DM-ICE (eight scientists, Sheffield, STFC-Boulby), SuperCDMS (one scientist, Durham-IPPP). Activities are supported by the particle physics consolidated grant, PRD, EU and US funding.

9.6. The UK LZ community plan to participate in a 3rd Generation liquid xenon experiment. A Statement of Interest for a three year programme to develop the technologies necessary to reduce backgrounds and increase detector scale was submitted to Science Board in 2017, and referred to this evaluation. The panel ranked the proposal (‘G3R&D’) as **a4 – early, i3.** The panel recognise the importance of capitalising on UK expertise and maximising previous LZ investment, and note that UK leadership in the area can only be maintained with an ongoing development programme. G3R&D was also assessed by the Particle Physics evaluation Panel.

9.7. The panel noted that Boulby, the UK’s only deep underground science lab, has already established a strong science programme that includes dark matter. Boulby could be a potential site for a 3rd Generation dark matter experiment, although technical capabilities would need to grow to support such an initiative.

9.8. An alternative technology to liquid xenon uses liquid argon. DarkSide20k, a two-phase liquid argon instrument, has started construction with data-taking foreseen in 2021. The panel invited and evaluated a proforma from the DarkSide collaboration. The panel noted the complementarity in dark matter detection reach with LZ, the synergies in technology with some neutrino physics experiments (e.g. DUNE) and the track record and leadership of UK participants. The science reach is similar to LZ and the panel awarded the same rating for science excellence **(a4 – developing, i3)**. A Statement of Interest for DarkSide was submitted to Science Board in 2018 and referred to the PA and particle physics evaluations for comment. Darkside was also assessed by the Particle Physics evaluation panel.

9.9. The TERAS (TEchnologies for RAre event Searches) project has been formulated, by the liquid argon and xenon dark matter community together with neutrinoless double beta decay, specifically to address the challenges of background reduction, and was submitted to the 2018 Developing a World Class Research Base exercise. The panel considered the submission. The panel recognised that housing such a facility, potentially at Boulby, would provide the UK with the facilities and capability to host 3rd Generation experiments, which would be of great strategic value and increase UK leadership in this area.

9.10. The panel agreed that direct detection of dark matter would be a major scientific breakthrough and that it is important the UK build on and exploit its current position in both technologies. Funding decisions are needed quickly as DarkSide20k construction has started and G3R&D should start soon. The panel recommended that Science Board invite full proposals for the two initiatives, including descope options, as soon as practicable. STFC is asked to explore an appropriate mechanism to evaluate these on the necessary timescale, using reviewers who are members of neither collaboration. **The panel are conscious that such a review be conducted with urgency, and recommend it complete in autumn 2019.**

Recommendation 3: Full proposals for DarkSide and G3R&D should be invited as soon as practicable and STFC should explore an appropriate mechanism to evaluate these on the necessary timescale, using reviewers who are members of neither collaboration.

9.11. Alternative approaches are used to search for different classes of dark matter. For example, the ADMX experiment uses a tuned resonant cavity to search for axions converting to photons in a static magnetic field. A UK initiative explores a low-cost upgrade to the ADMX electronics to allow significantly faster scanning of axion masses and potentially enhanced sensitivity. Another UK initiative (MAGIS, and the proposed UK AION project) explores the use of light pulse atom interferometry to search for dark matter. Directional dark matter technology is also under development, and provides an important route to confirming a dark matter signal.

9.12. The panel noted a number of opportunities to add breadth to the dark matter area, (which are not listed in this review). The panel recommend that STFC conduct a focussed review of the dark matter subfield to establish a clear strategy for longer term investment that maintains a UK presence at the cutting edge of the field, takes into account future opportunities, and possibly leads to hosting a 3rd Generation instrument.

Recommendation 4: Following the outcome of Recommendation 3, STFC should conduct a focussed review of the dark matter subfield. The review should establish a clear strategy for longer term investment that maintains a UK presence at the cutting edge of the field, takes into account future opportunities, and possibly leads to the hosting of a 3rd generation instrument.

10. Neutrino astronomy

10.1. Neutrino astronomy is an expanding field that has already contributed meaningfully to our understanding of the universe. Neutrino astronomy began with the Homestake experiment's observations of solar neutrinos in the 1960s. The field has enjoyed steady growth into new energy regimes and new experimental technologies, notably open volume water Cherenkov experiments such as Kamiokande, IMB, and Baksan which each observed neutrinos from Supernova 1987a.

10.2. Neutrino astronomy facilities comprise solar and supernova neutrino experiments at low energies (MeV scale) and a range of high-energy (TeV and above) experiments. Current facilities are supported by the particle physics programme area.

10.3. Low energy neutrino astronomy experiments include SNO+, SuperNEMO, the SK-Gd project, the future Hyper-Kamiokande and DUNE experiments, and aspects of IceCube/KM3NET. SK-Gd, HK and DUNE will perform neutrino oscillation measurements, but will have sensitivity to supernova neutrinos. SNO+ and SuperNEMO are intended to study NDBD, but SNO+ will also measure solar neutrinos. Proforma for SNO+ and SuperNEMO were received and their synergies with PA noted, but the panel did not rank the experiments. The Particle Physics Programme Evaluation will perform the ranking and the panel felt this to be appropriate.

10.4. High energy neutrino astronomy experiments include IceCube, KM3NET, ANITA and ARA. High-energy neutrino astronomy measurements are connected with UHE cosmic rays, the extreme universe, and transient sources such as active galaxies. The recent observation and interpretation of a high energy neutrino by the IceCube neutrino astrophysics experiment illustrates an important synergy between neutrino astronomy and photon-based astrophysics. UK scientists (UCL) are leaders in the radio telescopes ANITA and ARA.

10.5. In its recent review of PA, the IOP concluded that the UK could develop a coherent and successful effort in neutrino astrophysics, with a recommendation that the UK community of scientists involved in the area should develop a more strategic approach to the topic. STFC's PAAP concurred with this recommendation.

10.6. The panel noted that the UK community working in neutrino astrophysics is smaller than in other PA areas, and supported mainly via consolidated grants. However it is an expanding field and high profile future opportunities exist with a range of high energy neutrino experiments. **The panel supports the statement made in the IOP review of Astroparticle Physics recommending that the community seek to support a single project in this area, which may then develop sufficient critical mass to strengthen the case for investment.**

10.7. The panel considered IceCube-Gen2, which is a leading experiment in neutrino astrophysics and appears prominently in several international roadmaps (and was also submitted to the 2018 Developing a World Class Research Base exercise). The panel felt that inviting a proforma at this stage would not be indicative of future scientific strength given the early stages of community coherence, and did not rank the experiment. The panel encourages the community to cohere around the proposal, and to consider how to develop technical expertise for future instrumentation.

10.8. The panel note that neutrino astrophysics has no development funding line, and experimental activity is only supported by consolidated grant funding. The panel stress the importance of continuing consolidated grant support to support the area.

Recommendation 5: The panel stress the importance of continued consolidated grant funding to support the area of neutrino astronomy in the PA Programme.

11. Particle astrophysics theory

11.1. A world class programme should contain theoretical and experimental elements. Theoretical models developed within the programme motivate experimental work to test predictions and constrain model parameters, and experiments provide results to challenge and extend theory. The UK has a strong theoretical programme in PA in tandem with the experimental PA programme.

