Balance of Programme Exercise – PPAN

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1. Executive Summary

1. This review forms part of the newly established three-yearly process to evaluate STFC's core programme. Science Board appointed a Sub Group in July 2016, chaired by Professor Richard Harrison, to assess the balance within the particle physics, particle astrophysics, astronomy and nuclear physics (PPAN) science programme as a whole, together with the accelerator and computing aspects that support this. It did not look at the skills element (i.e. studentships and fellowships) or the public engagement and innovations programmes that are funded by Programmes Directorate. The Sub Group considered the strategic direction, balance and breadth within and across the science areas for three financial scenarios (flat cash +/- 5%) but did not review individual projects. This light touch review will be followed in the intervening years before the next Balance of Programme (BoP) exercise by detailed reviews of each of the subject specific programmes.

2. Input was sought from the Advisory Panels, which provided updated roadmaps as well as answering specific questions posed by the Sub Group. Further material, background information and financial data were provided by the programme managers. Each of the disciplines was assigned expert rapporteurs to provide an overview and lead discussion. It was noted that spend across the programme had been kept within a flat budget as had future planning lines.

3. The Sub Group noted that the BoP exercise has taken place following an extended, non-indexed period of funding. The 2013 Programmatic Review[1] noted that 'flat cash would result in a cumulative 37% reduction in volume if extended over the next four years'. A flat cash environment, imposed on the programme over many years, clearly erodes the UK's ability to deliver broad and high quality science, and to maintain leadership in instrumentation, facilities and exploitation. It has a significant and adverse impact on the UK's underpinning scientific output. It risks disadvantaging the UK's position and reputation on the international scene. It erodes the knowledge-base on which we should anticipate future UK economic and academic returns. In terms of the current BoP exercise, it is important to stress that we are considering a programme that is already under extreme pressure and has lost opportunities and encountered restrictions on its ability to maintain and develop the UK's scientific strengths for some years. Whilst the exercise identifies excellent science in the UK, makes recommendations on a number of key issues, and considers financial scenarios, it must be remembered that this is addressing a programme that cannot be stretched much further.

4. The Sub Group found that all areas support only excellent science and had equally felt the impact of long-term constrained finances. It was noted that STFC is unable to fund

[1] http://www.stfc.ac.uk/files/programmatic-review-report-2013/

additional, internationally-leading science proposals, and this constrains programme breadth.

5. The Sub Group noted that the consolidated grants, which fund exploitation, blue skies research and in some fields core support for construction projects, were identified as the highest priority by the Advisory Panels. This position was endorsed by the Sub Group, which noted the continuing reduction in the effort that could be maintained by these grants.

6. The Sub Group saw no reason to propose major change to the balance but does recommend modest modifications in response to the pressures resulting from the evolutionary changes in the science programme. Several high-level findings requiring action were noted; for Computing support, where demands are growing rapidly, Particle Astrophysics, which is an emerging field that needs to mature into an established element, Nuclear Physics, where support is at a critical level following a poor settlement in the last consolidated grant round, and Accelerator physics, which is also seen to be at a critical level.

7. The Sub Group considered the financial situation of the three funding scenarios. It noted the pressures and the need for continued tensioning within the subject areas, which should be considered in the subject-specific reviews. It recommended modest additional support for Nuclear Physics to provide an appropriate level of PDRA funding, a modest increase to Computing to cover the cost of the PRACE subscription, and additional support in Particle Astrophysics to maintain gravitational waves funding at flat cash. The Accelerator science programme is also identified to be at critical level and it is recommended that a modified funding model for that area be adopted. The Sub Group recommended a temporary suspension of the Project Research and Development (PRD) programme, to create some headroom in the PPAN programme, of no more than two years, as this could potentially cause increased risk to essential technology development over time. In the flat cash minus 5% funding scenario the Sub Group recommended cuts associated with reducing, or stopping, participation in planned construction projects to protect committed project funding and maintain the consolidated grants at the current level. These have been eroded by inflation during years of flat-cash budgets and protection will minimise any further loss of scientific leadership and reduce risks that previous project investment will not be exploited. In a flat cash plus 5% scenario PRD should be restored and all areas should receive some share of the uplift.

8. The Sub Group noted that this review can only be a snapshot and that external factors such as the Global Challenge Research Fund and loss of European Research Grants, will have an impact that will need to be monitored and assessed by future reviews.

9. STFC's science programme is providing critically-important support for the UK's world-class research across the disciplines. The Sub Group submits this report as a strategy to steer the current programme in a way that is best suited to the current and near-future evolution of the UK's research community across those disciplines.

2. Introduction

10. The purpose of the BoP exercise is to define a balanced programme of excellent science within a constrained financial planning envelope.

11. In December 2015 STFC's Executive Board discussed and agreed a new process for evaluating STFC's core programmes. Executive Board are responsible for the overall balance of the programme and will receive advice on the future direction etc. through both individual programme evaluations and through financial information based on the strategic financial planning. As part of this process, it was agreed that, every three years, Science Board will consider the balance within the PPAN programme (excluding studentships), Innovation Advisory Board (IAB) will review the balance within the innovations programmes, and the Skills and Engagement Advisory Board (SEAB) will review the balance of the skills (including studentships) and public engagement programmes.

12. Accordingly, a Sub Group of Science Board was tasked with reviewing the balance of the programme within the PPAN element of the core programme during 2016. In particular, this current review aims to ensure that STFC is in a good position to make the strategic decisions needed after the 2016 spending review. The programme under review includes not only the four PPAN programme disciplines:

    - Particle Physics
    - Nuclear Physics
    - Particle Astrophysics
    - Astronomy

    but also:

    - Accelerator programme for the above disciplines
    - Computing programme for the above disciplines

13. The review does not include the skills element of the programme (i.e. studentships and fellowships), public engagement or the innovations programme.

14. A flat cash environment places great pressure on STFC's programme, and STFC Executive Board needs to be well informed to make any challenging decisions. At the time of the 2013 Programmatic Review it was stated that continuation of flat cash without indexation beyond the Comprehensive Spending Review (CSR) in 2015 would require further decisions as the programme had been developed under the assumption that beyond 2015/16 constant volume would be sustainable i.e. that there would be an increase in budget above flat cash. However, the resource allocation from the Department for Business, Energy and Industrial Strategy (BEIS) in 2016 which gave firm allocations for the period 2016/17 and 2017/18, and indicative allocations for the

period 2018/19 and 2019/20, remains flat for all four years and capital will be flat until 2019.

15. Excellent science is conducted and delivered across the PPAN programme. All areas have suffered from the reductions in funding. There are no longer any easily identified areas for reduction that do not impact core science output, and many new opportunities for investment in internationally-leading science cannot be realised within the current budgets. It is recognised that areas grow at different rates and the approach of each subject area to optimise its activities to produce this excellence is based around the strengths of its community. It is not beneficial to abandon this tailored approach.

16. STFC PPAN Research funding is mainly supported by two types of grants: consolidated grants and project grants. Consolidated grants last three years and mainly support science exploitation and blue skies research in universities and other research groups. The subject areas approach this in different ways; Particle Physics and Nuclear Physics consolidated grants include a mix of both exploitation and core support for construction/R&D projects, and the entire programme is reviewed every three years[2]. Consolidated grants for Astronomy are only used for exploitation as development and construction projects are funded separately: the entire programme is reviewed over three years, with around one third of the community reviewed each year. In all areas consolidated grants have remained at flat cash since the 2013 Programmatic Review, causing considerable strain in maintaining world-class exploitation programmes. Project grants last until the end of the period for which the award was made, typically 3-4 years, and support projects that are considered to have significant scientific priority across the PPAN areas.

17. Another STFC source of PPAN funding is through PRD[3] grants. These provide funding for generic small scale R&D projects which enable STFC to deliver the science programme objectives in the PPAN areas. PRD funding is limited with an approximate budget of £1.2M/year to fund several short-term projects (~2 years in duration). PRD funding is an important tool within the PPAN areas, as it provides breadth to the programme by allowing early investigative work.

18. The PPAN planned resource budget for 2017/18 is ~£107M (including PRD and Accelerator science). Figure 1 shows the split across the PPAN disciplines in 2017/18. Pie charts representing the balance and breadth of each subject area in 2016/2017 can be found in Appendix 6.

[2] Reviewed a year in advance of the end of the grant to allow for a four year planning horizon.
[3] http://www.stfc.ac.uk/funding/working-with-industry/project-research-and-development-scheme/

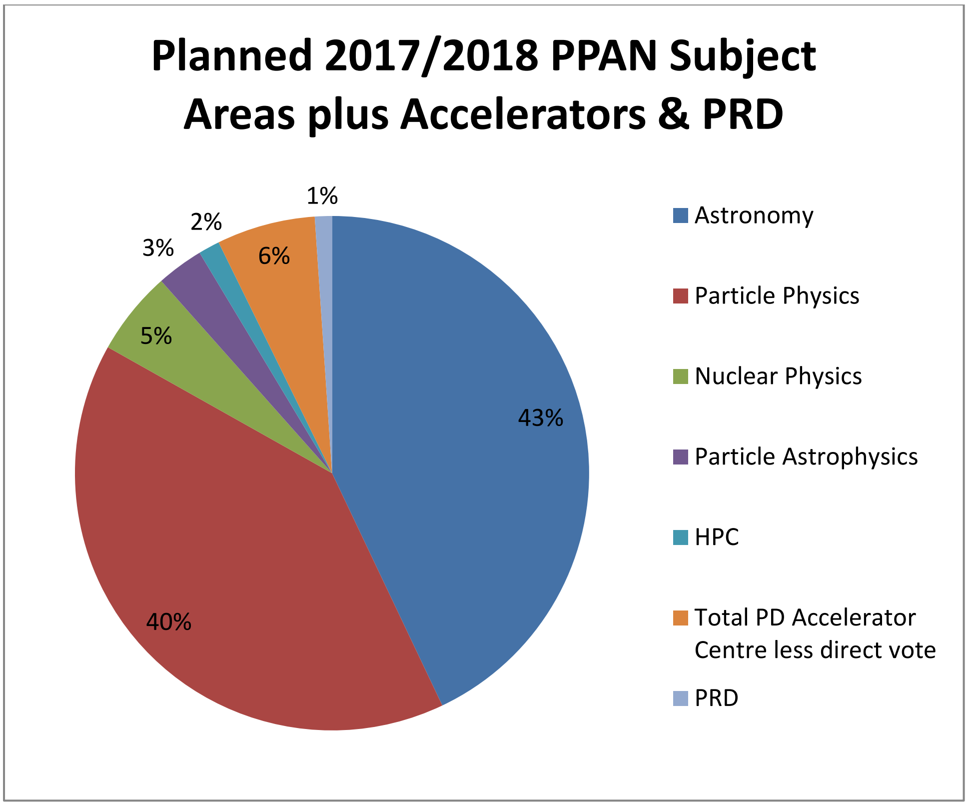

Figure 1. Resource planned spending breakdown in 2017/2018 for PPAN subject areas plus accelerator science and PRD (as of October 2016)

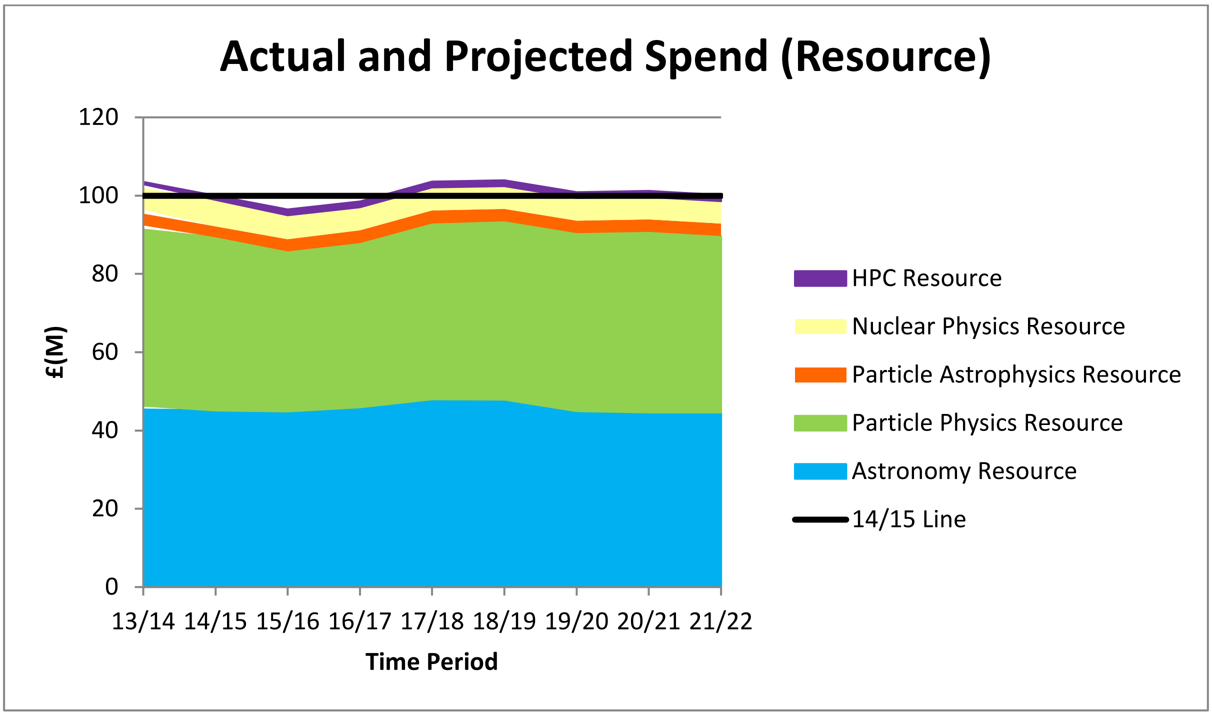

Figure 2. Resource actual and planned spend for PPAN subject areas (does not include accelerators or PRD) (as of October 2016)

19. Figure 2 represents the actual and planned resource costs for the PPAN subject areas between 2013/14 and 2021/22. The graph does not include accelerators as this was not included in the 2013 Programmatic Review for PPAN. GriddPP support is folded within the particle physics programme.

20. The 14/15 line represents the flat funding allocation awarded after the 2013 Programmatic Review. This line therefore represents the anticipated level of flat cash for the future programme at that time. The Sub Group noted the assumptions that dictate the profile of Figure 2. In addition, the Sub Group noted the intention to maintain an overall flat cash budget.

21. To achieve the objective and keep the STFC PPAN science programme within a flat cash environment, the BoP exercise examined the appropriate balance between subject areas and between R&D, construction, operations and exploitation (and how that can be adhered to in a flat cash environment). Its findings will inform planning decisions and aid STFC in the planning and implementation of its strategic priorities.

3. Balance of Programme Exercise Process

22. The BoP exercise is an evolution from the previous Programmatic Review in 2013. The current exercise carried out a general review of the PPAN subject areas and the related computing and accelerator areas, examining the strategic direction, balance, breadth and distribution in each area, as well as providing financial scenarios of flat cash, +/-5%. It did not review individual projects.

23. This is not a peer review process but a light touch review that provides a strategic framework in which peer review decisions can be made. The Terms of Reference can be found in Appendix 1.

24. The BoP exercise began in July 2016. The duration of the BoP exercise was governed by the need to present findings and recommendations to Science Board at its first meeting in 2017.

25. <u>Members of the Science Board Sub Group:</u>

Professor Richard Harrison, STFC RAL Space (Chair)
Professor Tara Shears, University of Liverpool (Deputy Chair)
Professor Gary Barker, University of Warwick
Professor Stewart Boogert, Royal Holloway University of London
Professor Peter Clarke, University of Edinburgh
Professor Antonella De Santo, University of Sussex
Professor Janet Drew, University of Hertfordshire

Professor Simon Hands, Swansea University
Professor David Ireland, University of Glasgow
Professor Bob Nichol, University of Portsmouth
Professor Alberto Vecchio, University of Birmingham

26. Schedule of meetings:

15 August 2016	First BoP Sub Group teleconference
21 September 2016	Second BoP Sub Group teleconference
17-18 October 2016	First Sub Group meeting, Swindon
28-29 November 2016	Second Sub Group meeting, Swindon
17 January 2017	Third Sub Group teleconference
February 2017	Report findings to Science Board

27. Members reviewed all PPAN science areas and the related computing and accelerator programmes, to allow for collective decision making. Each area reviewed was also allocated rapporteurs to provide an overview and to lead discussions in that area.