11.2. Synergies exist with the wider experimental frontier science programme. Large-Scale Structure surveys such as those performed by the Dark Energy Survey (DES), Large Synoptic Survey Telescope (LSST) and the Euclid satellite provide data that constrain models of dark matter and energy. These surveys and particle physics neutrino experiments provide constraints on neutrino predictions. CMB observations test models of inflation and the origin of structure in the universe.

11.3. The area also has synergy with particle physics phenomenology, particularly in dark matter, with future opportunities noted in neutrino phenomenology, the physics of gravitational waves and neutron stars. There is also some broadening of lattice field theory into cosmology.

11.4. Proforma were not requested from the theory community. Instead, the panel drew on the 2018 Review of Particle Physics Theory and statistical information accumulated from STFC grant funding to inform its review. Noting the panel concerns around the collection of PA data, the office and the panel have made judgements as what counts as PA and what does not, since the distinction is often blurred.

11.5. Within the UK, there are PA theory groups in 22 institutions (Birmingham, Cambridge, Cardiff, Durham, Edinburgh, Imperial, Kings, Liverpool, Lancaster, Leeds, Newcastle, Nottingham, Manchester, Oxford, Portsmouth, QMUL, Royal Holloway, Sheffield, Southampton, Sussex, Swansea, UCL). The level of activity varies from being the main area of activity in some institutions, to being relatively minor at others.

11.6. PA theory activities cover a wide range of subject areas but can be categorised into (i) areas that support experimental areas, such as gravitational waves, which are part of the PA Programme, and (ii) those where the experimental effort is supported by another programme, usually astronomy. Areas which fall into the latter category are typically within the area of cosmology – often called particle cosmology – and constitute the bulk of the activity at present.

11.7. Within particle cosmology the UK has significant leadership in numerical field theory modelling of topological defects and phase transitions, dark energy and modified gravity models, inflationary model building, cosmic microwave background theory, models for baryo/leptogenesis and constraining models of dark matter.

11.8. There is also a strong UK community in the area of General Relativity and the theory of gravitational waves. The recent detection of gravitational waves is likely to lead to an increase in theoretical activity in this area. A number of institutions have or are considering making academic appointments in this area including Birmingham, Cardiff and Portsmouth.

11.9. The panel noted that the UK PA theory community is highly regarded and ranked activity as **(g3 – mature)**. The panel agree that the support of PA theory is crucial to enable emerging research areas to be exploited and maximum value to be extracted from the science programme.

11.10. The panel concurred with the views expressed in the 2017 Review of Particle Physics Theory that the low level of PDRA support across particle physics is a threat to the programme, and that increased support was essential to maintain the quality of the current programme and its international competitiveness. The panel believe that the same skills shortfall exists in PA theory. A shortfall in theoretical activity limits the scientific output of an area. The panel recommend that STFC consider how to increase PDRA support within theory to maintain the quality and international competitiveness of the PA Programme.

Recommendation 6: STFC should consider how to increase PDRA support in Particle Physics Theory (and astronomy) to maintain the quality and international competitiveness of the PA Programme.

12. Cosmic Microwave Background

12.1. CMB is relic radiation from the Big Bang. The energy spectrum and the angular distributions of temperature anisotropies and polarisation of the radiation can yield information about the state of the Early Universe. Measurements have had a significant impact in the fields of astrophysics, cosmology and fundamental physics.

12.2. The key science drivers in CMB research are to understand the physics of neutrinos, dark energy and the physics of inflation. For example, a detection of the primordial B-mode polarisation signal would provide us with a probe of physics at Grand Unified Theory (GUT) energy scales, far beyond the energies accessible to ground-based particle physics experiments

12.3. CMB research is carried out with ground based instruments or satellites that make full sky maps. Ground based research is dominated by US-led projects with UK and other European researchers as collaborators, most recently with ACT and Polarbear in Atacama, and SPT and BICEP at the South Pole. There have been three recent satellite missions; COBE and WMAP (NASA) and Planck (ESA).

12.4. The UK has a long history of research in this area, including previous involvement in CLOVER (supported by the PA Programme) and Planck (supported by Astronomy). PPARC funded projects included the Very Small Array (VSA) and QUest at DASI (QUaD).

12.5. Planck was awarded the 2018 RAS Group Achievement Award, as well as the 2018 Gruber prize in cosmology. UK scientists constructed major components of the Planck instruments and led many of the headline science analyses. In addition the Cardiff group has provided filters for most of the CMB experiments worldwide, and many UK scientists have been asked to play roles in the present crop of ground based CMB experiments.

12.6. UK CMB theorists have led the world in a number of areas including power spectrum predictions, power spectrum estimation methods, CMB lensing, non-Gaussianity and secondary anisotropies. COSMOMC, the main cosmological parameter estimation code used by all collaborations, was developed in the UK.

12.7. At present there is no specific funding line for CMB development within the STFC's frontier science programme. The UK CMB community are supported through the astronomy consolidated grant funding, fellowships, and non-STFC funding.

12.8. The panel recognised CMB to be an area of high interest and importance that addressed several STFC science challenges. Although CMB is currently considered under the astronomy programme, the panel noted that CMB had been included in the most recent APPEC strategic prioritisation and that motivated its consideration in this evaluation. The CMB community was invited to submit a proforma to the PAPE.

12.9. Future opportunities in the area cover a range of timescales:

- Simons Observatory (SO): a ground-based observatory presently being constructed in Chile already with significant UK involvement.

- Litebird: a Japanese-led satellite undergoing phase A study by JAXA;
- NEXTBASS: a concept for a low frequency array to measure the foregrounds which could hinder the extraction of the CMB polarization signal;
- CMB S4: a concept for the ultimate ground-based CMB observatory;
- PRISTINE: a proposed F-class ESA mission to measure spectral distortions of the CMB.

12.10. Of these opportunities, only SO occupies a timescale relevant for the evaluation. The SO was submitted to the 2018 Developing a World Class Research Base exercise and has also been submitted to the Fund for International Collaboration (Wave 2). Given the advanced stage of the UKRI funding submission the panel noted that the proposal was clearly already a strategic priority of STFC, and felt that there was no need to rank the proforma.

12.11. The panel noted that while the consolidated grant funds exploitation activity in CMB, the area did not appear in current STFC roadmaps. As no future opportunities are supported and a future route to funding is not clear, UK leadership and science output in the area is at significant risk of being lost. The panel recommended that both the PAAP and AAP add CMB to their roadmaps as a separate research theme to mitigate the risk of accidental loss.

12.12. The panel noted that the scientific goals of CMB research – probing fundamental physics using astronomical observations - are very much aligned with the PA Programme. Furthermore the nature of CMB experiments, being driven by statistical measurements as opposed to specific objects, is closer to particle physics and PA experiments than traditional astronomy. Accordingly, the panel recommended that development projects in CMB be considered as part of the PA Programme (exploitation should be retained by the Astronomy Grants Panel). It follows that if the Simons Observatory proposal is successful in its UKRI bid, then this should be managed by the PA Programme. If it is unsuccessful then STFC should consider other options to fund the SO (still to be managed by PA).

Recommendation 7: CMB development projects should become part of the PA Programme, with exploitation funding retained by the Astronomy Grants Panel.

Recommendation 8: If the Simons Observatory proposal is successful in its UKRI FIC bid, then this should be managed by the PA Programme. If it is unsuccessful then STFC should consider other options to fund the SO (still to be managed by PA).

Recommendation 9: CMB should be considered explicitly as a separate research theme in both the PAAP and AAP roadmap reports, with PAAP as the lead and synergies noted by the AAP.

12.13. The panel agreed that the UK had played a significant role in developing the CMB area and that the community was world leading. Evidence of quality was given by the number of ERFs, URFs and ERC consolidator grant holders currently held in the area (seven in total).

12.14. Since there is currently no specific funding line for CMB, the panel considered ways to tension future CMB opportunities against other future opportunities in the frontier science programme. While the panel noted that this is also a concern for other areas of PA, and is explored further later in this report, **CMB was noted as a specific example of how an established community can find itself without a funding line and with few options to secure funding for future opportunities.**

13. Programme breadth and balance

13.1. Having assessed each science area, the panel concluded that the breadth of the current funded PA Programme is severely restricted. Of the PAAP roadmap areas, only three contain development projects at the level of one project each—and one of these ends in 2019. For emerging areas like gravitational waves the breadth is appropriate and reflects available opportunities. For other topics like dark matter one project represents a subset of opportunities within the area.

13.2. The panel noted that the programme is too restricted to strike any balance between development and exploitation. Exploitation is awarded by PPGP and AGP, and cannot be guaranteed for PA experiments. While grant panel recommendations should be driven by this evaluation, there is a risk that exploitation and value for money may be curtailed should grant panel priorities differ from those of the PA community. It is therefore essential that where a PA proposal is to be assessed that grant panels draw on sufficient expertise from the PA community to facilitate the peer review.

13.3. Conversely, PPGP and AGP give opportunities for additional support beyond funded projects entering exploitation. For example, the field of neutrino astrophysics is now only supported by PPGP, which also offers low levels of funding to support dark matter experiments. Additional breadth and balance for PA is therefore offered by the wider frontier science programme.

Recommendation 10: STFC should ensure suitable representation from the PA community on grants panels that assess proposals that contain PA research.

14. Skills and technology synergies

14.1. The PA Programme contains a number of synergies with other frontier science areas. Scientific synergies exist with particle physics when the particulate nature of PA phenomena is probed, and with astrophysics when optical probes of phenomena are necessary to study underlying physical mechanisms. One implication of PA scientific synergies is that much detector technology is shared between frontier science areas. The skills required to drive this technology are therefore common to much of the frontier science programme.

14.2. Dark Matter and NDBD detectors are made of high purity materials, manufactured in clean rooms using low-dust technology, a requirement shared by gravitational wave instrument construction. Facilities developed to screen detector materials, including the germanium detector facility at Boulby and the ICP-MS facility at UCL, are used by a range of experiments which face similar sensitivity challenges and share many common detector components. The design of some general purpose neutrino experiments has been informed by components and experimental techniques developed for dark matter detectors. HV feedthroughs developed for LZ informed the design and construction of feedthroughs for SBND, and gas purity monitoring and outgassing measurement techniques have been used in ProtoDUNE. High photon detection efficiency SiPMs being developed for DarkSide are of interest to DUNE and NDBD experiments, and the Darkside cryostat is being delivered by the Neutrino Platform at CERN using technology developed for DUNE.

14.3. Further technology synergies exist between neutrino astrophysics and general purpose neutrino experiments. Photomultiplier R&D to develop multidimensional digital optical modules for KM3net is of interest to Hyper-K, and the GPU-based data acquisition developed for ANITA is of interest to DUNE.

14.4. Gravitational wave detector R&D has links to technologies developed for applications outside the frontier science programme: high power lasers, high performance optical coatings, computational materials modelling, precision measurement and frequency standards, machine learning, numerical relativity, geophysical monitoring, quantum optics and cell biology[6]. The quantum noise reduction technology developed for the area is of strategic interest to EPSRC, and the University of Glasgow lead the EPSRC-funded UK Quantum Technology hub in quantum enhanced imaging. Some of the techniques required for gravitational wave infrastructure, including contamination control and cleanliness issues, share synergies with activities in the dark matter and space sectors.

14.5. The fast high throughput single photon counting technologies used for CTA are in demand for other fields too. Within the frontier science programme similar technology is used for fast timing imaging detectors in particle physics, e.g. in LHCb, while outside the programme they are used in inertial confinement fusion diagnostics, biological and clinical diagnostic applications involving fluorescence lifetime imaging, and remote sensing applications such as LIDAR have similar requirements and use similar technology.

14.6. **The panel recognise that these synergies represent a focus of expertise that benefits STFC more widely. However, the benefit is accompanied by increased risk; as the programme becomes more reliant on synergies this (i) restricts new technology innovation and (ii) increases dependency on skills prioritisation in other programme areas.**

14.7. Ensuring an adequate balance of skills in the PA career pipeline would moderate this risk. The panel identified some shortcomings in the skills pipeline, in particular that there is no route for promising early career detector physicists to be recognised and establish an independent programme of research. Combined with the PRD scheme currently on hold, this gives limited opportunities to develop skills in the next generation of technology that may also benefit other areas of the programme.

14.8. No specific skills shortages have been highlighted by the PAAP in their input to this evaluation. However, the panel noted that should the UK wish to host a future dark matter facility, additional skills may need to be developed to meet the stringent engineering and cleanliness challenges that would be presented.

15. Societal and economic impact

15.1. In addition to the impact generated by GCRF and ISCF projects, the PA community has a good track record of societal benefits and continues to have productive collaborations with industry through the industrial engagement programmes of the university groups which support knowledge exchange and the development of future REF returnable impact cases.

15.2. Annex 2 lists ongoing industrial collaborations by the PA community reported in proforma returns to this exercise. The collaborations span a range of technology readiness levels from initial prototyping (supported by STFC or Royal Society equipment funds in the cases of prototype PET scanner detectors, using liquid argon

[6] See the PAAP submission to this evaluation for more details.

dark matter technology, and improved heart magnetic field measurements), to patent applications and field tests, to processes and improvements generating quantified economic impact. For example the use of gravitational wave analysis techniques to validate QA processes for Optos, a leading medical technology company specialising in ophthalmoscopes, has resulted in a 25% increase in yield in one of the major device components and an estimated annual cost reduction of about US$500,000 on this component alone.

15.3. The direct search dark matter programme has led to substantial industrial impact, supported in part by STFC Impact Acceleration Awards. Among other developments, muon transport models used to estimate backgrounds due to cosmic rays have been adapted as a tool for muon tomography, including studies of carbon capture and storage facilities, illicit nuclear materials detection and volcano tomography. Aspects of the low background assay techniques are being considered as a route to rapid evaluation of lead levels in water to improve health prospects in developing countries, while the high sensitivity alpha-particle assay capabilities are being applied in single-site interaction error studies for silicon wafers. The germanium screening instruments themselves are being improved to deliver lower backgrounds and better energy resolution. The BUGS facility working together with Lead Shield Engineering Ltd, has improved the lead shielding capability for its detectors, resulting in interest from and new purchases by AWE. These efforts are being made in conjunction with a number of UK and European based companies including Agilent, Analytics and Mirion.