28. As this is a strategic exercise where neither funding nor peer review took place it was not felt necessary for any member to be removed from the discussions. The members were mindful of their interests and any discussions at the level of projects where a conflict of interest occurred needed to be declared. Each member provided a short biography of their expertise (Appendix 2).

29. The reports for the Long Baseline Neutrino Experiment Review and the LHC Detector Upgrade Tensioning Review –ATLAS/CMS Phase II Upgrades were reviewed during this exercise. Conflicts of interest were noted and can be found in Appendix 3 along with the list of documentation reviewed.

30. Although the exercise involved no direct community consultation, community input into the review was deemed necessary to inform the Balance of Programme Sub Group in its deliberations. This was done through STFC Advisory Panels, specifically through responses to a set of questions (Appendix 4).

31. The chairs of the Advisory Panels were invited to two teleconferences with the BoP Chair and Deputy Chair. The first was held on 28 July 2016, to help with any questions or concerns the Advisory Panels may have had. The second teleconference was held on 26 October to seek any clarification or input from the Advisory Panels before the final BoP meeting on 28 and 29 November.

32. The first BoP meeting allowed the Sub Group to discuss and understand the different PPAN areas and the financial constraints and implications on each area. The Sub Group had received information from programme managers, updated roadmaps from the Advisory Panels and their responses to the questions. In the second meeting the Sub Group evaluated the balance within and between each area, provided financial

scenarios of flat cash and +/- 5% flat cash and identified the recommendations that follow.

4. Subject Areas

33. The PPAN programme is driven by STFC's science priorities, which are identified by the key science challenges listed at https://www.stfc.ac.uk/research/science-challenges/. In Appendix 5 the specific challenges that are addressed directly by each of the PPAN disciplines, which we discuss in turn below, are identified.

4.1 Astronomy (including Solar System)

A. Overview of Programme

34. The Astronomy programme is supported by two Advisory Panels, namely the Astronomy Advisory Panel (AAP) and the Solar System Advisory Panel (SSAP), in recognition of its two active, but distinct, research components. The programme serves a large UK research community that plays pioneering, leading and innovative roles on the international stage, and has a long-standing heritage. Research in astronomy is conducted via a wide range of space-based and ground-based instrument development, and operation and exploitation projects. The UK's main observational and experimental interests in this area are covered by membership of the European Southern Observatory (ESO) and the European Space Agency (ESA). On the ground, ESO offers critical optical/infrared and sub-millimetre telescope access for UK astronomers, whilst in space the ESA missions (e.g. Planck, Herschel, Gaia, XMM, Solar Obiter, Cluster) support a number of key lines of UK space science research. These subscriptions also support astro-particle activities.

35. The challenging scientific and technological aspects of the astronomy programme provide excellent opportunities for the UK's high-tech industries as well as an environment for the training of highly-skilled scientists, technologists and engineers.

36. Funding for astronomy is complex, due to the division of responsibilities between STFC and the UK Space Agency (UKSA). STFC funds the development and operation of ground-based astronomy projects, through the PPAN programme, whilst UKSA funds the development and operation of space-based astronomy projects. However, all astronomy exploitation (other than some aspects of planetary research which are covered by UKSA for the ESA Mars exploration programme) and novel technology funding is in the remit of STFC.

37. The current PPAN programme carries astronomy costs of £59.4M, which break down as half for exploitation grants (£29.7M/year), and the rest for development

(£22.2M/year) and operations (£7.6M/year). In the development area, funding for SKA (radio astronomy) and E-ELT (optical/infrared) are the two major components, accounting for 45% and 37% respectively. The operations element, the smallest part of the overall budget, reflects a similar split with radio astronomy accounting for 51% of the spend, while a spread of optical/IR facilities accounts for 40%.

38. According to current plans, the astronomy budget remains close to flat cash except for a minor uplift in spending during 2017/18 due to commitments to the instrument research and development costs of the E-ELT (ESO's 30 metre optical/IR telescope), as well as the profiling of funding for the MOONS and DESI projects and, in a small part, to preparation funding for ESA's Cosmic Vision programme. A reduction back to flat-cash in 2019/20 is expected because of the removal of the organisation charge and lease for the SKA (which will then be covered out of subscriptions), the completion of critical multi-object spectrograph projects underway (MOONS, DESI, WEAVE), and the removal of the Liverpool Telescope (LT) which is partly off-set by the full operations payment to the LSST.

39. With regard to space-based projects, the marriage of UKSA hardware development and operation and STFC exploitation, for space-based projects in the astronomy area demands a close collaboration between the two funding agencies, and any consideration of the balance between the investment in development, R&D, operations and exploitation requires an assessment of the contributions from each (see sub-section E).

40. The exploitation element of the astronomy budget services a huge range of astrophysical phenomena, encompassing the Solar System, exoplanets, stars, galaxies and cosmology. The overall size of the research community bidding into the Astronomy Grants Panel (AGP) for support has increased causing intense pressure on exploitation funding. Evidence of the competitiveness of UK astronomy, and of the recognition of the need to seek funding from sources outside the highly stretched AGP line, can be derived from the high success rates in gaining ERC grants in recent years (more applications are submitted from the UK and are awarded than for any other eligible nation[4]), and in the continuing high standings in leading journal citations[5]. Nevertheless, signs of strain are becoming apparent in publication statistics that suggest a reducing capacity for international leadership[6].

41. An important consideration here is the withdrawal of the UK from the European Union (EU), as this creates the prospect of further pressure on exploitation grants. UK researchers have done particularly well in recent years in winning EU funding, especially European Research Council (ERC) grants. The removal of such EU funding

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4 See https://erc.europa.eu/projects-and/results/statistics PE9 under physical sciences covers astronomy.

5 UK authors are 2nd only to the USA in the Thomson-Reuters "highly cited researchers" list.

6 Data supplied by OUP/MNRAS (A. Leary) for the last decade show that UK researchers continue to co-author papers at a nearly constant frequency relative to international competitors. But there is a noticeable decline in the share of first authorship: this has declined steadily from 26% in 2006/7 to 18% in 2014/15. MNRAS is the main astronomy journal used by the UK community, including some aspects of Solar System science.

would mean that the community successfully bidding into EU schemes will return to seeking STFC funding instead: for example, 67% of existing ERC grants in the PPAN area are astronomy related, and amount to an annual income in the region of £20M per year[7]. We must recognise that the potential impact is huge but is difficult to assess quantitatively until the final details of the UK's EU departure are known.

42. The Sub Group feel that the overall balance of the programme is about right, and just adequate in breadth. There are however signs that UK scientists do not have the resources needed to lead in the key scientific exploitation of the large, international projects we are involved in - often known as the 'batteries not included' problem. This situation appears likely to get significantly worse with the UK's withdrawal from EU membership.

R1: **<u>Recommendation</u>: In line with the 2013 programmatic review, we recommend that the present level of exploitation funding for astronomy is maintained (flat-cash) even to the detriment of other areas of R&D and operations. This is consistent with the clear message coming from the community.**

R2: **<u>Recommendation</u>: Noting the potential impact of the loss of ERC funding to the astronomy exploitation programme, we recommend that this significant risk be monitored carefully as the UK transition to non-EU membership is completed, and action be taken by STFC as required.**

B. Changes to Science Priorities since the 2013 Programmatic Review

43. Since the 2013 Programmatic Review, there have been a number of changes to science priorities due to discoveries, evolution of the programme and in response to new opportunities. This is illustrated by the following examples. There has been a significant rise of UK activity in research linked to exoplanets (not mentioned in the 2013 document), while in 2015 the first clear detection of an astronomical gravitational wave source was announced. The UK has successfully bid to host the international headquarters of the ambitious SKA project – a new radio facility that has benefited from additional government BIS/BEIS support and an injection of capital funding. On the Solar System side, there has been growing interest in the impacts of space weather in the UK (e.g. hazards due to extreme space weather are now highlighted on the national risk register of civil emergencies[8]) and within ESA (through its maturing Space Situational Awareness programme, to which the UK is the largest contributor[9]).

7 http://cordis.europa.eu/home_en.html

8 National Risk register of Civil Emergencies, 2015, Cabinet Office publication, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/419549/20150331_2015-NRR-WA_Final.pdf.

9 https://www.gov.uk/government/news/uk-commits-to-european-collaboration-on-science-and-exploration-satellite-technology-and-services

44. With regard to exploitation funding, astronomy is by definition a broad subject – the study of everything in the Universe outside the atmosphere of Earth. It is therefore unsurprising that the UK astronomy community is likewise broad; studying the Universe over a vast range of physical scales, densities and temperatures. Astronomy demands access to a wide range of facilities and techniques, often used in combination, and this is reflected in advice from the Advisory Panels giving preference to general multi-purpose facilities (e.g. ESO, LSST, SKA and ESA's space observatories). This breadth is also reflected in the range of projects funded by AGP and the continued desire by the community to maintain that breadth of support.

45. Pressure on the grants line remains high, and is driven not only by the breadth of the programme it serves, but also by sustained growth year on year in the size of the UK astronomy research community. This growth is fuelled partly by healthy undergraduate recruitment to physics departments with significant astronomy groups. The breadth of science encompassed by astronomy and space science, results in a community that covers a range of needs from engagement in small projects to large international collaborations. AGP must serve these diverse needs and timescales. Given this diversity, it is important AGP ensures an efficient process for all. We support AGP's principle of funding the best science, and suggest it considers if there are ways to improve community coordination around the structure of peer review for large projects.

R3: **<u>Recommendation</u>: We support AGP's core principle of simply funding the best, most timely, science. However, we encourage AGP to continue to critically assess projects within the context of the breadth and quality of science that comes before it, noting that the structure of peer review could become more efficient if, for larger projects, there were better use of community coordination.**

46. The operations spending for ground-based astronomy has been kept under control, despite the in-roads of inflation, thanks to the recently completed UK withdrawal from the ownership of the island observatory sites, which started some years ago. The development funding profile has been carefully managed since 2013 to avoid a concentration of astronomy facilities to only the SKA and ESO's E-ELT. This has been possible because of the slower than expected ramp-up of the development costs for these major facilities. Smaller international projects like MOONS (IR), WEAVE (optical), DKIST (solar) and NGTS (exo-planets) have all received investment as a result. It was also possible to reverse reductions in e-MERLIN and removal of support for LT operations. Looking ahead, this creates pressure in the case of continuing in a flat cash environment.

47. A deal to join the LSST, now in its construction phase, was brokered on behalf of the UK community and we now need to consider the financing of the membership fee[10]. SKA and E-ELT spending will continue to be prominent in anticipation of operations in

10 R&D spend has already started.

the 2020s. Whilst there is no expectation of major new builds for either exoplanet or gravitational wave science over the next few years, the former will certainly gain momentum from the flow of Gaia data (a mission set to make a fundamental breakthrough in the astronomical distance scale) and the launch of the NASA/ESA JWST in 2018. Likewise, Euclid - ESA's upcoming dark universe mission - will fly in 2020 and there are on-going discussions about the future of Cosmic Microwave Background (CMB) research. This new science will flow through as continued pressure on AGP, as indeed is already the case for spending on gravitational wave science: some active groups in this particular area already choose to seek, and receive, support through AGP rather than via the Particle Astrophysics funding line. Indeed there are signs that the roles of AGP (expected to fund theory relevant to the production of gravitational waves and the search for counterparts) and of the Particle Astrophysics funding line (expected to fund experimental/facility development) have started to blur (see the Particle Astrophysics section).

48. On the Solar System side, a number of (UKSA-funded) instruments are being developed for missions such as Solar Orbiter, BepiColombo and JUICE, targeting research in solar physics, Mercury and the Jovian system. The next generation of instruments are being proposed for the ESA Medium mission opportunities (M4 and M5), including the impending selection of the M4 mission, where two of the three contenders have considerable UK interest (ARIEL, an exoplanets mission with a UK Principal Investigator (PI), and THOR, a magnetospheric mission). Exploitation of these new missions will supersede some present Solar System research and continue to make demands on the AGP line.

49. The AAP and SSAP have both renewed their top ranking for the protection of exploitation funding. The AAP also continues to associate highest priority with the UK's membership of ESO, giving access now to the sub-millimeter array, ALMA, as well as to the VLT and the survey telescopes. Both panels also identify high-performance and high-throughput computing (HPC and HTC) as top priority on account of their key role in enabling theory, simulation and observation data processing/mining. Today's astronomy is very much in the vanguard of 'big data', and rests on good access to advanced HPC/HTC facilities. There is an awareness that past arrangements cannot continue e.g. DIRAC-3 justifies some support from the astronomy line. In addition, the recent UKT0 initiative is viewed very positively: this may in time fold in some of the advanced processing activities seated within astronomy data centres, possibly including the well-regarded wide field units.

R4: **Recommendation: We recommend that STFC pursue new money for new investments in computing infrastructure, which remains fundamental to a wide range of observational and theoretical astrophysics. If UKT0 is successful, then STFC should review the role of the wide field astronomy units in relation to such a potentially PPAN-wide initiative.**

50. The E-ELT and SKA are acknowledged as critical developments for the future, and support for instrument development at current levels is ranked high priority by the AAP, a rung below the top. As a reflection of the diversity innate to astronomy, the same high priority is attached to the suite of smaller development projects as well as to LSST membership – a new opportunity involving all astronomy groups across the country. On the next rung down, the AAP report places the continued operations of e-MERLIN, LOFAR (both radio) and LT (optical time domain) at medium priority. This view makes sense given that the research communities using these facilities are respectively looking forward to the large SKA, and financially more modest LSST, investments in the future. In the case of radio astronomy, it can be argued that the total cost to STFC is now high relative to the overall volume of activity and UK interest in the area.

51. Further planning challenges raised by the astronomy programme managers are: uncertainties in local SKA costs created by delays; the planning assumptions of adding 2nd generation instrumentation to the E-ELT R&D budget; assuring the computing needs for theoretical and observational astronomy and the Solar System programme. There is awareness on all sides that present arrangements are not sustainable into the future.

C. Critical Decisions

52. In March 2018, the contract between STFC and Jodrell Bank in respect of e-MERLIN operations comes to an end, and a decision on bridging funds will be needed by then. If this is not enacted, radio interferometry within the UK is no longer supported, and continued involvement in observations of this kind in the run up to SKA may only proceed through international facilities (e.g. the VLA, the SKA pathfinders ASKAP, MeerKAT). STFC will also need to decide on the continuation of LOFAR by mid-2018.

53. Over the next two years, there will be significant milestones for the SKA, including convention signing (Q1 2017), construction phase approval (2018) and Critical Design Review (CDR) for Phase 1 R&D (Q1 2018). As seen in the past, there could be significant fluctuations in the astronomy budget caused by unexpected costs and slippage of this high profile experiment.

R5: **Recommendation: We recommend an immediate review of UK involvement in all on-going, and planned, radio facilities and experiments (including UK leadership of MeerKAT and ASKAP radio surveys) to create a strategic roadmap for radio astronomy towards the SKA era. This review, in consultation with the radio community, should assess and tension the range of facilities available to UK astronomers and determine the key SKA 'pathfinders' (surveys and telescopes) in preparation for the main UK-led SKA science.**

54. On the same timescale, continued operations support for the LT is up for review: this item is worth £0.25M/year compared with £2.0M/year estimated for e-MERLIN. If LT operation support were cancelled, the UK community would lose access to a robotic telescope dedicated (uniquely) to time domain astronomy – a science area highlighted as a priority in the AAP report. A decision will also be needed about NGTS operations and other modest support functions (e.g. Gaia data centre, future CMB experiments) in early 2018.