15.4. CTA technological impact includes well-established funded work on technology transfer of calibration using Unmanned Airborne Vehicles (UAVs), transfer of high-speed photon counting technology to industry and medical imaging (at development level), and possible applications of mirror technology to solar energy generation.

15.5. Gravitational Wave technological impact includes the “Find A Better Way project”, worth £2.8M total, to fund the first clinical trials (planned for 2020) of bone graft technology, the "ATTMEDS" project which support improvements in the measurement of the magnetic field of the heart, allowing doctors to better assess which patients are in need of extensive triage, and the “Wee-g” MEMS gravimeter which is developing precision gravity sensors which can be applied to environmental monitoring, defence & security or the oil & gas industry, with field trials being undertaken by BP in 2019-2020.

15.6. On the societal impact side, the PA community has a strong public engagement footprint. The science is newsworthy and popular; in the last year some 200 online news articles have mentioned gravitational waves, dark matter and blazars in the UK alone[7]. The community delivers tens of public events each year, including talks in schools and at science festivals, Soapbox Science, Pint of Science, Café Scientifique, master classes, presentations to UK businesses and innovation groups. As an example dark matter scientists organised ten public outreach events across the UK together with the launch of an app and a professional video for the first international Dark Matter Day (31/10/2017), and collaborate with a group of UK artists through an STFC Sparks award.

15.7. The panel found the track record of community engagement with outreach and impact extremely strong, and commended the community. The panel noted the wider added value these activities brought to STFC investment.

[7] Google news search performed on 19/08/18.

16. Computing needs

16.1. The next generation of PA experiments will rely heavily on large scale computing. Dark matter experiments, and in the future CTA, use the GridPP paradigm of high throughput computing and data management and access, and will require similar computing to particle physics users. Gravitational wave modelling/data analysis harnesses techniques deployed in large scale computing clusters, with additional developments in the areas of machine learning and AI techniques, while particle astrophysics theory require skills in high performance computing that are similar to those required in astrophysics. As with particle physics and astronomy, PA theory will rely on access to HPC resources.

16.2. PA experiments, in common with those across the frontier science programme, require advanced skills in computing to access, analyse and exploit data. Machine learning techniques are becoming more common within particle astrophysics (the UK co-leads the Machine Learning Task Force in CTA, and machine learning techniques are becoming increasingly important to isolate gravitational wave signals as detection rates increase and to separate dark matter signals from background), and across the frontier science programme as a whole. PA students form part of the cohort trained in STFC's CDTs in Data Intensive Sciences.

16.3. **In the future, the need for computing, data handling and data storage from existing and next generation experiments will increase beyond current capabilities. Data storage will need to be addressed by not only the PA community but the science community as a whole.**

16.4. The panel noted that an upgrade is planned to the Raven HPC cluster that will cover the needs of A+. PA theory and CMB will be reliant on obtaining adequate access to the DIRAC facility, and share a wider HPC requirement that adequate investment is provided to the facility to maintain competitiveness. The future computational needs of LZ and DarkSide already form part of GridPP planning. However CTA does not currently have a complete computing model or form part of GridPP planning, and will need to be integrated.

PROGRAMME FUNDING SCENARIOS

17. Overview

17.1. The panel was asked to recommend an appropriate PA programme in the following financial scenarios - Flat cash and Flat cash + / - 10% over the next five years (2019/20 to 2023/24) based on the current £3.6M pa flat cash envelope. The panel noted that, based on their assessment, none of these scenarios would deliver an optimal programme. Additional scenarios were included with the £0.5M UKRI resource uplift for gravitational waves currently only secured until FY19/20, incorporated into baseline funding.

18. Increased funding scenarios

18.1. **Scenario A: Flat cash funding with £0.5M UKRI resource uplift for gravitational waves incorporated into baseline funding, plus 10% (£4.5M):** This scenario maintains the current volume of activity within the programme. The panel noted that continuation of the additional funding secured through UKRI is essential to be able to maintain research volume and underpin exploitation of the new field of gravitational wave astronomy.

18.2. The uplift enables ground based gravitational wave research to be supported at least at constant volume. It allows exploitation of STFC's previous investment and UK M&O commitments to aLIGO, R&D towards the next generation of experiments, and the resource required to support the A+ upgrade, so that a sustainable and effective programme of research can be delivered. The panel considered the new field of gravitational wave astronomy to have extremely high potential to deliver impact and transformational science, and regard it as essential that the uplift continue. CTA construction and a future dark matter programme can also go ahead. The panel regard this as a minimum viable level to maintain the current programme. The panel note that this funding level is insufficient to build breadth back into the programme.

Recommendation 11: Additional funding secured through UKRI to FY19/20 should be baselined within the PA Programme to maintain research volume and underpin exploitation of the new field of gravitational wave astronomy.

18.3. **Scenario B: Flat cash funding with £0.5M UKRI resource uplift for gravitational waves incorporated into baseline funding (£4.1M):** In this scenario, gravitational waves support can be maintained, including support for A+ and future R&D. There is sufficient funding for UK participation in CTA construction as currently foreseen (~£1.0M p.a. over five years). Some small headroom remains after LZ moves to exploitation in 2020 to support R&D for future experiments of approximately £300k pa. This headroom would provide limited support for the next generation of dark matter experiments. Care would be needed to manage the different investment timescales of CTA and future dark matter to support both at a minimum viable level. There is insufficient funding to build breadth into the programme.

18.4. This scenario is similar to a **'flat cash plus 10%' scenario (£4M pa)** where a 10% increase of £0.36M, without the UKRI uplift, would be used to maintain support gravitational waves as the highest priority at the £2.6M/year level.

19. Reduced funding scenarios

19.1. **Scenario C: Flat cash <u>without</u> continuation of the UKRI uplift after 2019/20 (£3.6M):** The UKRI uplift for gravitational waves is secure only until 2019/20. If the uplift does not continue into the next CSR period then it will not be possible to sustain leadership in all three PA priority areas. One science area, either VHE gamma ray physics or dark matter, is likely to be lost from the programme.

19.2. At flat cash, the panel agreed that gravitational waves astronomy exploitation, which includes R&D towards the next generation of experiments and support for A+, is the highest priority and should be maintained if possible. The panel considered options for redeploying effort and limiting future R&D, but agreed that this would put the UK at risk of not fulfilling its international commitments to aLIGO or maintaining its leadership in future developments. In particular, funding gravitational waves below the current (flat cash) level risks losing UK leadership (e.g. in key technologies) and return on our long term investment, and could cause reputational damage from pulling out of UK led activities. The programme would continue in the short term, but in the long term would cause irrevocable damage and withdrawal from whole areas of research.

19.3. The panel considered the level of funding required for CTA construction. They noted that the current planning line reflects the best estimate of the level of funding that is required to meet the UK's statement of interest in CTA and is the minimum level to ensure return on UK investment and without having to renegotiate UK participation and potentially damage the UK's reputation as a reliable international partner. As noted in paragraph 8.5, ESO membership does not give access to the Key Science Programmes of the CTA Consortium.

19.4. If gravitational wave research is funded at flat cash and CTA funded at the level currently foreseen, then there is no headroom and opportunities to broaden the programme or participate in new projects are not possible. This would also mean **the UK having to consider withdrawing from the globally important area of dark matter research,** missing out on a major scientific discovery with implications for our understanding of physics and the Universe.

19.5. Withdrawing from dark matter research would also mean a loss of UK leadership and expertise (e.g. best scientists and engineers would leave) and could impact other areas particularly NDBD, which shares underpinning technology. The UK would also fail to build on its past investment and it would be difficult to reinstate dark matter research a later date. The opportunity to develop a route to host a future experiment would be lost.

19.6. If CTA construction was not funded, then there is sufficient funding to support future developments in dark matter. However, **the UK would need to consider withdrawing from investment in VHE gamma ray physics in the short term and it may not be possible to reinstate this at a later date,** again risking return on investment to date and reputational damage as an international partner.

19.7. **Scenario D: Flat cash minus 10% (£3.2M):** In a below flat cash funding scenario, the panel agreed that the quality and science output of the whole programme would be damaged irrevocably. **It may not be possible to participate in either VHE gamma ray physics or dark matter at a viable level.**

19.8. The panel agreed that gravitational waves should be prioritised ahead of CTA and dark matter as this is the highest ranked priority area. However, in this scenario leadership and capability in both VHE gamma ray physics and dark matter would have to be lost, and the UK would no longer be a credible partner in either area. Not participating in CTA construction would damage the UK's reputation and delay the international project (while other members pick up UK responsibilities), while prioritising CTA, even at a low level of funding, would mean the UK effectively withdrawing from dark matter research.

20. Exploitation

20.1. The panel noted that a reduction in gravitational waves exploitation puts R&D for future development e.g. Einstein Telescope at risk, and potentially limits the opportunities for new groups that are emerging in this field. A reduction in the particle physics consolidated grant potentially puts the areas of NDBD and neutrino astronomy at risk; as it is, the number of PDRAs in theory is considered to be critically low. Reductions in the astronomy consolidated grant would place further pressure on CMB and potentially fail to fully exploit CTA. To ensure value for money for PA investment it is critical that exploitation grant lines are well funded.

Recommendation 12: Healthy funding of exploitation grant lines is a high priority for the PA Programme regardless of financial scenario.

21. Funding summary

21.1. The current funding for the PA Programme means that 10% amounts to approximately £360k/year. Other than in Scenario A, it is not possible to maintain the current research volume, and no scenario provides scope to broaden the programme. In flat cash and below flat cash scenarios it is necessary to compromise research activities and leadership in at least one of the currently funded PA Programme areas – gravitational waves, dark matter direct searches, and VHE gamma ray physics. While support for ground based gravitational wave astronomy is maintained (as the highest priority for the PA Programme), there are risks associated with VHE gamma ray (CTA) funding and the UK's ability to participate in future dark matter research.

21.2. The panel concluded that in a programme where there is only one project in each science area, that losing a research area is very likely. Unlike a similar reduction in funding for the larger science disciplines (particle physics and astronomy), where it may be possible to retain some involvement in all research areas, this would have a long lasting effect on the PA Programme from which it may not be possible to recover. An increase in funding of ~10% would enable each of the three PA Programme priority areas to be supported. However, a larger increase in the funding available to the programme (i.e. at or above 10% plus current UKRI uplift) would be needed to consider building breadth into the programme.

Recommendation 13: The PA Programme needs a 10% uplift to maintain UK visibility and leadership in the current projects, and a greater than 10% uplift to build breadth back into the programme and exploit the opportunities available to UK scientists.

22. Additional (non-core programme) funding opportunities

22.1. The PA community are active in pursuing new sources of funding introduced by Government and have already been successful in securing support through the Newton Fund, GCRF and ISCF. The table in Annex 1 lists currently funded awards and future applications identified by the community proforma returns to this exercise.

22.2. Although these new funding streams do not currently support the core programme directly, they provide a mechanism for the UK to influence and shape the development of international collaborations in high priority science. For example, funds have been awarded to gravitational wave physicists for capacity building in China and India (the latter involving a LIGO-India extension to the LIGO network). CTA also plans capacity building applications to provide training in and build partnerships with SKA partner countries. Both GCRF and ISCF funds can also be used to enable detector development and industrial impact. DarkSide physicists have been awarded GCRF funds to support a collaboration developing liquid Argon scintillation readout techniques. Spin-offs from detector technologies developed for DM, GW and CTA have been identified for forthcoming GCRF and ISCF bids in areas as diverse as healthcare, energy, defence and electronics packaging industries.

22.3. The panel strongly supported efforts to further exploit the opportunities these schemes represented, which rely on the leadership and capability developed within the core frontier science funded programme.

22.4. With the creation of UKRI in April 2018, additional funding schemes have been introduced. These are directed more at supporting the core programme to ensure that the UK remains a leading science nation by building strong international partnerships, attracting the best international talent and investing in strategically important research and innovation. The schemes include the **Strategic Priorities Fund** (SPF), **Fund for International Collaboration** (FIC), and **Strength in Places Fund** (SiP). These funds are open to the UK science community and aim in part to ensure fundamental research is supported at a sustainable level to ensure a future pipeline for future technology development and impact. The panel felt that the FIC and SPF schemes present opportunities to fund projects for which there is currently no STFC funding available in the core programme and welcomed the recent success of A+ in securing ~£10.5M via the FIC without which the UK would have been unable to participate.

22.5. The panel agreed that these new UKRI funding streams present a significant opportunity and provide a valuable route to funding excellent research that cannot be accommodated within the STFC's current flat-cash core programme. The panel welcomed the opportunity to secure additional funding for the programme, but noted that these routes do not guarantee funds and as such are not a replacement for core funding to underpin the long term health and viability of the PA programme in the UK. The panel reiterated that STFC should maintain pressure for additional uplift to the core programme as part of its bid to the next Government CSR to underpin core capability and leadership and ensure a future pipeline for future skills and technology development and impact. The panel also noted the importance of ensuring that exploitation funding is sufficient to support these projects once they are in operation.

Recommendation 14: STFC should maintain pressure for an uplift to its core programme as part of the next CSR to underpin core capability and leadership for development and exploitation and ensure a future pipeline for future technology development and impact.

FUTURE PROGRAMME SCOPE AND STRUCTURE

23. Funding of gravitational waves

23.1. The BoP1 raised a specific issue with the current structure of gravitational waves funding, that "*the current approach makes it difficult to ensure that all research challenges (and opportunities) are adequately addressed and that proposals are meaningfully tensioned against each other*" and agreed that no gravitational waves research project should fall between the remits of the astronomy and PA programmes. BoP1 also highlighted the importance of ensuring that the "*bidding structure and scope of the grant calls are clear and that all the areas of the programme have the opportunity to bid for support and be assessed appropriately*"[8].