55. In 2018 and beyond, there are several key decisions that will shape UK astronomy into the next decade. As noted above, preparations need to be made for the 2nd generation of E-ELT instruments and funding may be required to ensure UK leadership roles in the R&D of at least one of these instruments (UK has leadership in two existing instruments, MOS and HiRES). Opportunities to bid for VLT instruments and ALMA development are also expected in the next 2-3 years. On a longer time-scale, exploitation of key projects like Euclid and LSST will put significant demands on the grants line and our computational resources (e.g. data centres and HPC). In addition, it is anticipated that funding will soon be sought for UK involvement in the European Solar Telescope (EST). Investing in these opportunities will be challenging in a flat-cash environment.

R6: **Recommendation: We recommend that STFC seeks possible savings within the R&D budget for E-ELT instrumentation. It is not seen as a high priority that the UK should aim for leadership in more than one 2nd generation E-ELT instrument, given the present large cost and schedule uncertainty.**

56. On the space-based instrumentation side, 2017 will see ESA's selection of the M4 mission (three missions are still in the frame, including ARIEL and THOR, with considerable UK interest). We also look forward to the subsequent ESA M5 opportunity, which is being targeted by a wide range of potential projects of UK interest. In parallel, the community retains a strong interest in bilateral missions for future years that address areas of strong scientific interest to the UK.

D. Impact of flat cash plus +/- 5% flat cash

57. With regard to ground-based astronomy, the development programme has avoided crisis in the last few years because of below-profile spending on E-ELT and SKA development – the big ticket items in the astronomy development budget. This will not continue and therefore there is little flexibility for starting new R&D projects in the near future. This is a bleak outlook for instrument builders in the UK and is critical for the handful of world-class astronomy instrumentation groups in the UK. STFC will need to monitor carefully the impact this may have on UK talent in advanced technology development; a key selling-point for BEIS funding.

58. Exploitation funding has remained flat for many years while demands on the funding have risen, and are likely to continue to rise as current ERC grant awards complete and are not replaced. There is a continued squeeze on academic applicant full time equivalent (FTE) costs; academics are now typically awarded 5% to 15% (with 40% of applicants given zero). The situation will deteriorate as new claims are made on AGP funding by an enlarged pool of applicants continuing to propose world-leading science exploiting gravitational wave facilities, E-ELT, LSST, SKA and ESA missions in the future. Continued flat-cash for exploitation funding is regarded as the barest minimum for continued viability of the overall programme under all scenarios. In the +5% scenario, the uplift would be used to maintain the volume in the exploitation programme, helping to preserve the breadth of the programme and to ensure that previous investments in development projects are exploited.

59. Noting the growing demands on the exploitation programme (the highest priority for AAP and SSAP) and the need for better provision for HPC/HTC computing, it was recognised that the current harsh environment places additional pressure on R&D and/or operations support. Looking ahead, only projects sharing costs internationally, at the price of lower overall facility access, appear feasible. Accordingly, in either flat cash, or -5%, the area of spend to re-examine lies in (i) the 2nd-generation E-ELT instrument programme (given that the 1st generation programme is already committed and underway), and (ii) the overall radio astronomy facilities budget.

60. The funding scenarios that the above paragraphs indicate, are the following:

- **Flat cash:** In this harsh environment, as a top priority we recommend holding exploitation grants at the same level as the last 3-year AGP cycle; this is a common view expressed by the community and the Advisory Panels. We also see the need to fund adequate computing resource for HPC and HTC and recognise that a contribution to this from the astronomy line would be justified. We hope new funding from BEIS can be found to alleviate this problem. Given that grants are to be protected, any savings necessary to support HPC/HTC computing should be sought from uncommitted E-ELT instrumentation and a strategic tensioning of radio facilities available to UK astronomers (recommendations R5 and R6).

- **-5%:** Even in this very harsh environment, we recommend holding the exploitation grants at flat-cash (as above) as this is the top priority of the whole UK astronomy community. As noted in the AAP report, we would suggest deeper savings within the E-ELT instrument budget and/or through further tensioning of radio facilities. We recognise that this would jeopardise long-term UK investments and global leadership in key areas of astronomical research e.g. E-ELT and SKA.

- **+5%:** As recommended in the 2013 Programmatic Review, any extra funding should be used to increase exploitation funding. This would help restore the erosion of many years of flat-cash on the AGP grants line and foster greater capacity to regain UK science leadership in many areas of astronomy.

E. Relationship with UKSA

61. As stated earlier, the development and operation of astronomy facilities and instruments in space is usually split between STFC and UKSA (while exploitation funding always remains in the STFC remit, except for some elements related to the Mars exploration programme). This 'dual-key' approach appears to be working but there are some concerns. For example, STFC has Advisory Panels driving strategy within the disciplines, which are not fully integrated into the assessment and decision making processes of future projects. Discussion on tensioning any proposed project with upcoming projects and opportunities that only the communities, through their advisory bodies, can really address fully is critical in delivering STFC science. STFC interfaces with the PPAN disciplines through its Advisory Panels, which could be integrated into the mission acquisition, approval debate. Even if the current structure and processes are working, the process has the potential for UKSA to fund missions that STFC does not really see as the highest priority. This is not a criticism of any party, but an observation that might suggest a need for an improved joint process.

62. One concern is with the securing of new missions beyond those currently under development, especially beyond ESA. The UKSA priority is for involvement in ESA missions, seeking the best return on the UK subscription. However, the UK astronomy and solar system community has scientific strengths that some would argue are not sufficiently supported by the relatively few launches by ESA in any particular discipline, and we have a heritage with active involvement in seeking new missions not just through ESA, but also NASA and JAXA. To support the UK's scientific world-class strengths we must look at securing hardware roles in missions with, and beyond, ESA, including NASA and JAXA. In particular, the AAP and SSAP have called for recognition that the UK should engage in bilateral missions.

R7: **<u>Recommendation</u>: We recommend a review of the working relationship between STFC and UKSA to ensure an appropriate balance of support to the elements of the space-based projects and to ensure that the best processes are in place for an integrated approach to project selection and approval, development and exploitation.**

4.2 Nuclear Physics

A. Overview of Programme

63. Nuclear physics research is concerned with the study of the strong nuclear force, and the observed strongly-interacting particles. It comprises a wide range of phenomena, from the structure of nucleons to the limits of existence of nuclear species, and from the origin of the elements in nucleosynthesis to their role in the evolution of the Universe. Nuclear physics also studies how collective phenomena emerge from the interactions of the basic constituents.

64. The nuclear physics scientific activity supported by STFC currently comprises two broad topic areas: i) Stable, Unstable and Exotic Nuclei, and ii) Hadronic Constituents. This categorisation is based upon the type of accelerator facility that is required for the different experimental programmes.

65. The former area requires a wide range of beams of stable and unstable isotopes, and this is reflected in the need to carry out experiments at many different laboratories[11], each of which offers a different configuration of beam species, energies and intensities. Hadron physics experiments generally require higher energy facilities[11] that deliver beams of electromagnetic probes, or heavy ion collisions at relativistic energies.

66. From 2025, the new Facility for Antiproton and Ion Research (FAIR) at Darmstadt, Germany will start to operate. There are four main areas of research covered by FAIR, of which one (Nuclear Structure, Astrophysics and Reactions – NUSTAR) has STFC funded UK involvement.

67. In addition to this, a small theoretical community carries out work on a range of topics including effective field theories, nuclear reactions, density functional theory and correlated nuclear matter. Whilst funded through the Particle Physics Theory grants panel, theoretical work in Lattice QCD has direct relevance to the hadron physics programmes.

68. In addition to fundamental physics research, members of the nuclear physics research community engage in high-impact activities, such as: industrial nuclear data measurements (funded in part by STFC through the Nuclear Data Network under its Global Challenge Network Funding scheme), public engagement/outreach, and several applications and innovation projects, such as the development of detectors for healthcare, security monitoring and nuclear decommissioning[11].

69. Whilst a relatively small community compared to countries with similar aspirations, UK nuclear physics enjoys a high international reputation, in part due to the number of

[11] For a detailed list, see the NPAP Roadmap of Nuclear Physics.

laboratories at which projects are carried out, and the associated network of collaborators, but also the UK's highly valued core instrumentation development expertise funded through the consolidated grants. Citation indices now place the UK as number 1 for nuclear physics[12]. The UK was also recently awarded the 2019 International Nuclear Physics Conference, the world's biggest nuclear conference.

70. The budget for Nuclear Physics in 2015-16 was approximately £6.2M/year, and is currently projected to run at around this level for the period until 2021-22. Of the current £6.2M total, £4.2M/year (68%) is for consolidated grants and covers both exploitation (operations and analysis) and some development activities (the cross-community instrument development support). Project grants are funded at £1.55M/year (25%), £0.15M/year (2%) is for subscriptions and maintenance and operations (M&O), and £0.3M/year (5%) goes on capital. This funding supports 52 out of a total of about 65 academics, although some funding is at the level of only providing modest travel funds, reflecting the need to travel to undertake research in this area.

71. The biggest issue facing Nuclear Physics is the limited number of posts that can be supported on the consolidated grants. The previous Nuclear Physics Grants Panel (NPGP) round was required to make a 12% reduction in total FTE numbers for post-doctoral research assistants (PDRAs) (from 18.3 to 16.1 FTE) and a 15% cut in cross-community engineering/technical support FTE (from 12.1 to 10.3 FTE[13]). The number of core posts remained about constant (8 FTE). The reduction was attributed to the flat cash settlement imposed by Council (whereas the 2013 Programmatic Review had recommended maintaining volume), and an over-commitment from the previous consolidated grants round.

72. Recognising that this would lead to a major loss of expertise and research capability, the NPGP reduced the length of supported PDRA posts from 38 months to 30 months, in order to maintain the number of posts as far as possible. Principal Investigators have had to work out how to manage the shortfall, and this has been achieved largely because of the expectation that the next consolidated grants round would be able to revert to fully funding the volume of posts. However additional funding sources, such as EU grants, and goodwill arrangements to support PDRA posts locally are running out. A similar issue with the funding of cross community posts was ameliorated by the award of three STFC grants (ALICE upgrade, ISOL-SRS and JLab upgrade), where some cross community posts that would normally be fully covered in the consolidated grant were partially funded from the project grants.

R8: **Recommendation: We note that Nuclear Physics currently has a critically small level of support. For the 2017 grants round review in process, we recommend that additional funds be used to enable the restoration of fully-funded PDRA positions to the level of the 2011 grants round.**

[12] STFC Impact Report 2015.
[13] These numbers reflect a changing fraction in cross-community support that was supported from the Consolidated grants line. The shortfall was obtained through project grant funding.

73. As mentioned above, for some of the posts in the consolidated grants round, such as core and cross-community posts, the shortfall in funding was made up by additional support from the new project grants. However, this meant that the cross-community effort was overloaded, and was not able to support the full requirements of both the exploitation and the new project programmes.

74. Given the issues mentioned, the balance between exploitation grants and construction projects is currently around 3:1, when small-scale construction of new equipment in consolidated grants is taken into account. A more healthy balance is generally held to be around a ratio of 2:1, but there is a strong steer from the community that, given the extremely challenging financial constraints, a period where the consolidated grants line is maintained at the cost of the new projects line would be preferred[14].

75. The UK portfolio of nuclear physics research is relatively diverse. Significant contributions are made to the research programmes at several international laboratories, so the breadth of the programme is adequate. Further diversification would dilute already strained resources. The main issue is the level of support for consolidated grants required to keep the small but vibrant programme viable.

76. UK nuclear physics groups have had a good track record in attracting EU funding (FP6, FP7 and H2020). A large fraction of this funding has enabled the building of effective collaborations with networks and transnational access, and has seen UK groups attain significant positions of influence. Currently there are two ERC grants in nuclear physics held in the UK.

B. Changes to Science Priorities since the 2013 Programmatic Review

77. There have been several science developments since the 2013 review. The discovery of new heavy elements, the discovery of octupole ('pear-shaped') nuclei and the determination of the neutron skin in heavy nuclei are just three of the highlights.

78. The 2013 Programmatic Review advocated the maintenance of the capacity for research in Nuclear Physics in all the considered scenarios (+10%, approximately flat cash, -10%). It recognised that the subject, whilst still viable, was at the point where further reductions in volume of posts would result in major cutbacks in research capability. It noted that several projects were held up at the Submission of Interest (SoI) stage, awaiting the completion of the 2013 Programmatic Review, and recommended that they be tensioned and reviewed by the Project Peer Review Panel (PPRP). The process was carried out in 2014.

79. The outcome of the process was that three new projects were approved: ALICE upgrade, ISOL-SRS and JLab upgrade. These projects are now all ongoing. In the meantime, the one Nuclear Physics project that had previously been supported,

[14] NPAP Response to the Balance of Programmes Sub Group questions.

NuSTAR, came to an end in 2016. In addition to this, STFC negotiated Associate Member status for the UK at FAIR.

80. Following on from a recommendation of an Institute of Physics subject review of nuclear physics in 2012, a new Nuclear Theory chair was created at the University of York. The initiative was driven by York, but obtained matched funding from STFC to support the post for three and a half years. This has helped to revive nuclear theory in the UK, which had been at a critically small level for several years.

81. Several new international projects are foreseen on the five- to ten-year horizon[11]: an Electron-Ion Collider in the US, a Scintillator Tracking Array (STA) at RIKEN (Japan), an Advance Charged-Particle Array (ACPA) at ELI-NP (Bucharest, Romania), an AGATA Upgrade and the start of FAIR operations (now expected in 2025).

C. Critical Decisions

82. At the time of writing, there is a live consolidated grants round, assessing submissions for the consolidated grant period that begins in October 2017. The balance of funding between exploitation and new projects will be a critical factor in the award settlement, and is thus a critical decision to be made almost immediately.

R9:	**Recommendation: We recommend that in any future scenario, the current NPGP grants line be funded at a level required to support the number of fully-funded PDRA posts in the 2011 grants round. This aligns with the community-supported preference to maintain the consolidated grants at least at constant volume, at the expense of new project grants.**

83. In addition to this, the UK Contribution to FAIR must be addressed. Currently slated for a start of operations in 2025, this greatly delayed start has not been helpful in delivering the science programme that had been hoped for. However, the nuclear physics community has been agile in taking opportunities to make use of instrumentation that is destined for FAIR, such as experimental programmes at RIKEN in Japan.

84. A significant investment in FAIR by STFC has already been made, through the £8M NuSTAR project grant. This has resulted, through the provision of new equipment, in an in-kind contribution of €4.6M to FAIR. However, an additional in-kind contribution of €0.4M is required to make the total up to the stipulated €5M (at 2005 prices) for associate membership of FAIR. In addition to this, a minimum of 0.5% of FAIR operating costs would be required as a requirement of associate membership, as and when the facility starts delivering beams to experiments.

R10:	**<u>Recommendation:</u> We recommend that a review of the benefits of FAIR membership be carried out as part of the Nuclear Physics programme review in 2018, in light of delays to FAIR and the adoption of alternative facilities to exploit UK-built equipment.**

D. Impact of flat cash plus +/- 5% flat cash

85. A +5% scenario would leave enough headroom to accommodate modest new projects, provided that the timing was managed carefully, but the priority would be to maintain the consolidated grants programme at least at constant volume to avoid further eroding this critically small area.

86. Given the current status, any reduction in support in Nuclear Physics would lead to a large impact on a critically small community. Significant savings would be difficult to achieve without major reduction in PDRA numbers, resulting in a large loss of exploitation potential and will put the future viability of some groups at risk. There is also the likelihood of loss of cross-community instrument development support. Given the STFC investment in world-leading nuclear physics projects, this would be a poor return and would inevitably lead to reputational damage.