23.2. In order to address these concerns, the panel considered the different aspects of ground-based gravitational waves support and how this aligns with the current funding mechanisms i.e. the gravitational waves consortium grant in the PA Programme and the astronomy consolidated grant:

- *Operations (covered under PA):* operations support the commissioning, characterisation and operation of the aLIGO detectors and the operation of GEO-HF to ensure continuity of observation and improved level of sensitivity of observations. This includes on site detector support and shifts undertaken by UK groups in the LIGO collaboration.
- *Detector development (covered under PA and astronomy):* Within PA, this includes (1) R&D for development and operation of the aLIGO and Virgo detectors (2) R&D for upgrading gravitational wave detectors (including resource for A+) and for a future generation of detectors e.g. Einstein Telescope and Cosmic Explorer and (3) development of new technologies, using theoretical analysis and simulations to improve detector potential and developing technology to improve sensitivity of future detectors. Within astronomy, the Birmingham group undertakes some R&D

[8] STFC Balance of Programme Review 2017, p.34

activities in hardware development. The new Portsmouth group will be working on detector characterisation, which spans the instrument/data analysis activities.

- *Exploitation (covered under PA and Astronomy):* exploitation is required for the development and application of data analysis tools to perform searches and analyse data from the global network of gravitational wave observatories, as well as modelling of gravitational wave sources, which is necessary for detection and astrophysical interpretation.

23.3. The panel felt that it was possible to differentiate between the activities funded through the PA Programme and astronomy. For example, for exploitation, the research drivers (e.g. the nature of gravitational waves or probing the astronomical sources) can be used to determine whether funding should be requested from PA or astronomy programmes. The panel recommended that STFC agree a statement clarifying the boundary between the aspects of gravitational waves research that falls into the PA and astronomy remits. Where there are areas of overlap, the panel agreed that a threshold could be set to determine which funding route should be followed.

23.4. Such a statement should ensure that no proposal falls between the PA and astronomy remits, addressing the concerns expressed in BoP1. The statement should also avoid duplication with proposals being reviewed by both PA and the AGP.

Recommendation 15: STFC should develop and publish, in consultation with the community, a statement clarifying the boundary between the aspects of gravitational waves research (i.e. for development, operations and exploitation) that fall into the PA and astronomy remits and the funding arrangements.

23.5. The panel was also concerned that there are currently limited routes to support new research opportunities in gravitational waves.

23.6. This could be potentially be mitigated by allowing proposals in gravitational waves to compete with the consortium grant within the PA gravitational waves funding line. In any such call it would be important to observe Recommendation 15 and avoid duplication with proposals that should be funded through the AGP.

Recommendation 16: Following on from Recommendation 15, STFC should consider how best to support new opportunities in gravitational waves research within the PA funding line.

23.7. The panel also noted that the gravitational waves programme in PA is funded separately to the funding for Advanced LIGO operations. The panel recommended that the review of support for both the gravitational waves programme and operational support for gravitational waves should be carried out through one review process. This will enable a more efficient process for STFC, the review panels and the community. Suitable arrangements would need to be made for the transition.

Recommendation 17: The gravitational waves programme and the ongoing operations for gravitational waves should be reviewed together in future.

24. Evaluation of future funding mechanisms

24.1. The panel looked at options for future funding mechanisms to reduce the risk of losing a PA science area in future years and increase breadth in a programme where each science area has the potential to deliver world-leading science.

24.2. The panel was also concerned that there are limited routes to support early stage R&D for new PA opportunities. This includes those arising from the 2018 ‘Developing a World Class Research Programme’ or future schemes.

Option 1 - Maintain the current scope of the PA Programme

24.3. PA is a globally recognised and rapidly evolving field and the panel agreed that it was important for STFC to recognise PA as a separate area of research for strategic investment. While few university departments have a PA group, international partners both recognise and fund PA as a science area or programme e.g. as defined by the APPEC roadmap, and there are significant scientific and technical synergies between PA and the particle physics and astronomy programmes. If the UK did not have a PA Programme then this could potentially damage the UK’s capability and reputation in this area. It is therefore important for the PAAP Roadmap to be retained.

24.4. Another benefit of maintaining a PA Programme is so that STFC can identify and provide strategic support in high priority research areas so that leadership and impact in these areas can be achieved. The panel noted that identifying PA in this way has, for example, allowed ground-based gravitational wave research to grow and evolve, resulting in Nobel prize-winning research outputs, which might not have been possible had it been part of the broader astronomy or particle physics programmes.

24.5. The panel felt that it was important that other PA areas of strategic importance should be developed in a similar way. In particular, the panel recommend that STFC conduct a focussed review of dark matter research (Recommendation 4) after completing full proposals from DarkSide and G3&RD (Recommendation 3), to establish a clear strategy for longer term investment to place the UK at the cutting edge of the field and possibly lead to the hosting of a 3rd Generation instrument.

24.6. The panel noted that the current mechanism supported the PA Programme adequately within the current budgetary envelope, but was restricted (i.e. gravitational waves, high energy gamma, and dark matter). So while the current PA Programme protects strategic areas, its small size and narrowness means there is no flexibility to develop other emerging high priority areas or support new opportunities. Small fluctuations in funding can also have a disproportionately large effect on a small programme; once a project is lost the corresponding PA area is irreparably damaged.

Option 2 - Re-assign PA Programme elements to particle physics and astronomy programmes

24.7. Having no PA Programme with research areas and projects being developed either as part of the astronomy or particle physics programmes would enable more effective tensioning of future development opportunities within the larger astronomy and particle physics programmes. While this could provide greater potential for more PA projects to be funded, the panel felt strongly there was a risk that new or emerging activities in the PA area may not be prioritised highly if not considered to align strongly with the rest of the astronomy and particle physics programmes and potential synergies between particle physics and astronomy (both scientific and technological) could be lost.

24.8. This risk could be mitigated if the PA Programme is recognised within the PP and astronomy programmes along with a specific funding line, consistent with the approach taken by international partners. The particle physics experiment exploitation and development programmes are already structured and assessed by research areas; energy frontier (e.g. ATLAS, CMS), flavour (e.g. LHCb), neutrinos (e.g. DUNE) and non-accelerator physics and this could be refined to include PA. Within the astronomy consolidated grant a PA panel could be established to recognise PA exploitation to have sufficient expertise to assess PA projects within a larger programme.

24.9. However, overall, the panel concluded that, while the risks of reassignment can be mitigated in a number of ways, having a defined PA Programme was considered to be essential.

Option 3a - Broaden the scope of the PA Programme (exploitation)

24.10. The panel considered broadening the scope of the PA Programme to better reflect the PAAP (and APPEC roadmaps) and looked at the arguments around establishing a separate grants funding line for exploitation, similar to the astronomy and particle physics consolidated grants. The panel agreed that this would need to be broad in scope to ensure that there was a critical mass of researchers applying and to justify the effort needed to manage a separate grants panel review. This could include, for example, the areas of non-accelerator dark matter and neutrino physics in particle physics as well as gravitational waves, CMB, high energy gamma, and neutrino astronomy in astronomy.

24.11. The main advantage to this approach is that the exploitation programme could be more directly tensioned to support the development programme, as for other STFC programme areas. The broader programme could also encourage synergy between research areas and there is potential for cross-fertilisation with astronomy and particle physics, which could be a catalyst for developing future projects together.

24.12. However, while a PA exploitation funding line would need to be broad it would need to be carefully defined to ensure that boundaries are clear for applicants and that it is coherent. Many researchers in these areas would not identify themselves as particle astrophysicists, for example, in the particle physics neutrino programme, many researchers working on DUNE, Hyper-K, NDBD, and dark matter experiments work within particle physics groups.