R11:	**<u>Recommendation:</u> We recognise the near-critical level of support that the nuclear community receives and wish to ensure that this is protected, regardless of financial scenario.**

4.3 Particle Physics

A. Overview of Programme

87. The particle physics (PP) programme encompasses both experimental (PPE) and theoretical (PPT) activities. In theoretical particle physics the underlying framework necessary to interpret and predict experimental results, the Standard Model, and potential alternative ‘new physics’ models that describe phenomena beyond our current understanding, are developed. In experimental particle physics the limits of the Standard Model are probed using data obtained from experiments, to search for evidence of new physics that may augment or replace it.

88. The PPE programme is closely aligned to the European Strategy for Particle Physics[15]. It supports the exploitation and development of experiments to take data at the highest energies (‘energy frontier’), perform precision measurements of particle properties

[15] https://council.web.cern.ch/en/content/european-strategy-particle-physics

(‘flavour physics’), study neutrino behaviour, and perform measurements and searches in kinematic regimes inaccessible at current accelerators (‘non-accelerator experiments’). The UK holds senior or physics leadership positions in the majority of these experiments[16]. It should be noted that much of the programme breadth is currently supported through non-STFC sources and by consolidated grant funds, which allow for a greater diversity in the portfolio than would otherwise be possible. UK groups in PPE (PPT) currently hold awards totalling approximately £2M (£5.7M) from the FP7 and H2020 ERC schemes[17].

89. In energy frontier physics the top priority identified in the 2013 Programmatic Review, and largest area of UK activity, is science exploitation of the ATLAS and CMS experiments at CERN, where the UK provides 10% and 4% of collaboration authors respectively. Upgrade programmes for both experiments are ongoing. Work continues on the next generation of energy frontier facilities; linear colliders (ILC[18] and CLIC[19]), future electron-hadron colliders (LHeC[18]) and future circular colliders (FCC[19]).

90. In flavour physics the major activity is science exploitation of the LHCb experiment at CERN, where the UK provides 18% of collaboration authors. An upgrade programme for LHCb is ongoing. The UK is also involved in NA62[18], g-2, COMET[18], and the future Mu2e[19], Mu3e[19] and SHiP[19] experiments. These dedicated experiments focus on new physics searches and Standard Model measurements specific to and accessible with different particles, that cannot be made with LHCb: kaons for NA62 and muons for g-2, COMET, Mu2e and Mu3e. SHiP is a general purpose experiment to look for evidence of new physics theories that can account for dark matter, baryon asymmetry and neutrino oscillations.

91. The main neutrino experiment in exploitation is T2K, where the UK provides 21% of collaboration authors. The UK is also involved in NOvA[18], a complementary experiment to T2K, and a number of smaller neutrino experiments which explore different aspects of neutrino behaviour (PINGU[19] will probe the neutrino mass hierarchy, microBooNE[18] and SoLiD[18] the existence of sterile neutrinos, and CHIPS[19] is a water Cherenkov detector technology demonstrator). The neutrino development programme includes support for the neutrinoless double beta decay experiments SNO+ and SuperNEMO, and the future long baseline DUNE and Hyper-K experiments.

92. Experimental support for non-accelerator physics includes the Lux Zeplin (LZ) and DEAP-3600[18] dark matter search experiments, the electron eEDM[18] experiment at Imperial College and the neutron nEDM[18] experiment that provide background-free ways to search for very high energy scale new physics. These dedicated experiments probe new physical phenomena and parameter regimes that are inaccessible elsewhere.

16 See the PPAP Particle Physics Roadmap for more information.
17 Values from the STFC Brexit working group, current for 2016.
18 Supported through consolidated grant funds.
19 Supported through non-STFC funds.

93. In theoretical physics, thematic activity is split into five areas: Quantum Field Theory (QFT), Phenomenology, Lattice QCD, String Theory and Cosmology, although for practical purposes it is convenient to consider QFT and Strings together.

94. Approximately one quarter of theory academics work in phenomenology, the area of PPT of most direct interest and relevance to PPE that supplies the majority of predictions for experimental observations. The UK community is world-leading in parton distribution functions (PDFs), Monte Carlo event simulation and precision QCD calculations, and internationally strong in model building, supersymmetry (SUSY) and Higgs physics[20]. The UK hosts a National Centre, the Institute for Particle Physics Phenomenology (IPPP) which is a centre of scientific excellence and plays a key support role for both theoretical and experimental communities[21].

95. Much UK lattice QCD (11% of academics) activity has a strong phenomenological component - there are world-leading activities in flavour physics, hadron structure, hot/dense QCD, and Beyond Standard Model scenarios for electroweak symmetry breaking. There are also international strengths in code and algorithm development, and in QCD contributions to the muon anomalous magnetic moment[18]. The field is critically dependent on HPC (DiRAC, also PRACE and HPCWales).

96. QFT/String theory forms the largest fraction (45%) of the UK theory community, a major motivation being the promise of a unified description of particle interactions and gravity. The UK has world-leading activities in M-theory, integrable systems, SUSY QFT, the gauge-gravity correspondence and advanced techniques for calculating scattering amplitudes[22].

97. Cosmology (20% of academics) enters PPT through quantum theory descriptions of the Universe's earliest moments, and from the constraints placed on modern particle theories by observation. UK cosmologists working in PPT excel on the international stage in areas such as inflation, structure formation, theories of Dark Matter and Dark Energy, and modified theories of gravity[20]. The field is also critically dependent on the HPC resources offered by DiRAC.

98. Parts of the PPT programme have overlap with other scientific areas. For instance, lattice QCD work in hot/dense QCD informs our understanding of relativistic heavy ion collisions (HIC) and nuclear matter, in Nuclear Physics. There is great overlap in theoretical cosmology between PPT and Astronomy. Finally it should be noted that gauge/gravity duality, developed to relate QFT and string theory, has achieved influential results based on a hydrodynamical approach to many-body theory. These results have found applications in HIC and in theories of condensed matter systems such as superconductors.

20 Externally reviewed rankings from the 2015 Review of UK phenomenology.
21 The importance of maintaining a National Centre was the main finding of the 2015 Review of UK Phenomenology.
22 As described in the 2015 PPAP Roadmap for Particle Physics.

99. In 2016/17 the Particle Physics budget was approximately £49M/year (including ~£6M/year Capital/CGPS). Of this, 53% is committed to experimental and theory consolidated grants (including support for IPPP), 33% to experiment operations, and 14% to future experiment development. The budget includes support for the Rutherford Appleton Laboratory Particle Physics Department (RAL PPD).

100. RAL PPD support is treated differently to institutional support and is no longer considered by the Particle Physics Grants Panel (PPGP). A review of RAL PPD funding was carried out in 2015[23] and final decisions on future funding arrangements (and levels) are awaited from STFC's Executive Board.

101. We note that the 2013 Programmatic Review recommended reducing RAL PPD funding to maintain programme breadth and allow for future development, and that STFC Council decided to maintain funding until the next review period. This has placed additional pressure on available funds to support the approved programme. We ask that the 2015 review of PPD funding conclude soon, so that support can be awarded according to the review recommendations.

102. Support for computing for the LHC and other PP exploitation (via GridPP) has also had to be built back into the PP programme above the level recommended by the 2013 Programmatic Review. This has also placed additional pressure on available funds within flat cash to support the approved programme.

103. Although the budget includes capital uplifts from the 2014/15 and 2015/16 Autumn statements, and an increased baseline allocation from the 2016 comprehensive spending review, it is insufficient to support current activities over the next five years. In particular, at flat cash[24] there are insufficient funds to support the ATLAS and CMS Phase II upgrades, to maintain UK leadership in the DUNE and Hyper-K future neutrino experiments, and to maintain the current programme diversity (by supporting a programme of precision muon and neutrinoless double beta decay experiments). Upgraded EDM experiments have already been lost from the programme.

B. Changes to Science Priorities since the 2013 Programmatic Review

Priority	Grant panel funded programme (i.e. experiment	PPRP funded projects

23 RAL PPD Review 2015-16.
24 "Flat cash" assumes the continuation of the uplift (which is not guaranteed).

	and theory)	
Highest	ATLAS, CMS, LHCb, T2K, theory	ATLAS/CMS/LHCb upgrades, IPPP
High	eEDM, g-2, Mu2e, COMET, NA62, HepData, MINOS+	GRIDPP, SNO+, SuperNEMO
Medium-high		nEDM

Table 1: 2013 Programmatic Review Priorities

104. Table 1 shows the top three bands of priorities determined for the Particle Physics programme in the 2013 Programmatic Review. The priorities remain current, with some updates. Based on the 2013 Programmatic Review recommendations, DUNE and Hyper-K have been added as highest priority future neutrino projects. SNO+, SuperNEMO and nEDM are no longer PPRP funded projects and now receive exploitation funding through the grants line. It should be noted that IPPP will enter the grants panel line from 2018[25]. GridPP, now in its operational mode, is part of the PPE exploitation programme. Support for COMET is only through the grants line. MINOS+ has completed data-taking.

105. Strategic reviews of phenomenology[26], energy frontier physics[27] and neutrino physics[28] have been undertaken as part of the 2013 Programmatic Review implementation plan. Delays in the LHC schedule, and reductions in support for the Phase II upgrades, long baseline neutrino programmes and GridPP to minimum viable levels, have allowed the programme to be broadened following 2013 Programmatic Review recommendations. The relative balance of future and current experiments is now felt to be broadly correct.

106. However, the constant volume necessary to support the programme cannot be maintained within the flat cash available. PPAP note that the balance between future and current experiments has been achieved by placing damaging cuts to exploitation in consolidated grant rounds[29]. PPAP recommend that resources devoted to exploitation (operation and physics analysis) should be at a level that allows appropriate exploitation to ensure proper return upon the original investment.

107. We agree that protecting exploitation budgets is the priority in a constrained funding environment. We note that the current level of funding for future projects is already inadequate to support the full programme of world class particle physics projects the UK community is involved with. Any reductions from the current level would inevitably curtail further the diversity of the programme in the UK, with consequences for the future of the subject.

108. The main update in energy frontier physics since the 2013 Programmatic Review is the approval of the high luminosity (HL-LHC) project by CERN Council. UK groups plan to contribute substantially to the ATLAS and CMS Phase II upgrades to exploit HL-LHC

25 IPPP has a CG award to cover 2018-2020.
26 The review of UK phenomenology (2015).
27 The LHC Detector Upgrade Tensioning Review – ATLAS/CMS Phase II Upgrades (2016).
28 The Long Baseline Neutrino Experiments Strategic Review (2016).
29 PPAP Response to BoP Sub Group Questions.

operation. A scale of funding for both experimental upgrades has been agreed by the LHC Experiments Committee/Resource Review Boards (LHCC/RRB) and ATLAS and CMS are now proceeding to produce technical design reports (TDRs), although the funding available for UK involvement is below the levels recommended in the 2013 Programmatic Review. The UK retains an interest in several international collider projects for the longer-term future, which have milestones expected towards the end of this decade. These include linear colliders (ILC (in Japan) and CLIC (CERN)), circular colliders (FCC) at CERN and China), and the Large Hadron electron Collider (LHeC) project. Conclusions from physics, detector and accelerator design studies are expected in 2017 as input to the European Particle Physics Strategy Update in 2019. Finally, a muon collider remains a long-term possibility.

109. LHCb remains the main focus in flavour physics; the upgrade is scheduled for installation during 2019-20, and possible further upgrades to extend physics reach are being investigated for installation in 2024-26. The science and financial implications are unclear at this early stage. UK groups are involved in studies for the future precision muon experiments COMET, Mu2e and Mu3e. UK involvement in COMET is only supported through the consolidated grant, while involvement in the existing g-2 experiment concludes in 2017 and future involvement in Mu2e and Mu3e has been proposed at a minimum level. Future kaon experiments are under study internationally (a new CERN experiment and a third run for NA62 have been proposed), but the scientific and financial implications of continued UK involvement have yet to be formulated. The UK retains an interest in the (as yet unapproved) future SHiP experiment; should the project go ahead its case will need to be evaluated further and the UK position reviewed. There is currently no funding available in the baseline flat cash programme to support any of these future project opportunities.

110. The major update in neutrino physics is the addition of DUNE and Hyper-K long baseline experiments which are regarded as the highest priority future neutrino experiments. The UK particle physics community, with support from STFC, is already making vital contributions to the preparatory R&D phases and the projects are now moving into pre-construction, but funding for UK involvement in future construction is constrained.

111. T2K running has been extended until 2026. NOvA is expected to operate until 2020. The neutrinoless double beta decay experiments SNO+ and SuperNEMO are proceeding and UK groups are now involved in a number of other small neutrino or neutrino-related projects: SoLiD, SBND/MicroBooNE, MICE, nuSTORM, PINGU, CHIPS, but only through support of the consolidated grant.

112. In non-accelerator physics the UK community has converged on LZ as the major UK dark matter experiment. Commissioning is expected in 2020. DEAP-3600, which has received limited consolidated grant funding, has started data taking. The community are aware of the necessity to continue R&D towards directional sensitivity, in view of a future, third-generation dark matter experiment[16]. Future eEDM and nEDM experimental approaches are under study, but, again, there is no funding in the current

programme to support these future opportunities. A limited number of UK particle physicists participate in the LSST, to make contributions in large scale data processing, large scale detection systems and DAQ.

C. Critical Decisions

113. Funding for Mu2e at FNAL and involvement in Mu3e at the PSI has been requested from April 2017. This follows from the support for g-2 at FNAL, which is due to end in March 2017. A funding decision is needed in early 2017. The decision affects the future breadth of the flavour physics programme. Should funding above flat cash not be available then precision muon physics would be lost from the programme.

114. The DUNE and Hyper-K projects are funded for R&D until September 2017. Subsequent funding is divided into a pre-construction phase 2017-19 (with a funding decision needed in 2017), and a construction phase from 2019 (with a funding decision needed by December 2018). The strategic case for funding long baseline neutrino experiments has been considered in the context of the wider Particle Physics development programme by a review in 2016[28]. The review recommends funding pre-construction for both experiments at a level below the 2013 Programmatic Review recommendation, and notes that participation in DUNE construction, as currently proposed, is predicated on additional capital funding from BEIS and the availability of additional resource. Should additional capital become available, the review recommends that STFC explore funding both experiments. In the event of no additional funding (when it may only be possible to fund one experiment), down-selection or scope reductions will be required. The review panel recommend a review process be initiated in 2018 to determine the best way forward. We support the findings of this review. Pre-construction proposals to PPRP for both experiments have been invited by Science Board.

115. A planning line is shared between the ATLAS and CMS Phase II upgrade projects. ATLAS funding is due to start in April 2018 and a funding decision is needed by December 2017. CMS funding is due to start in April 2019 with a decision needed no later than December 2018. A strategic review has considered the case for funding both upgrades in the context of the wider PP development programme[27]. The review recommends that both projects be funded within the reduced project planning line agreed in 2014, and with no overall increase in consolidated grant (or RAL PPD) effort over that awarded in the PPE 2015 grant round. If insufficient funds are available, the review recommends further reducing the scale of the ATLAS upgrade as far as is possible to retain participation in the CMS upgrade. If only one experiment can be supported, the review prioritised the ATLAS upgrade. We support the findings of this review. A proposal for ATLAS Phase II construction and a SoI for CMS Phase II construction have been invited by Science Board.

116. The review notes that the resource level for the upgrades and of computing for the LHC (via GridPP) are comparable and suggested that computing provision should be revisited for LHC Runs 3-5. We endorse STFC's call for CERN to undertake a global scoping review of computing support requirements for Runs 3-5 with the aim of identifying efficiencies and minimising costs. If timescales allow, the future level of resource for computing to be allocated at the next consolidated grant round could then be informed by the outcome.

D. Impact of flat cash plus +/- 5% flat cash

117. The breadth of the PP programme has already had to absorb additional demands (e.g. from the build back of GridPP support above 2013 Programmatic Review levels) and will inevitably be further eroded even under the scenario of flat cash funding continuing. The UK will move away from its current position of having some scope to react to developments and important new opportunities, to a more limited programme that focuses on the highest priorities in energy frontier, flavour physics and long baseline neutrinos. Existing and important activities will be lost in each of these areas, known opportunities will be missed and the programme will have very limited scope to plan for the future and react to new opportunities. We note that progress made since the 2013 Programmatic Review in achieving a healthier breadth of activity will be lost; in particular precision muon and kaon flavour experiments and neutrinoless double beta decay experiments are unlikely to be supported. Future EDM development already cannot be supported.

118. We note that any reduction in funding (a cut, or loss of the assumed capital uplift in the CSR 2016 baseline allocation), runs a higher risk of withdrawal from international experiment(s), which would have serious implications for the future health and standing of the PP community. Such an action would result in severe reputational damage, subsequent loss of leadership and loss of access to a scientific area, potential inability to extract value from international subscriptions, and may not deliver immediate savings.

119. We agree that any uplift in funding should be used to reinstate breadth in the Particle Physics programme rather than increasing spend on the ATLAS, CMS, DUNE and Hyper-K projects, as noted in[27], [28]. We note that even a 5% increase is insufficient to retain the current programme breadth and it is likely that UK leadership will still be eroded in this scenario.

120. In all financial scenarios, we note that key decisions must be made before the next BoP exercise. Some of these decisions (e.g. DUNE and Hyper-K construction) depend on the availability of external funds. The decisions could affect the overall balance of the programme, which should be evaluated and adjusted if necessary.

R12:	**<u>Recommendation:</u> We recommend a Particle Physics programme evaluation be carried out in late 2017, with a view to ensuring that the programme is optimal, balanced, coherent and sustainable.**

121. The evaluation should be used to inform subsequent funding decisions and could consider the following:

- The scope of participation in DUNE and Hyper-K construction, given the available level of external funds at that time.
- The relative balance between exploitation and development and between different experimental areas (energy frontier physics, neutrino physics, flavour physics and non-accelerator physics), as well as the balance between theory areas and between theory and experiment.

122. In the medium term, the programme should be evaluated in the light of developments in any area of the science programme, the European strategy review, any CERN review of computing resource requirements and so on. This evaluation should be used as input to the next Balance of Programme exercise.

R13:	**<u>Recommendation:</u> We recommend that the Particle Physics programme evaluation be updated, with any relevant additional funding scenarios, shortly before the next Balance of Programme exercise.**

123. The funding scenarios that the above paragraphs indicate, are the following:

Flat cash: It is recommended that the current level of exploitation funding be maintained. We also recommend that DUNE and Hyper-K construction, and ATLAS and CMS Phase II Upgrades, be funded following the recommendations of the Long Baseline Neutrino Experiment Review, the LHC Detector Upgrade Tensioning Review – ATLAS/CMS Phase II Upgrades and the programme evaluation recommended above, within the available financial envelope, and noting the need for additional capital.

+5%: It is recommended that extra funds be used primarily to support the breadth of the programme in world-class projects where the UK is making key contributions and, in many cases, has already established leading roles (e.g. precision muon experiments, neutrinoless double beta decay experiments or EDM experiments).

-5%: It is recommended that committed funds should not be withdrawn, and that the current level of exploitation funding be maintained. Instead, additional savings should be made by funding DUNE and Hyper-K construction and ATLAS and CMS Phase II upgrades at a reduced level, according to the recommendations of the Long Baseline Neutrino Experiment Review, the LHC Detector Upgrade Tensioning Review –

ATLAS/CMS Phase II Upgrades and the programme evaluation recommended above.

4.4 Particle Astrophysics

A. Overview of Programme

124. Particle astrophysics is the study of elementary particles of astronomical origin. The UK particle astrophysics programme has brought significant success to the UK in recent years, as the recent detection of gravitational waves has demonstrated. As with the other PPAN areas, the development, construction and science exploitation of particle astrophysics instruments lead to ambitious international projects that require advanced technologies, help to train highly-skilled personnel, and facilitate knowledge exchange with industry.

125. Particle astrophysics is a growing field in which the UK has a very strong track record[37]. The UK has large and influential communities in three areas[30]: gravitational wave astronomy[31], gamma-ray astronomy[32], and direct dark matter detection[33]. These are the sub-fields on which the STFC programme is currently focused[34].

126. The STFC Particle Astrophysics (PA) funding in 2016/17 is £3.5M (including £250k capital/CGPS), with the following balance within the science areas and activities:

- Gravitational waves: £2.2M (63% of overall PA budget), including £0.4M for Advanced LIGO operation and a £1.8M programme for wider development, operation and exploitation (10% operations, 59% development and 31% exploitation);
- Dark matter: £0.7M (20% of overall PA budget) for development/construction of LZ;
- High energy gamma ray astronomy: £0.5M (14% of overall PA budget), development/pre-construction of CTA;
- Other (ad hoc grant support and UK contribution to CTA Observatory GmbH operation costs): £0.1M (3% of overall PA budget).

127. In addition, the UK Particle Astrophysics community has attracted a range of European funding (FP6, FP7 and H2020), including training networks, EC funded design studies

30 See PAAP response to the BoP Sub Group questions for more details.
31 The facilities that support this programme are (Advanced) LIGO, including LIGO-India, and its upcoming upgrades, GEO 600, the planned third generation ground-based instruments – the Einstein gravitational-wave Telescope in Europe and the LIGO Cosmic Explorer in the USA – and the space-based instrument LISA, Laser Interferometer Space Antenna.
32 The high energy gamma-ray facility with strong UK involvement is the Cherenkov Telescope Array (CTA).
33 The dark matter facility with strong UK involvement is LUX-ZEPLIN.
34 There is also potential for significant UK impact in high-energy neutrino astronomy. The Particle Astrophysics Advisory Panel (PAAP) supports the statements made in the 2015 IOP review of UK particle astrophysics that the UK community should seek to coalesce around support for a single project and would support such a project's inclusion in a future PAAP roadmap.

and ERC grants. Further work needs to be carried out to capture these data. There are three known ERC grants supporting Particle Astrophysics research that are held in the UK and an ITN for a total estimated contribution of ~£900k/year, in addition to a few Marie Curie Fellows.

128. The STFC-funded Particle Astrophysics programme focuses mainly on R&D and construction, with some support for the operations/exploitation of gravitational wave experiments. The AGP and PPGP also supports the science exploitation of instruments developed under the Particle Astrophysics programme. Although the current STFC budget allocated to Particle Astrophysics is able to support a healthy breadth of interest, it remains at a minimal level. Nonetheless, the UK has been able to ‘punch above its weight’ (in selected areas) and secure world-leading positions in those projects[30].

B. Changes to Science Priorities since the 2013 Programmatic Review

129. The first direct detection of gravitational waves announced in February 2016, marked the dawn of gravitational astronomy and opened up a new range of science exploitation activities at the interface between particle astrophysics and other fields of the PPAN programme, in astronomy, cosmology and fundamental physics. UK groups made leading contributions[35] to the instruments, operation and analysis, science exploitation and theory. Future research in this area may reveal as-yet unknown astrophysical systems and/or physical processes in the early Universe, and the subject is attracting tremendous interest and investments by UK universities. A community survey conducted by the Particle Astrophysics Advisory Panel (PAAP) during the Balance of Programme exercise has revealed an expected 50% increase over the next 3-5 years in academic staff engaged in gravitational-wave activities at UK institutions[36].

130. The detection of gravitational waves has also significantly accelerated the planning for, and development of, future detector upgrades and new instruments, an area in which the UK holds unique strengths. The LIGO-India project has been approved (operation around 2022). Plans are already in place for upgrades of Advanced LIGO. The so-called A+ upgrade would be operational by 2022. LIGO Voyager is a proposed larger upgrade giving a further increase in survey volume by a factor of 8, and would start data taking in 2028. In the US this programme strategy leads to a possible separate third-generation facility, ‘Cosmic Explorer’, for operation in the 2030s, in parallel with

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[35] The UK developed the fused-silica suspension technology – one of the key factors for the exquisite sensitivity performance of Advanced LIGO – designed and built the suspension systems for the detectors, and pioneered data analysis techniques and modelling of radiation from binary black holes, which are at the heart of the direct detection of gravitational waves and the science results enabled by these observations. Scientists at UK institutions co-led the key science papers reporting the detections of binary black holes and the implications for astrophysics and fundamental physics.

[36] The responses of the PAAP community consultation have shown that Birmingham, Cardiff, Glasgow, Imperial, Sheffield, and possibly Cambridge and Portsmouth, intend to recruit a total of over 10 faculty involved in gravitational-wave related research over the next three years. For comparison, the three largest gravitational-wave groups in the UK currently have a total of 23 faculty members.

the Einstein Telescope in Europe, to which the UK has already made many leading contributions. ESA has issued the L3 mission call for the selected theme “gravitational universe”, with a scheduled launch of a space-based observatory in 2034. A large UK consortium is securing UKSA funding to contribute to key hardware and ground-segment provisions for this LISA mission. Space-based observations will open a complementary observational window to the one accessible from the ground and as such, will strengthen and augment the ground-based effort.

131. These new opportunities in gravitational wave studies come alongside the maturing of direct dark matter searches (LZ) and very high-energy gamma-ray experiments (CTA).

132. LZ will probe the WIMP parameter space for masses above a few GeV down to cross-sections near the irreducible neutrino coherent scatter background. The experiment is transitioning from construction to operation and science exploitation in 2020, and there is a need to maintain an R&D programme for third-generation instruments. UK scientists lead several LZ work packages, and have made major contributions for the cryostat, phototubes and low-background analysis.

133. CTA, the first global observatory for very high-energy photons, with sensitivity an order of magnitude better than any previous facility, has entered its pre-construction phase, with construction planned to start in mid-2018. For CTA, the UK provides the spokesperson for the Small Size Telescopes (the largest set of telescopes), and leads the development of silicon photomultiplier-based cameras considered for implementation in all dual-mirror telescopes.

134. All of these developments would allow the UK to capitalise on past investments and be at the forefront of transformative science. They are however in stark contrast with the projected STFC budget allocated to Particle Astrophysics, which marks a slow but inexorable deterioration of the UK position across the board. The current financial envelope does not allow the UK to retain its leadership positions in all these areas. The research capability and international credibility will be eroded at best and there is a serious risk of having to withdraw from at least one of these fields.

135. A ranked list of the priorities (with 1 being the highest), following the recommendations of the PAAP[37] is:

1. **Advanced LIGO**: exploitation to profit from major UK investment and leadership in this new field of astronomy, and development and implementation of initial upgrades to the system.
2. **LZ**: exploitation, building on current investment and substantial UK expertise and leadership.
2. **CTA**: construction and exploitation, building on current investment and substantial UK expertise and leadership.
3. **Einstein Telescope**: support of R&D for future gravitational wave detectors, to facilitate future UK participation in ET.

37 PAAP roadmap for UK Particle Astrophysics (2016).

3. **G3 Dark Matter**: support of R&D to facilitate UK participation in a future G3 experiment.

C. Critical Decisions

136. The Particle Astrophysics programme faces critical decisions that will have repercussions for UK international standing and affect the long-term role of the UK in this field.

137. There is a need to define the future scope and balance of the gravitational wave activities and the level of funding. The 2013 Programmatic Review decreased support for gravitational waves from 2019/20 to open up a development line for the Particle Astrophysics programme. Due to the scientific developments in this area a critical decision is required by April 2017 on the level of funding needed to maintain the current 2016 ground-based gravitational-wave consortium grant programme at flat cash until September 2020.

R14: **<u>Recommendation</u>: We recommend that the gravitational wave consortium grant be increased to ensure the current gravitational wave support can at least be maintained at flat cash.**

138. In addition, in order to fully capitalise on the new opportunities and the established leadership positions in the field, a decision on participation in the initial Advanced LIGO upgrade will need to be made. Such participation would require a capital investment during the period 2018-2022.

139. More broadly, STFC's Particle Astrophysics activities, most notably in the gravitational-wave area, are moving rapidly from just construction/operation to science exploitation. The rapid evolution of the fields, the new opportunities available and the changing landscape of groups/universities involved in these science areas require a revision of the way in which particle astrophysics research is funded.

140. Particle Astrophysics does not have a dedicated exploitation grant line. Support for direct dark matter searches is provided by the PPGP, whereas the AGP provides support for other areas.

141. The majority of gravitational wave research is funded through a consortium grant encompassing some universities, while the remainder is funded through the AGP. This approach makes it difficult to ensure that all research challenges (and opportunities) are adequately addressed, and that proposals are meaningfully tensioned against each other. For example, gravitational wave observations now have direct impact and application in astronomy and astrophysics, raising the question of how to properly fund gravitational wave related astronomy research. A number of different solutions are

possible, provided 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: instrument building (including R&D for future instruments); observation (instrument operation and commissioning, as well as the development and application of data analysis tools) and theory (astrophysical model building and the interpretation of observations for astrophysics and cosmology).

R15: **Recommendation: 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.**

142. UK funding for CTA pre-production finishes in June 2018 and construction funding will be necessary from July 2018 onwards, for a capital contribution of the order of £5M. By January 2018, a decision on UK participation in CTA construction will need to be made.

143. In 2020 LZ construction is scheduled to draw to an end, with UK deliverables expected to be completed by 2018. As the primary focus of the activities moves to the operation of the detector and science exploitation, there is a need to continue to pursue R&D and technology development for third generation dark matter experiments.

D. Impact of flat cash plus +/- 5% flat cash

144. Given the modest size of the programme, 5% amounts to approximately £175k/year. A flat cash scenario would leave the programme without the opportunity to capitalize on the recent results in gravitational-wave astronomy. A 5% reduction would surely further compromise research activities and leadership in at least one of the areas of the programme. A 5% increase amounts approximately to the recommendation of the Sub Group to restore the flat-cash support level of the gravitational wave consortium grant.

R16: **Recommendation: We recognise the near-critical level of support that the Particle Astrophysics community receives and recommend that it be at least maintained at flat cash.**

4.5 Accelerators

A. Overview of Programme

145. Development of accelerators supports both the STFC science programme and the development and operation of STFC's science accelerator based facilities (e.g. Diamond Light Source, ISIS Neutron Source) and STFC supported European research laboratories (XFEL.EU, European Spallation Source (ESS)).

146. The accelerator field in the UK can be broadly divided into four main themes: high energy physics accelerators (e.g. ILC/CLIC, FCC and LHC); light sources and neutron sources (closely related to STFC facilities); accelerator applications (e.g. medical, industrial, etc.); and pure accelerator development (e.g. plasma wakefield acceleration).

147. The UK, led by STFC, has invested significantly in accelerator R&D over the last decades via two university-based accelerator research institutes. The Cockcroft Institute (Lancaster, Liverpool, Manchester, Strathclyde) and the John Adams Institute (Imperial, Oxford, Royal Holloway) are typically funded for four-year periods, and resources support all the main accelerator research themes. Concentrating resources in institutes allows synergies to be exploited (for example between ILC and FEL work or high luminosity LHC and future circular hadron colliders). Institutes have also leveraged significant non-STFC funding (approximately 3 times the core STFC grant awards). The recent external peer review of the two accelerator institutes noted the excellent breadth and quality of research conducted at the institutes.

148. The STFC UK academic accelerator community, which is supported through the Programmes Directorate programme, is concentrated in the Cockcroft and John Adams Institutes, with some non-accelerator institute research activity ongoing at Huddersfield, Southampton and UCL. The STFC-funded accelerator community as of 2015/16 consists of 35 academics, 29 research associates and 17 research students. The overall community including non-STFC and STFC facilities funded elements is significantly larger.

149. The exploitation and operation of accelerators is performed via national or international laboratories and the accelerator programmes in the UK could be viewed as effectively R&D and small scale construction (compared to a complete facility). There is strong complementarity between international projects and national scale projects, for example work on ILC/CLIC is feeding down towards a UK FEL, and work on LINAC4 and high power proton drivers is synergistic with work on the ISIS neutron source.