24.13. This could mean that for particle physics experiments that have a PA component, researchers may need to apply to two grant rounds, which increases the administrative load on the university groups, and could lead to uncertainty in funding until both rounds conclude. Also, at a time of limited funding, it would be necessary to restructure the funding for the PP and astronomy grant reviews to establish a new grant review and funding line, and this would be contentious.

24.14. The panel concluded that this option would not address breadth, unless funding could be substantially increased. It could mitigate against the loss of an area, by placing both development and exploitation under PA and giving flexibility to transfer funds between them. However, the option of tensioning an area outside the PA Programme also gives scope to mitigate risk without the additional administrative overhead. Establishing a PA exploitation programme is therefore disfavoured.

Option 3b - Broaden the scope of the PA Programme (development)

24.15. The panel explored the establishment of a broader programme for development to increase breadth in the PA Programme and better enable future opportunities to be tensioned.

24.16. This would require an increase in funding either in new money or at the expense of the particle physics and astronomy programmes, and, at a time of limited funding any additional funding for PA would likely come as a result of reduced funding for particle physics and astronomy. Feedback from the PPAP encouraged STFC to fund projects in dark matter and neutrino astronomy as these areas are also strategically important for particle physics so rebalancing the funding lines for particle physics and PA may be possible. The situation is less clear for astronomy.

24.17. The panel have recommended (Recommendation 7) that CMB development be included within the PA Programme. As no CMB development line is currently supported within STFC, reassignment from astronomy would not bring additional funds into the programme.

24.18. An alternative option would be to agree an appropriate mechanism to tension future opportunities consistently across frontier science areas. How this mechanism operates would need further consideration, but the intention would be that when an SoI is received by Science Board, advice can be given as to whether to invite a PPRP proposal, in terms of strategic priority and the overall development funding available. SoIs for new opportunities, which have not been part of this evaluation, can also be compared to this list, to help Science Board make a recommendation. However, while the mechanism could work for particle physics related PA projects collectively, a similar mechanism would need to be established for astronomy related PA projects for this approach to succeed.

24.19. The panel noted that such a mechanism could be adopted in any of the funding mechanism options, and this could provide a way to mitigate the risk of losing an area in PA and potentially even increase breadth in constrained financial scenarios.

25. Funding mechanisms summary

25.1. The panel re-affirmed its recommendation that a PA Programme should be retained by STFC. However, while the panel felt that there were advantages to establishing a PA exploitation programme, these were outweighed by the disadvantages and practicalities of doing so, and so the current distributed funding structure for exploitation should be retained.

25.2. The panel agreed that it was important for projects in the PA development programme to have a route to request funding. Given current funding constraints there are limited options for how funding for PA can be increased, other than through the new UKRI directed funding schemes, but the panel thought it was important for PA future opportunities to be tensioned consistently with other opportunities across the frontier science programme and funding allocated in line with the relevant science drivers and priorities.

Recommendation 18: STFC should retain PA as a separate science programme area for strategic investment, consistent with the scope of the PAAP roadmap, both to respond to new developments in the field and to engage with its international funding partners effectively.

Recommendation 19: Exploitation of PA projects/experiments should continue to be funded through the existing particle physics, astronomy grant programmes based on the relevant science drivers.

Recommendation 20: Funding for new PA development projects should be tensioned with the existing STFC frontier science development programmes for particle physics and astronomy based on the relevant science drivers.

SUMMARY OF RECOMMENDATIONS

26. Recommendations

26.1. This evaluation has considered the PA Programme and broader field as defined by the PAAP roadmap. It has examined the current research programme and future opportunities and the impact on the PA Programme of a number of funding scenarios. In doing so the panel has also considered the future scope and funding structure of the programme and responded to the feedback from BoP1.

26.2. The panel has made a number of recommendations concerning the definition of the PA Programme and monitoring, recommendations for individual subject areas, funding in different financial scenarios, and funding mechanisms. These are listed below:

Recommendation 1: STFC should ensure that PA research activity is identified consistently across STFC programme areas and funding mechanisms, to enable accurate data on the scale and impact of PA to be monitored.

Recommendation 2: The astronomy community should assess their level of interest in CTA, so that opportunities for growth can be understood and a priority for exploitation funding established.

Recommendation 3: Full proposals for DarkSide and G3R&D should be invited as soon as practicable and STFC should explore an appropriate mechanism to evaluate these on the necessary timescale, using reviewers who are members of neither collaboration.

Recommendation 4: Following the outcome of Recommendation 3, STFC should conduct a focussed review of the dark matter subfield. The review should establish a clear strategy for longer term investment that maintains a UK presence at the cutting edge of the field, takes into account future opportunities, and possibly leads to the hosting of a 3rd generation instrument.

Recommendation 5: The panel stress the importance of continued consolidated grant funding to support the area of neutrino astronomy in the PA Programme.

Recommendation 6: STFC should consider how to increase PDRA support in Particle Physics Theory (and astronomy) to maintain the quality and international competitiveness of the PA Programme.

Recommendation 7: CMB development projects should become part of the PA Programme, with exploitation funding retained by the Astronomy Grants Panel.

Recommendation 8: If the Simons Observatory proposal is successful in its UKRI FIC bid, then this should be managed by the PA Programme. If it is unsuccessful then STFC should consider other options to fund the SO (still to be managed by PA).

Recommendation 9: CMB should be considered explicitly as a separate research theme in both the PAAP and AAP roadmap reports, with PAAP as the lead and synergies noted by the AAP.

Recommendation 10: STFC should ensure suitable representation from the PA community on grants panels that assess proposals that contain PA research.

Recommendation 11: Additional funding secured through UKRI to FY19/20 should be baselined within the PA Programme to maintain research volume and underpin exploitation of the new field of gravitational wave astronomy.

Recommendation 12: Healthy funding of exploitation grant lines is a high priority for the PA Programme regardless of financial scenario.

Recommendation 13: The PA Programme needs a 10% uplift to maintain UK visibility and leadership in the current projects, and a greater than 10% uplift to build breadth back into the programme and exploit the opportunities available to UK scientists.

Recommendation 14: STFC should maintain pressure for an uplift to its core programme as part of the next CSR to underpin core capability and leadership for development and exploitation and ensure a future pipeline for future technology development and impact.

Recommendation 15: STFC should develop and publish, in consultation with the community, a statement clarifying the boundary between the aspects of gravitational waves research (i.e. for development, operations and exploitation) that fall into the PA and astronomy remits and the funding arrangements.

Recommendation 16: Following on from Recommendation 15, STFC should consider how best to support new opportunities in gravitational waves research within the PA funding line.

Recommendation 17: The gravitational waves programme and the ongoing operations for gravitational waves should be reviewed together in future.

Recommendation 18: STFC should retain PA as a separate science programme area for strategic investment, consistent with the scope of the PAAP roadmap, both to respond to new developments in the field and to engage with its international funding partners effectively.

Recommendation 19: Exploitation of PA projects/experiments should continue to be funded through the existing particle physics, astronomy grant programmes based on the relevant science drivers.

Recommendation 20: Funding for new PA development projects should be tensioned with the existing STFC frontier science development programmes for particle physics and astronomy based on the relevant science drivers.

ANNEX 1: GCRF and ISCF activities

Funded awards and future applications, current as of January 2018, identified by proforma returns to this exercise.