150. The UK accelerator physics R&D has developed over the last decade to a world-leading position, most notably R&D for ILC and CLIC, High Luminosity LHC and plasma wakefield acceleration. The UK has held numerous positions of responsibility within the HL-LHC project, for example.

151. At the time of the 2013 Programmatic Review, the Programmes Directorate (PD) Accelerator element remained flat. The total funding envelope for the STFC Accelerator programme covering Programmes Directorate and the Accelerator Science and Technology Centre (ASTeC) was £10.7M/year (resource), but there have been some short-term increases[38]. However, indexation of the ASTeC element has increased pressure on the PD element, which currently stands at £6.2M but will reduce to £5.7M over the next two years. The split of the PD programme is: £1.2M additional funding for Accelerator Science Technology Centre (ASTeC), £3.5M is awarded to the Cockcroft and John Adams Institute and £1.5M is awarded through project grants. The project grant element will continue to be eroded due to the indexation of ASTeC funding.

R17: **Recommendation:** **We recommend that indexation be removed from ASTeC funding, in order to reduce pressure on the rest of the Accelerator programme.**

152. The Accelerator programme is diverse and largely focused on facilities development. The construction and operation of facilities such as Diamond Light Source and ISIS Neutron Source are largely the responsibility of STFC national laboratories but activities related to the LHC upgrade at CERN and elsewhere also exist. The accelerator institutes continue to engage and actively support all aspects of the programme.

153. Planning of the programme has leaned towards supporting large facilities with the areas of expertise within the UK community (e.g. HL-LHC)

154. The UK programme is now broader with activities associated with novel acceleration (e.g. Wakefield Acceleration) and light sources as well as the high-energy field.

155. Greater certainty over the timescales of any future construction of a UK based facility would benefit the programme by increasing focus, as would engagement with overseas construction towards other international facilities.

156. The current activities within the UK towards international facilities strengthen the technical capability of the UK and its ability to move towards a UK facility.

B. Changes to Science Priorities since the 2013 Programmatic Review

157. Reviews relating to the Accelerator programme since the last programmatic review include the 2014 Accelerator Strategic Review[39] (which should be taken as the basis

[38] the curtailing of the MICE project moved its funding from capital to resource.
[39] http://www.stfc.ac.uk/files/accelerator-review-report-public-complete/

for the programme), the 2016 Free Electron Laser (FEL) Strategic Review[40], and the ongoing STFC facilities roadmap and STFC Accelerator Strategy.

158. The Accelerator programme continues to evolve reflecting the needs of the different STFC communities and supporting developments and upgrades of the accelerator facilities, as well as novel acceleration techniques. This is reflected in the programme most notably by reductions in:

- Muon collider research and development through to facility (MICE) over the last programmatic review period, in line with the US P5[41] report, which called for a reassessment of the muon accelerator programme;
- UK research activities towards the International Linear Collider (ILC), in part due to the uncertainty of the possible construction of the facility in Japan but mainly because critical R&D has been successfully completed and the project has become construction ready.

159. Correspondingly the community has responded to a need to develop and expand activities in HL-LHC, UK-FEL and novel acceleration. The community developed, with STFC support, a coherent and effective strategy to engage with CERN on HL-LHC and leverage CERN funding for UK accelerator R&D. Novel acceleration (e.g. laser plasma wakefield acceleration) has effectively integrated into activities of the institutes with Strathclyde and Imperial joining the Cockcroft and John Adams institutes respectively. STFC is currently coordinating relevant R&D towards a possible future UK-FEL, involving ASTeC and the accelerator institutes, which is consistent with the recent FEL strategic review.

C. Critical Decisions

160. Upcoming critical decisions can be separated into those supporting STFC science, and those supporting STFC facilities. The accelerator R&D for high energy particle physics is coupled to the 2013 European Strategy for Particle Physics[42], which will be updated in 2020. The UK accelerator programme broadly follows the high-priority large-scale scientific activities in the 2013 strategy (from which the quotations below are taken).

161. "Europe's *top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030"*

162. STFC, in collaboration with CERN, UK accelerator institutes and universities started a four-year programme in April 2016 to develop some key technologies required for HL-

40 http://www.stfc.ac.uk/files/fel-report-2016/
41 http://science.energy.gov/~/media/hep/hepap/pdf/May-2014/FINAL_P5_Report_053014.pdf
42 https://cds.cern.ch/record/1567258/files/esc-e-106.pdf

LHC, including crab cavities, beam instrumentation and collimators, whilst simultaneously performing the required simulations. The current funded R&D programme will conclude in April 2020, and will require a continuation in funding to ensure the science goals of the LHC are achieved through construction, operation and exploitation. This will also enable the UK academia and industry to fully exploit the potential benefits.

163. *“CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines”*

164. There is limited activity in both accelerator institutes towards the hadron-hadron Future Circular Collider (FCC-hh), supported financially by the core accelerator institutes funding and EU FP7 support. The baseline design of a 100 km, 100 TeV collider will be completed by 2018 and a decision on continued involvement in a future CERN based higher energy hadron machine will be required.

165. *“The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. Europe looks forward to a proposal from Japan to discuss a possible participation.”*

166. A Japanese decision on ILC construction is expected before or around the time of the next European strategy update in 2020. The UK historically invested significantly in the R&D towards a linear collider (both ILC and CLIC) and has developed key technologies deemed essential for both facilities. The motivation and rationale for construction of ILC has not changed since the discovery of the Higgs boson and worldwide efforts are ongoing to reduce the cost of such a facility. If the Japanese government decides to invest in the ILC, the focus and level of UK involvement will need to be decided.

167. *“CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.”*

168. The PPAN programme supports proposals associated with the high-power proton accelerators and target systems required for future long-baseline neutrino experiments.

169. STFC published the FEL Strategic Review in Autumn 2016. The UK’s longer term projected need to access X-ray light sources will outstrip supply (at LCLS and XFEL.EU) by 2020, when the UK community is projected to grow from 20 to 50 active user groups. The review supports a timeline where a FEL specification and technology R&D will occur over the next 4 years, so a likely decision on building a FEL could be taken in 2020. STFC would then be in a position to start a six-year construction period, and a UK-FEL could be operational and supplying users by 2026. Currently the UK-FEL R&D is supported by STFC through ASTeC and core accelerator institute funding.

Continued investment would allow the UK to exploit opportunities and assume a key international role in this area of science.

R18: **Recommendation: We recommend an R&D strategy is developed in collaboration with the accelerator institutes and ASTeC to support the aspirations of the FEL Strategic review.**

D. Impact of flat cash plus +/- 5% flat cash

170. A reduction of 5% will significantly erode STFC's and the community's ability to develop new projects and contribute effectively to national and international projects. There will be no continued strategic investment in HL-LHC, high power proton drivers, targets for neutrino beams or beam driven plasma wakefield acceleration projects. The majority of the Programmes Directorate funding in this scenario will be used to support the accelerator institutes and therefore strategic projects must be entirely funded from the John Adams Institute and Cockcroft core grants. The John Adams Institute and Cockcroft grants support core technical staff and competences and a 5% reduction in funding will significantly damage the institutes' abilities to deliver on specific projects.

R19: **Recommendation: We recommend that flat cash funding continue for the Cockcroft Institute and the John Adams Institute with all elements of the programme including ASTeC subject to appropriate external peer review.**

R20: **Recommendation: We recommend that the funding level for future accelerator projects be reviewed at the time of the next European Strategy Update: specifically future high energy facilities HL-LHC, HE-LHC and FCC for hadron colliders and ILC and CLIC for lepton colliders.**

171. An uplift of 5% would allow a continued programme on HL-LHC beyond 2020 and possibly a range of small scale but important activities that allow the UK community to remain active in key future high energy accelerators and facilities. If critical decisions on future high energy facilities are made for the next update to the European strategy for particle physics (expected in 2020) then a funding uplift will be essential for the UK accelerator community.

R21: **Recommendation: If a funding opportunity within STFC programmes arises, we recommend that the funding levels for highly speculative future accelerator technologies including beam and laser plasma wakefield acceleration (for example the AWAKE experiment at CERN and the experimental programme at CLF) should be reviewed.**

4.6 Computing

A. Overview of Programme

172. Computing for PPAN falls into two complementary categories; High Performance Computing (HPC) and High Throughput Computing (HTC).

173. HPC facilities use specially configured computer architectures to allow complex calculations to be carried out. They are used by the theory communities within all areas of PPAN for simulation. HPC machines satisfy a specific requirement that cannot be satisfied by simple commodity clusters. By their nature they are more expensive than HTC commodity clusters.

174. HTC machines are used primarily for handling, reducing and analysing the data from experiments and observational instruments, and for event-based simulation. Particle physics is mainly associated with HTC, however other areas within PPAN also require significant HTC. In particular, the Astronomy programme requirement is growing quickly.

175. These two components are funded in different ways for historical reasons. The capital element of HPC has come from separate government sources with the PPAN programme providing a total resource funding of £1.5M/year for power (£860k), operational (£220k) and staff costs (£440k for 5.4 FTE). HTC is provided through GridPP5 and embedded in the Particle Physics funding lines. This project has recently been reviewed and is funded at approximately £2M/year capital and £4M/year staff resource (27 FTE).

Existing HPC

176. HPC computing for PPAN is mainly furnished by DiRAC. DiRAC-2 was established in late 2012 with a £15M capital investment from BIS and provided PPAN scientists with a world-competitive facility. It comprises four components optimised for different science challenges. It is now reaching the end of its life and quickly becoming uncompetitive in comparison to its national and international peers. It has been given a short-term uplift via a 1-year grant for “DiRAC2.5” comprising the re-purposing of old Hartree equipment. Its total capacity is 2Pflop and 5Pbyte storage.

177. DiRAC usage is critical for a well-defined fraction of the particle physics theory community, notably lattice QCD, and underpins modelling and analysis across virtually all theoretical activity in astronomy, including large scale structure and inflationary dynamics (COSMOS, VIRGO), galaxy, star and planet formation and structure, and Solar System MHD codes (UKMHD). Other applications include: simulation of black hole mergers for gravitational wave observations, many-body problems in nuclear physics; Monte Carlo studies for CTA and numerical gamma-ray studies in particle astrophysics; plasma wakefield simulations in accelerator physics.

178. DiRAC time is allocated via a Resource Allocation Committee (RAC), which considers both scientific and technical cases. Calls are issued every six months for three types of application, Seedcorn (small requirements for test activities), Short (one year projects), and Long (three year projects).

179. In addition the PPAN community has use of PRACE (the European HPC facility) and accounted for approximately 2% of the total PRACE resource between 2010-15[43]. Users also make some small use of ARCHER (the EPSRC-funded national HPC machine)[44]. The STFC Hartree Centre has significant HPC capacity, which is primarily targeted at industrial and commercial interactions. Hartree is not available for large-scale PPAN science production work, but can be used for development and testing.

HTC + Data Storage

180. HTC computing for PPAN is provided mainly by the GridPP project. This is focused upon the LHC experiments but includes resources for some existing non-LHC particle physics experiments. HTC facilities include both the central processing units (CPU) needed to process and analyse data, as well as the large volume data storage capacity (disk and tape).

181. GridPP is a part of the Worldwide LHC Computing Grid (WLCG) and provides approximately 10% of its global resources[45]. The overall level of computing resources required by the LHC is determined annually by the experiments, subjected to scrutiny by the CERN Computing Resources Scrutiny Group (C-RSG), and approved by the CERN Resource Review Board (RRB). The share for each funding agency is determined by publication author fraction (similarly to common fund contribution calculation for experiments). GridPP5 is funded to provide the UK's share for four years from 2016/17 to 2019/20[46].

182. GridPP5 provides some support for other existing non-LHC particle physics experiments. However it does not have the resources to support fully the requirements of all of the new and emerging particle physics experiments, or additional communities within the UKT0 initiative (see below). In practice local goodwill and leverage are used to provide access to resources where possible, at a low level. Other activities using GridPP at present include T2K, NA62, LZ, SNO, ILC, PhenoGrid, LSST, and exploratory use by Euclid.

183. GridPP and DiRAC liaise closely at both management and technical levels. Both are participating with collaborators in other science areas in a joint project funded by all

43 Overall UK scientists used 8% of the PRACE resources between 2010 and 2015.
44 There are cross-over points in MHD (Plasmas, Fusion and Solar Physics), Planetary Physics, Atmospheric Physics and Spectroscopy. So there a few PIs with resources on DiRAC and Archer, but formally they are for different science programmes.
45 Current provision amounts to approximately 50,000 logical cores, 32 PB of disk and 14 PB of tape.
46 However, It should be noted that the LHC requirements have increased in 16/17 due to better than expected LHC performance.

Research Councils to enable users to work across all domains. Long-term tape storage for DiRAC is provided by the Tier-1 centre at RAL, and HTC experts participate in the DiRAC RAC. Both are working to harmonise further under the UKT0 initiative, which brings together all aspects of STFC's computing.

General

184. Efforts have been made across the Research Councils to make the case for Government capital investment in a National e-Infrastructure (NeI), which was submitted to BEIS in the autumn of 2016. This includes (i) £56M for DIRAC-3, (ii) £10M for HTC PPAN activities. A decision on funding is awaited.

185. In addition to DIRAC and GridPP, a small volume of computing resources is awarded on other projects generally through the consolidated grants.

186. Power costs for the different areas of computing are treated differently.

- DiRAC-2 power costs of ~£0.85M come from the resource line within the PPAN programme area, though this is the 2016/17 figure that is set to rise with DiRAC-2.5 due to inflation added cores etc., to £1.2M (17/18).
- The GridPP Tier-1 power costs of ~£1M at RAL are paid by STFC but do not accrue to PD. The GridPP Tier-2 power costs are currently paid by the Universities and are approximately £1.5M/year.

B. Future Requirements

HPC

187. The HPC capacity of DiRAC-2/2.5 is now outdated, resulting in PPAN-supported theoretical physicists and astrophysicists becoming less and less competitive with their international peers. The DiRAC-3 proposal (science and technical cases) was prepared and reviewed in 2014-15.

188. The case is made for a total capacity of 15 Pflop/s + 100 PByte storage distributed over four components: (i) Extreme Scaling optimised for e.g. lattice QCD production, (ii) Memory Intensive, permitting effective all-to-all communications suitable for e.g. VIRGO, (iii) Data Intensive for confronting models with data (CMB, GAIA) and QCD post-production analysis, (iv) centralised data management, disaster recovery.

189. The total capital requirement for DiRAC-3 is part of the previously mentioned NeI bid to BEIS.

190. The PPAN community will continue to have competitive access to PRACE as part of a Research Councils UK (RCUK) agreement. Until now the Engineering and Physical

Sciences Research Council (EPSRC) has covered the nominal charge to the UK of this access, however, a new charging structure has been introduced for 2017 and STFC will pay its share of the increased subscription of approximately £200-400k/year. This new cost will come as an added burden to the existing HPC funding line.

HTC + Data Storage – UKT0

191. The need for HTC computing resources is growing rapidly within PPAN. Particle astrophysics already uses HTC and there are many astronomy projects that will have significant HTC requirements in the future including Euclid, LSST, Advanced LIGO and the SKA among others. In addition, there are growing pressures from further particle physics requirements including Hyper-K and DUNE, and the better than expected LHC performance, that were not factored into the GridPP5 award.

192. All of these PPAN activities have self-organised under the UKT0 initiative to work together to use a shared HTC infrastructure in the future, the purpose being to minimise costs per unit resource, avoid duplication, and share infrastructure and staff where it makes sense to do so. It is estimated that the requirement for the next four years, for all of PPAN science, is approximately 50% greater than the resources funded under GridPP5 (i.e. total resources required = 1.5 x resources awarded to GridPP5) until 2019/20.

193. The total additional capital requirement across PPAN (in addition to the existing GridPP5 award) amounts to £10M over the next four years and is included in the BEIS bid.

194. In the meantime GridPP is providing expertise and limited resources to allow the cross programme UKT0 initiative to progress and to enable piloting to proceed.

Staff resource and power costs

195. There is a requirement for 'middle-layer' computing staff who are distinct from both front line science exploitation experts and the staff primarily associated with keeping hardware running. These people develop, deploy and run the scientific software infrastructure[47] needed to carry out science data processing for a broad class of activities on the physical infrastructure and are ensuring that it runs efficiently and effectively. This would remain a requirement even if all hardware resources were hypothetically contracted out to a cloud provider. These specialist staff fall outside the traditional grant funding routes; often given lower priority by grants panels than project

[47] Examples of such roles include:

- Data management services, workload management services, coherent software distribution and deployment, performance monitoring and accounting, infrastructure evolution, documentation and training, ticketing response and escalation, security policy coordination and incident response, certification authority.
- Maintenance and development of key simulation code, Software engineering.
- Developing and maintaining astronomical archives.

or exploitation staff, they are not part of operational budgets and are not easily funded through capital.

196. The situation is particularly severe in the HPC sector where there is an urgent need for more software engineering to adapt important community code bases. The problem is growing in astronomy HTC as requirements increase due to activities including GAIA, Euclid, LSST and SKA and increasingly large datasets need curating into national data archives – demanding development of data processing and access centres and significant database related development. In general the particle physics experimental sector is broadly well served at present thanks to GridPP5, but the demands are growing due to new activities.

197. The demands for specialist computing staff for HPC/HTC are growing across PPAN as a consequence of the growth in data intensive science activities. The Advisory Panels emphasised the importance of HPC/HTC computing. As many of the new PPAN data intensive activities move forward there will be a growing requirement for specialist staff. The collaborative approach that underpins the UKT0 initiative offers a way forward through existing staff working together more efficiently to support the increased volume, and therefore reducing the overall cost per activity of computing support.

198. The diverse way in which the power costs for computing are funded is noted. However, at this time, it is difficult to see any practical way to harmonise the situation without incurring substantial additional costs to the PPAN budget (£3-4M). This results in DiRAC continuing to receive a contribution to computing power costs from the PPAN budget to host institutes.

199. Concern was expressed about the anticipated power costs associated with DiRAC-3 (~£3M/year). It was noted that hardware costs are assumed globally to remain at flat cash for the next few years for increased compute-power due to 'Moores law', but was felt this should not mean that it was accepted that electricity-power costs funded by STFC should rise linearly, they should be tensioned against other areas of the project at the peer review stage.

200. The funding scenarios that the above paragraphs indicate, are the following:

Flat cash: In the flat cash scenario a modest increase in computing support staff effort is recommended, which should target HPC and the Astronomy aspects of HTC communities.
In the current climate the number of computing support staff across PPAN cannot be increased within the budget, but every opportunity should be sought to find alternative sources of support (e.g. capitalising software projects).

The – 5% scenario: Any reduction to meet the -5% scenarios in this very harsh environment would affect the ability to deliver the science programme. It is important that the 'middle layer' computing staff levels are not reduced below flat cash levels.

The +5% scenario: Increases in funding should be aimed at additional staff support to enhance HPC and the Astronomy aspects of HTC requirements.

C. Effects of flat cash and 5% reduction

201. It is assumed that the substantial capital element required to build DiRAC-3 and the additional UKT0 resources required for PPAN activities other than the LHC will come from a BEIS capital initiative.

202. However, it should be noted that these requirements are integral to the exploitation of existing funded projects and the PPAN programme will be jeopardised without this investment.

R22:	**<u>Recommendation:</u> We believe that the scheduled review of the PPAN computing programme should take into account the strategic approach described in the above paragraphs, and the funding scenarios outlined.**

R23:	**<u>Recommendation:</u> We recommend that in order to meet the PRACE subscription, that STFC distribute this cost across areas of STFC which can make use of PRACE, with the expectation that costs would be initially determined in proportion to the relative usage of resources by those areas.**

R24:	**<u>Recommendation:</u> We recognise that additional investment in staff in HPC and HTC will become necessary. We support the idea of a review of future staffing levels across HPC and HTC that will fully evaluate the projected needs across the PPAN areas and programme, and take full account of e.g. opportunities for other sources of funding and efficiency gains from the UKT0 initiative. We recommend that STFC, in consultation with the communities, determine the fairest sustainable mechanism for the ongoing staffing of HPC and HTC resources.**

R25:	**<u>Recommendation:</u> We believe that the DiRAC power costs should broadly be maintained at flat cash and that any increase for DiRAC-3 would have to be tensioned either against other areas of the DiRAC project at the host site bid-**

tendering stage, or against other areas of the PPAN programme. These costs should not be reduced in the -5% scenario.

5. Programme Balance and the Funding Scenarios

203. The main aim of the BoP exercise is to assess the balance between the different disciplines of the PPAN programme, including accelerator development and computing. The appropriate breadth and balance between R&D, construction and scientific exploitation in each subject area was also reviewed. The detailed assessments are given in section 4 of this report, for each of the six areas under consideration, and, within those assessments, pointers are given for the best use of funding within different financial scenarios.

204. We find that excellent science is being carried out and delivered effectively across the PPAN programme. All areas have suffered reductions in funding and there are no longer any easily identified areas for savings that do not impact core science output.

205. We saw no pressures to suggest any major changes to the underlying balance of the programme that was carried forward from the 2013 Programmatic Review. Any major change to the balance would have to have been in response to a fundamental change to the UK research community and we see no evidence for that. We do note, however, that the community has grown, placing extra pressure on available resources.

206. We see a need to recommend modest changes, in response to evolutionary pressures, the status and development of different fields and the current funding environment. As the subsections of section 4 demonstrate, there are many areas where the disciplines have developed, which naturally lead to situations that were not foreseen or considered as part of the 2013 Programmatic Review. In most cases, responses to this are given as formal recommendations in section 4. Issues raised in section 4 that impact the programme balance are dealt with in this section.

207. Our findings assume that all external (non-STFC) funding is continuing at the same level. We have noted that at present there is uncertainty associated with the UK's departure from the EU, and the potential for severe impact on disciplines within PPAN's remit. We recognise that the terms of the UK's exit are yet to be decided and the situation needs to be monitored.

208. Whilst all PPAN disciplines have suffered in the continuing and extended flat cash environment, some disciplines are seen as being particularly at risk and we recommend taking action to protect them. Some disciplines are also recognised as requiring specific support to drive strategic development. Specific reviews have been

identified to address areas of concern and to identify areas where potential reductions could be made in the different funding scenarios that are being considered.

209. **Specific high-level findings that require action are:**

- **Computing support is at a critical level with computing demands expected to increase and an increase in capacity required in order to maintain UK competitiveness in the PPAN disciplines.**
- **Particle Astrophysics is an emerging international field, well-illustrated by the recent gravitational wave detection. We believe that the Particle Astrophysics area needs to be reviewed in order to allow it to mature into an established element of the PPAN programme.**
- **Nuclear Physics support is at a critical level, in particular, having suffered from a poor PDRA support settlement in the last round. Support is needed to provide an appropriate level for PDRA funding.**
- **Accelerator Physics support is also at a critical level, which has resulted from the way different elements of the programme have been funded.**

210. These high-level findings, along with the detailed findings of section 4, are considered within three funding scenarios: flat cash, -5 % and +5 %. The needs of the computing programme are intimately related to the needs of the science disciplines; we note that the Advisory Panels have called for better support for HPC and HTC computing, to bolster their research activities. Given the critical nature of the Nuclear Physics, Particle Astrophysics and Accelerator Physics programmes, it is recognised that any transfer of resource to the computing programme has to be found from tensioning reviews across the programmes which it supports. In addition, we find that imposing flat cash for all elements of the Accelerator Physics programme can alleviate the critical situation of that programme, but the Nuclear Physics and Particle Astrophysics programmes also require a modest increase of funds from other PPAN areas.

211. The recommendations made within section 4 address all of these issues, with the minimum of impact on the science, and this includes the identification of specific review activities. In addition to those recommendations (which we do not repeat here), we include the following further recommendations to alleviate the pressure on the PPAN programme whilst minimising the impact on approved projects:

R26: <u>Recommendation:</u> **We recommend that the PRD programme be temporarily paused to manage overspend and create some headroom for the PPAN programme for a period of no longer than two years.**

R27: <u>Recommendation:</u> **Each PPAN discipline requires the development of key technologies. We encourage the development of a cross-disciplinary technology strategy, which would be helpful for future planning and funding, and could potentially provide some savings. We suggest all communities**

consider whether this would be beneficial, and if so, whether this would require changes to the existing PRD scheme to make more strategic use of R&D funds.

212. Suspension of the PRD programme does not negate the clear need for development of new technologies for future projects. Rather, suspension allows headroom to be created within the budget without cutting committed funds. The risk of missing important technology developments increases with time and to mitigate this risk, the suspension should be temporary. We note that this period of suspension could allow time to review the programme and ensure that a future PRD scheme would make a more strategic use of a limited resource.

5.1 Funding Scenarios

213. The Sub Group was tasked with addressing three funding scenarios, i.e. flat cash, -5% and +5%. Given the PPAN programme budget of approximately £100M, these amount to scenarios involving zero, and approximately - £5M and + £5M. Taking into account the overarching strategy described above, and the findings described in section 4, the suggested funding scenario details are given here (for more detail see section 4).

214. We note that this exercise has taken place following an extended, non-indexed period of funding. The 2013 Programmatic Review noted that ‘flat cash would result in a cumulative 37% reduction in volume if extended over the next four years’. A flat cash environment, imposed on the programme over many years, clearly erodes the UK’s ability to deliver broad and high quality science, and to maintain leadership in instrumentation, facilities and exploitation. It has a significant and adverse impact on the UK’s underpinning scientific output. It risks disadvantaging the UK’s position and reputation on the international scene. It erodes the knowledge-base on which we should anticipate future UK economic and academic returns. In terms of the current Balance of Programme exercise, it is important to stress that we are considering a programme that is already under extreme pressure and has lost opportunities and encountered restrictions in its ability to maintain and develop the UK’s scientific strengths for some years. Whilst the exercise identifies excellent science in the UK, makes recommendations on a number of key issues, and considers financial scenarios, it must be remembered that this is addressing a programme that cannot be stretched much further.

Flat Cash

215. The flat-cash funding scenario responds to the conclusions of the previous sections, protecting the most vulnerable disciplines, and recognising modest uplifts in some areas, but whilst recognising that flat-cash will still drive an underlying scenario of extreme pressure in all areas, the specific losses that allow us to propose this scenario come from identified cuts in the Astronomy and Particle Physics programmes. We also recommend a temporary two year suspension of the PRD programme to create some

headroom in the PPAN programme, the temporary suspension does not negate the clear need for development of new technologies for future projects.

216. Committed funds across all disciplines should not be withdrawn.

Astronomy –

- Exploitation grants (AGP) to remain at the present cash level.
- A strategic tensioning of radio facilities available to UK astronomers and an assessment of the UK participation and leadership in the 2nd generation (uncommitted) E-ELT instrumentation should be done, potentially to identify modest savings necessary to protect grants and computing.

Nuclear Physics –

- The current NPGP grants line should be funded at a level required to support the number of fully-funded PDRA posts in the 2011 grants round.

Particle Astrophysics -

- The support for the Particle Astrophysics community should be maintained at flat cash. This includes restoring the gravitational wave consortium grant to the level necessary to maintain the current gravitational wave support at flat cash.

Particle Physics –

- Exploitation funding (PPGP) to remain at the current level.
- The DUNE and Hyper-K construction, and ATLAS and CMS Phase II Upgrades, should be funded following the recommendations of the Baseline Neutrino Experiment Review (2016), the LHC Detector Upgrade Tensioning Review – ATLAS/CMS Phase II Upgrades (2016) and the proposed programme evaluation, within the available financial envelope and noting the need for capital.

Accelerator Physics –

- Flat cash funding should continue for the PPAN accelerator programme. The Cockcroft Institute, John Adams Institute and ASTeC elements should be subject to appropriate external peer review.

Computing –

- Following the recommendations of a review of computing, support for UK involvement in PRACE and a modest increase of HPC/HTC specialist support staff effort, is anticipated.

Other -

- The PRD programme should be temporarily suspended for a period of no longer than two years.

Flat Cash Minus 5 % Scenario

217. A 5% reduction in funding will exacerbate the negative consequences of years of flat cash funding. The consequences of reducing support for the smaller areas of the PPAN programme, where levels of investment are already perceived to be critically low, could be catastrophic. To protect those areas of the programme, significant cuts would have to be applied to the Particle Physics and Astronomy programmes that still place the current and future PPAN programme at risk. Areas of UK leadership will be lost or eroded as the programme breadth shrinks, and UK scientific output will decline. UK international influence and reputation will be damaged should withdrawal from experiments or facilities result. UK leadership in instrumentation will decline if the PRD scheme cannot be reinstated (which seems unlikely in this scenario), and place the health of the future programme in jeopardy.

218. Committed funds across all disciplines should not be withdrawn.

Astronomy -

- Exploitation grants (AGP) to remain at present cash level.
- A strategic tensioning of radio facilities available to UK astronomers and an assessment of the UK participation and leadership in the 2nd generation (uncommitted) E-ELT instrumentation should be done, potentially to identify savings necessary to protect grants and computing. (This is the same as for the flat cash scenario but recognising that additional savings are required).

Nuclear Physics -

- The current NPGP grants line should be funded at a level required to support the number of fully-funded PDRA posts in the 2011 grants round (the same as the flat cash scenario).

Particle Astrophysics -

- The support for the Particle Astrophysics community should be maintained at flat cash. This includes restoring the gravitational wave consortium grant to the level necessary to maintain the current gravitational wave support at flat cash (the same as the flat cash scenario).

Particle Physics –

- Exploitation funding (PPGP) to remain at the current level.

- The DUNE and Hyper-K construction, and ATLAS and CMS Phase II Upgrades, should be funded following the recommendations of the Long Baseline Neutrino Experiment Review (2016), the LHC Detector Upgrade Tensioning Review – ATLAS/CMS Phase II Upgrades (2016) and the proposed programme evaluation recommendations. (This is the same as for the flat cash scenario but recognising that additional savings are required).

Accelerator Physics –

- Flat cash funding should continue for the PPAN accelerator programme. The Cockcroft Institute, John Adams Institute and ASTeC elements should be subject to appropriate external peer review (the same as the flat cash scenario).

Computing –

- Following the recommendations of a review of computing, support for UK involvement in PRACE and a modest increase of HPC/HTC specialist support staff effort is anticipated (the same as the flat cash scenario).

Other -

- The PRD programme should be temporarily suspended. We note that with a -5 % scenario it is difficult to see how the programme can be reinstated.

Flat Cash Plus 5 % Scenario

219. After the years of flat-cash, an increase of 5% would undoubtedly provide a significant boost to the PPAN programme, helping the UK to maintain its scientific strengths and international standing. All PPAN areas should receive a share of the uplift, following PRD restoration, the computing uplift, and the support specified for the Nuclear Physics and Particle Astrophysics disciplines, as stated in the flat-cash and -5% scenarios.

220. The increased funding scenario is discussed for the different PPAN disciplines in section 4. In astronomy, we prioritise the restoration of exploitation funding, after the erosion of many years, to allow us to maintain UK leadership in areas of the programme that have been restricted. In nuclear physics we prioritise consolidated grant support, and note the ability increased funding brings to consider new projects after many lean years. In particle physics we place emphasis on supporting the breadth of the programme, by funding world-class projects where the UK is already making key contributions. In particle astrophysics additional funds beyond the restoration of gravitational wave support to flat cash, can support investment in future projects. An increase for the accelerator programme allows a continued programme on HL-LHC beyond 2020, and the possibility of supporting small scale, important activities to ensure UK participation in key future high energy accelerators and facilities[48]. An increase for computing would fund the increased staff effort that is badly needed for enhanced HPC and astronomy HTC support.