Stream	Community	Description	Status
GCRF	LZ	Developing smart technology to evaluate lead content in water	funded
GCRF	LZ	Developing smart technology to detect dangerous heavy metals in water	potential
GCRF	LZ	Muon tomography of volcanoes in South America	funded
GCRF	Darkside	Developing Latin America-UK collaboration on LAr scintillation light readout	funded
GCRF	Darkside	Applying radioactivity screening techniques to identify lead contamination in water	funded
GCRF	GW	Gravitational wave excellence through alliance training (GrEAT) network with China	funded
Newton-Bhabha/GCRF	GW	Capacity building for LIGO-India	funded
GCRF	GW	Capacity building and training in Malaysia and Egypt	potential
GCRF	Gamma ray	Developing scientific partnerships with the gamma-ray and radio astronomy communities in South Africa	funded
GCRF	Gamma ray	Capacity building in SKA partner countries	funded
GCRF	Gamma ray	Applications of mirror technology to solar energy generation	potential
ISCF	LZ	Low background alpha detectors for the electronics packaging industry	potential
ISCF	Darkside	Developing industrial links with photon detection module production/qualification	potential
ISCF	GW	MEMS gravimeter use in oil and defence sectors	potential
ISCF	GW	Stem cell differentiation in bone raft technology	potential
ISCF	GW	Oscillation tracking methods to improve electric motor control	potential
ISCF	GW	Transferring optical thin film technology to industry	potential
ISCF	Gamma ray	Transfer of high-speed photon counting technology to industry	potential
ISCF	Gamma ray	Transferring airborne calibration UAV technology to industry	potential

The UK gravitational wave community is actively developing international partnerships funded via GCRF activities, including (a) the LIGO India Newton-Bhabha scheme supporting capacity building for LIGO India via staff exchanges, STEM/Outreach activities and entrepreneurial opportunities and (b) the Gravitational-wave Excellence through Alliance Training (GrEAT) Network, funded via an STFC Foundations Award, to support development of ground and space-based gravitational wave astronomy in China.

The UK VHE gamma-ray community is actively developing international funding opportunities and new research partnerships, with societal impact. These include a Newton fund award for Ph.D. exchanges with Southern African countries focussing on radio/VHE multiwavelength activities; participation in the DARA astronomy development project with emphasis on radio/VHE connection in Namibia; and a GCRF project to fund continuing operations at H.E.S.S. Future GCRF proposals will build on these activities, developing multi-wavelength scientific partnerships with the gamma-ray and radio-astronomy communities in South Africa and capacity building in the SKA partner countries.

ANNEX 2: Engagement with industry

Industrial collaborations identified by the PA community in project/experiment proforma returns to this exercise, current as of May 2018.

Description	Community	Status
Design of new detector shields with Lead Shield Engineering Ltd, exploiting Boulby gamma spectroscopy infrastructure	LZ	Shields available, several have been purchased by AWE.
Development of novel thin window S-ULB BEGe detectors with Mirion Technologies Ltd for low radiation products, using DM detector expertise	LZ	A model detector is in production and available to Mirion customers.
Performing sensitivity tests of heavy metal toxicity in water and food, using the ICP-MS facility developed for LZ.	LZ	Tests report to the UK Food Standards Agency; the facility is being registered as a National Reference Laboratory. Opportunities exist for technology and protocol development with Agilent and Analytix (UK).
Developing PET scanner detectors using LAr detection technology	Darkside	A prototype is in development with RS Equipment grant.
Validating QA processes for Optos using image quality metrics and artefact detection, based on GW data analysis methods	GW	25% yield improvement in major device component; use in new Optos product lines is planned
Using nanoscale vibrations to persuade stem cells to differentiate into bone building cells, using GW technology	GW	First clinical trials planned for 2020
Improving heart magnetic field measurements, based on GW analysis and seismic isolation techniques, to improve patient assessment	GW	STFC funded project 2018-2020.
Developing precise gravity sensors for environmental monitoring, defence & security or the oil & gas industry, based on GW suspension technology.	GW	Devices undergoing field trials in 2019-2020; industrial early adopters are BP, Schlumberger, DSTL, USGS, Clydespace and QinetiQ
Improving control schemes for electric motors, using GW analysis techniques	GW	Patent application pending from the University of Sheffield

Table 2: Industrial collaborations ongoing within the PA community

ANNEX 3: Ranking Criteria for Programme Evaluations

During the 2018/19 Programme Evaluations, projects/experiments/facilities within each discipline will be ranked. The ranking criteria will cover scientific excellence, exploitation within grants, and impact/industrial engagement. The exercise will look at all funded projects/experiments/facilities and ensure each is considered at whatever its stage of the exploitation cycle.

The panels will consider the merits or otherwise of supporting areas currently receiving STFC investment. This will include consideration of international engagement and subscriptions.

The ranking criteria will be largely based on that previously used by STFC, namely "α" rankings for projects/experiments and "g" rankings for science exploitation themes within grants as used in the last Programmatic Review. In addition a new "i" ranking will be introduced to cover evaluation of impact for the economy and society.

The Panel will be asked to consider the strategic value of the projects/experiments/ facilities that submitted proformas and how highly aligned they are to the mission of STFC. Consideration should also be given to the international standing and the potential for leadership of the area under review. Additional value, such as synergies within the STFC frontier science disciplines (Particle Physics, Astronomy, Nuclear Physics, Particle Astrophysics, Computing, Accelerators) programme should also be taken into account.
The Panel will be asked to score each of the projects/experiments/facilities on the following criteria and submitted 2 days before the meeting.

The Panel member should complete section 1 and 4 below for each proforma. A marking should be given for either section 2 or 3 dependent on which is most appropriate.

The below wording is generic for the six evaluations and may be slightly modified to suit the specific requirements of the individual reviews.

1. **What is the life cycle stage of the Project/Experiment/Facility?**
   Early / Developing / Mature

2. **Scientific Excellence of Project/Proposal**
   α5 - Highly innovative and very likely to result in seminal changes in knowledge.
   α4 - Likely to substantially advance the subject.
   α3 - Likely to make an important contribution to the subject.
   α2 - Competent, worthy science.
   α1 - Interesting science but outcomes considered doubtful.
   β - Poor quality, flawed or unlikely to deliver meaningful or interesting results.

3. **Exploitation**
   Projects in the science exploitation phase are funded via grant panels. Three categories are defined, intended as strategic guidance to the peer review carried out by grant panels. Please consider the value of exploitation when the area under evaluation reaches maturity.

   g3 - A project with high strategic importance in the STFC programme, which has received substantial investment. We would expect to see it adequately funded via grants after peer review
   g2 - A project with high potential for excellent science which should be considered via peer review
   g1 - A project which is not well matched to the STFC programme, we would be surprised if it were to receive funding via the grants panel.

4. Impact and Engagement

Please consider if there is important impact within industry and/or wider society that STFC should be looking to exploit and that will otherwise not happen elsewhere.

i5 - Very exciting impact already under IP management or a close working partnership or exchange with non-academic partners is already in place.
i4 - Very exciting opportunities proposed, with some first connections made.
i3 - Interesting opportunities suggested but needs significant further work.
i2 - Little opportunity, although some could evolve in near future.
i1 - Little opportunity and unlikely to develop significantly in near future.
i0 - No apparent opportunities at all.