[48] We note that any critical decisions made for the European Strategy Update may potentially require a uplift for the accelerator physics community.

221. We note that all new projects would be subject to the peer review process, but it is clear that a +5% scenario provides the overhead and flexibility to maintain and develop the scientific exploitation and the investment in strategically important projects, after a period of great pressure and inflexibility

5.2 Risk Analysis

222. Any rebalancing or cost-saving exercise has associated risks that must be recognised and managed. Any element of the PPAN programme facing cuts will inevitably lead to loss of science and the impact of that loss to the overall UK programme must be assessed. Specific cuts can lead to the UK not being involved in projects, leading to UK scientists lacking access to specific facilities, and to UK industry not being in a position to bid for projects. There is also the risk of inadequate exploitation of international subscriptions. The risks we have identified are listed and assessed in the table. Many of these are generic to all areas of the programme; those that are specific to particular fields are identified as such.

Number	Risk	Impact	Mitigation
1	Science exploitation is reduced by available funds.	a. Loss on the return of investment in projects and facilities. b. Further loss of leadership and reduced international influence on the future direction of the subject. c. Loss of global reputation in each discipline.	Funding scenarios have maintained the exploitation funding as a high priority, recommending no reductions.
2	Programme breadth is restricted.	a. A concentration to only a handful of instruments and facilities. b. Reduced capacity to understand extreme and complex phenomena. c. A reduced ability to develop the necessary technologies and/or exploit existing data and/or be able to respond in a timely fashion to new lines of research. d. Loss of opportunity for UK science and technology leadership on future lines of research. e. Loss of smaller (unfunded) groups. f. Reputational damage,	Recommendations and funding scenarios have been suggested that support vulnerable elements of the programme, have protected funds for exploitation and committed projects, and have attempted to minimize impacts on the remaining elements of the programme through identified tensioning/programme evaluation exercises, in consultation with the community where appropriate.

		should the UK need to withdraw from any experiment or facility.	
3	Lack of access to HTC resources.	a. Inability to store, access and analyse major new data sources leading to a loss of science exploitation. b. Degraded ability to exploit data. c. Potential loss of UK science lead. d. Inability to meet project commitments.	Steps taken to increase support in Computing area of the PPAN programme.
4	Lack of access to HPC resources.	a. Inability to store, access and analyse major new data sources leading to a loss of science exploitation. b. Lack of support for theoretical research programmes. c. Loss of leadership in theoretical research as unable to compete on global stage.	Steps taken to increase support in Computing area of the PPAN programme.
5	Programme balance is altered within a discipline by available funding.	a. Reduced scientific output in the UK, including the under-exploitation of UK subscriptions. b. Potential failure to obtain return on UK investment in construction projects. c. A reduced ability to develop the necessary technologies and plan optimal physics exploitation of future lines of research. d. Loss of UK science and technology leadership on future lines of research. e. Loss of UK leadership in instrumentation development and risk to specialist UK instrumentation groups.	This exercise has suggested strategic changes to the balance of the PPAN programme, identifying areas that need uplift and others that are vulnerable, and require support, whilst protecting funds for exploitation and committed projects. This does require cuts in some areas, the impacts of which will be minimised through identified tensioning/programme evaluation exercises. The net effect is a modest, rather than major rebalancing between the PPAN disciplines.
6	Loss of exploitation funding.	Reduced scientific output in the UK, including the under-exploitation of UK subscriptions.	All funding scenarios include the protection of exploitation funding.
7	Loss of agility to respond to new international developments.	Restricted funding provides no headroom to respond to opportunities.	The flat-cash and -5% scenarios clearly describe environments with very little headroom. The +5% scenario, will provide better

			flexibility than we have at present.
8	Loss of European funding opportunities on EU exit (especially ERC).	a. Loss of net effective income, funding UK science. b. Significant loss of research volume and opportunities for leadership.	Loss of EU funding (UK scientists have been particularly successful with the acquisition of ERC funding) can influence the balance of the UK's research in the PPAN area. At this stage, we recognise that the impact could be severe, but can only recommend that this is monitored as the exit is negotiated, and action considered if and when appropriate.
9	Resources not available for middle layer computing staff (Computing).	Reduced ability to run the software computing infrastructure services leading to loss of effective capacity and capability, and loss of efficiency through lack of ability to adapt software to new paradigms.	Steps taken to increase support in Computing area of the PPAN programme.
10	Shortfall of funds to meet DiRAC-3 power costs in full (Computing).	Reduced capacity available to PPAN community while maintaining capability of system.	Steps taken to increase support in Computing area of the PPAN programme.
11	External capital funding for DiRAC-3 not forthcoming (Computing).	The HPC capacity of DiRAC-2/2.5 is now outdated, resulting in PPAN supported theoretical physicists and astrophysicists becoming less and less competitive with international peers.	Awaiting decision from BEIS after Autumn statement. Need to assess options when this is known.
12	External funding for UKT0-HTC not forthcoming. (Computing).	a. CPU and disk capacity needed to handle the data arising from new approved projects will not be available. UK scientists will be unable to analyse data in timely and competitive way. Loss of publications and in particular loss of publications with lead author. b. No resources to share and hence the spirit of cooperation and sharing initiated under UKT0 will not be taken advantage of.	Awaiting decision from BEIS after Autumn statement. Need to assess options when this is known.
13	Lack of ability to	PRD funding is aimed at the	The decision to pause the

	develop new technology due to pause of PRD programme.	development of technology for future scientific applications. Loss of that funding will influence future project development opportunities.	PRD programme is not taken lightly. It is recognised as an option to make cuts that does not impact exploitation or committed project funding. Nevertheless, the sub-group recommends the reinstatement of the PRD programme as soon as possible.

6. Education and Training

223. Education and training is allocated 17% of the Programmes Directorate budget. The funds are used to support studentships and fellowships in PPAN science areas, and schools and workshops for student and early career researcher training.

224. Students contribute significantly to the delivery of the science programme by their thesis work, and to the wider economy by their subsequent employment. We note and support the recent STFC accreditation exercise to ensure that all departments provide good quality, broad training to students. The skills acquired during a PhD are highly valued by UK companies[49]. Students undertake many types of employment post PhD, and increasingly enter the knowledge economy sector due to the advanced computing skills they learn when analysing data. The 2016 STFC Career Path study[50] found that of the PhD students entering the private sector (28% of the 941 students who had completed their PhD between 2012 and 2015), 70% took jobs in software development, data analysis, engineering or finance.

225. The PPAN community believes that any reduction in the number of studentships would limit UK physics output, and adversely impact the wider economy. We note that studentships are funded from an overall flat cash budget, and maintaining (or raising) student numbers places pressure on the other areas of the programme. We welcome recent initiatives to increase student numbers in response to community and employer demand, i.e. the recent Centre for Doctoral Training (CDT) in data intensive science, and note that such specialist CDTs provide a mechanism to bid for additional funds from BEIS to address skills shortages.

226. Although Ernest Rutherford Fellowships have remained constant in number, the number of PDRA positions has declined, the postdoctoral fellowship scheme has been lost and a general lack of independent early career fellowships has been noted[51]. We

[49] As evidenced by the higher salary PhD students earn, see for example http://www.stfc.ac.uk/files/a-study-of-the-career-paths-of-pparcstfc-funded-phd-students-final-report/
[50] http://www.stfc.ac.uk/files/first-destinations/
[51] AAP response to Balance of Programmes Sub Group questions.

note that this has resulted in career pathways for early career researchers deteriorating during the past decade.

227. In contrast some academic communities have recently grown in size. Amongst many reasons for this, we noted the growth in physics undergraduate numbers[52], the attractiveness of PPAN science to undergraduates, the success of PPAN scientists at procuring European funding and potential Research Exercise Framework hiring strategies. We note the diminishing fraction of academic FTE that can be funded in the current financial environment, which longer term could lead to universities regarding these areas as less attractive options when hiring staff.

228. Some community skills shortages have been identified that could be addressed by providing additional training courses, schools or workshops. These skills shortages include software engineering[53], data intensive computing skills[51], firmware[54] and novel instrumentation development[53]. The community has also identified a shortage of skilled technical effort[55], software engineers and experienced project managers[56]. We note that care should be taken to resource these areas sufficiently when planning projects.

7. Economic and Societal Impact

229. UK groups in universities and the national labs make world leading contributions to technology through the development of a range of novel detectors, materials, detection and computing techniques for the PPAN programme. Examples include silicon sensors, cryogenics, high speed electronics, ultra-low loss materials, efficient algorithm design and advanced statistical methods with wide applications in industry. Many more examples of UK specialities are available [53,55,56,51,54]. UK industry benefits directly from collaborating with scientists in instrument or detector development[57] and building the contacts necessary to secure subsequent contracts. Where industries have established a track record of successful delivery, they may be subsequently contracted directly, e.g. to supply spacecraft[58] or instruments.

230. Support for developing underpinning technology has been provided by the PRD scheme. Project grants provide longer term support. It has been suggested that there is a perceived gap in funding technology development in areas insufficiently mature to

52 See, for example https://www.iop.org/publications/iop/2012/file_54949.pdf and the latest HESA data for a steady growth in physical science undergraduate numbers.
53 SSAP response to Balance of Programmes Sub Group questions
54 PPAP response to Balance of Programmes Sub Group questions
55 NPAP response to Balance of Programmes Sub Group questions
56 PAAP response to Balance of Programmes Sub Group questions
57 For example, the RAL/e2v collaboration that supplies camera systems for NASA missions, or Micron semiconductors that fabricate silicon detectors for PP and NP experiments.
58 For example, Airbus Defence and Space (UK) in Stevenage built large parts of Rosetta, and will help construct ESA's JUICE spacecraft https://airbusdefenceandspace.com/newsroom/news-and-features/airbus-defence-and-space-signs-e350m-contract-to-develop-and-build-juice-spacecraft-esas-next-life-tracker-inside-the-solar-system/

be deployed in experiments[54,53]. PPAN suggest reviewing whether the current mechanisms could be altered in any way to address this issue. The review could examine whether the UK would benefit from an overall technology strategy, if the PRD scheme should be reformed, and whether a single (new) body should form strategy and direct funding. We endorse the suggestion to derive a technology strategy and determine appropriate funding mechanisms. We suggest that the review also consider the match with STFC commercialisation schemes (for example, CLASP, IPS, follow on funds, impact acceleration accounts and others shown in[59]). We note that at present, there is limited support in PRD to fund software development projects.

231. PPAN technologies have yielded many opportunities for commercialisation across a wide range of industry sectors, including grid computing and software, spectroscopy, stem cell research, decontamination technology, unique 3D sculpture creation, educational app development and scientific instrumentation manufacture. To give just three examples, technology developed for gravitational wave detection has been used to grow new bone by vibrating stem cells, and could lead to cheaper methods to treat spinal trauma and osteoporosis[60]. Portable spectrometers, based on those developed for space applications, have been developed to detect gas leaks at petrochemical facilities[61]. Detector technology developed for use in nuclear physics experiments has been employed in the nuclear decommissioning and security sectors[55].

232. The full economic impact of technological developments requires further work to completely capture and evidence. Some studies have been performed to quantify the economic impact of innovations like the World Wide Web[62], developed at CERN. We note that Pathway to Impact statements in consolidated grant applications provide an additional source of information for specific UK PPAN impacts, as do ResearchFish entries and Research Excellence Framework impact statements.

233. PPAN science offers many opportunities for societal impact through public engagement. PPAN science is inspirational, as the strong public and press interest in the recent Rosetta mission and the Higgs boson and gravitational wave discoveries demonstrate[63]. Astrophysics, nuclear and particle physics are cited as the three most popular subjects that attract undergraduates to physics degrees[64], producing more STEM graduates and giving greater economic impact to the economy[65].

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59 https://www.stfc.ac.uk/innovation/ways-to-work-with-us/
60 http://www.telegraph.co.uk/science/2016/07/05/good-vibrations-jiggling-stem-cells-that-turn-into-bone-offer-re/
61 http://www.stfc.ac.uk/news/clasp-environment-funding/
62 See, for example, http://www.mckinsey.com/industries/high-tech/our-insights/the-great-transformer (2011) which estimates that the Internet accounted for 21% of GDP growth in mature economies over 5 years, or "The impact of e-commerce on the UK economy" (Office for National Statistics, 2015), which estimated that almost 20% of 2013 UK business turnover resulted from e-commerce.
63 For example, 12 million people in the UK watched television coverage of the Higgs boson announcement, and a further 14 million followed it on radio. http://www.stfc.ac.uk/news/the-higgs-bosonwhat-does-this-discovery-really-mean/
64 A 2007 survey of 800 undergraduates, see https://www.iop.org/publications/iop/2009/file_38212.pdf
65 The CBI estimate that the economic activity of physics-based sectors accounts for 6.4% of UK economic activity.

234. Members of the PPAN community undertake many public engagement activities to communicate their science as a matter of course. For example, ‘Stargazing Live’ is now an annual event, spearheaded by BBC programmes, to which a wide range of astronomy groups regularly contribute[66]. Nuclear and Particle Physics Masterclasses are run annually by university groups to engage schoolchildren in research. PPAN scientists give talks to a variety of audiences, exhibit their science[67], blog, construct apps and use STFC small and large award and public engagement fellowship schemes to fund and explore innovative ways of engaging. These public engagement activities increase communication skills; skills that also enhance the effectiveness of scientific presentations, improve teaching ability and that are in demand by employers.

235. Besides engagement, societal impact includes the provision of national capability to protect our assets. The solar, heliospheric and space plasma communities have applied their expertise to space weather. Severe space weather is on the national risk register. In extreme cases it can lead to power blackouts, damage national grids and satellites in space. Members of the PPAN community advise government, work with the Met Office to address the national interest, and contribute to the emerging ESA Space Weather Programme.

236. We note that ResearchFish and Research Excellence Framework impact statements and data could be used to survey and evaluate the societal impact arising from these activities, given that the information is passed to these databases.

8. Future Reviews

237. In approving the Balance of Programme exercise at its April 2016 meeting, Science Board agreed that this exercise will take place on a three year cycle. The next review should be completed by December 2019. The following points are emphasised to ensure an effective exercise takes place in 2019.

238. The BoP exercise commenced during the summer 2016. This was found challenging by the Advisory Panels who had to respond to the BoP questions in September and needed to consult their communities. It is essential that any future exercise includes effective interaction with the Advisory Panel chairs throughout the process. The next BoP exercise should take into account the timing of future evaluations (e.g. so as to avoid major holidays or exam periods), and ensure that the duration of the exercise provides sufficient time for proper consultation and feedback at different stages of the review. It would be beneficial for these exercises to start during the spring period of the relevant year (Spring 2019).

[66] See e.g. http://gostargazing.co.uk/2017/01/15/bbc-stargazing-live-2017/

[67] For example, in the 2016 Royal Society Summer Science Exhibition 7 of 20 exhibits related to PPAN science areas or STFC facility work.

239. Advisory Panel chairs should be provided with sufficient warning before the process starts, and given a clear understanding that this is a cyclical process, with relevant dates, to help them plan their input into this exercise. The Advisory Panel chairs also need to understand the timescales for the programme evaluation exercises for their own subject area.

240. The BoP evaluation exercise necessarily makes considerable use of the Advisory Panel roadmap documents and communications with the Advisory Panel chairs. Recognising this, it would aid the process if roadmaps are updated by the spring of 2019, before the BoP exercise starts. These documents should include clear statements relating to the priorities, breadth and future of each field in the UK.

241. It proved difficult to provide adequate recommendations without some examination at the level of projects. The forthcoming individual programme evaluations should cover all aspects of that programme and provide clear scientific and project priorities in each of the subject areas, which will aid future BoP exercises. It is noted that some specific reviews have been recommended in this exercise and STFC will need to consider how best this feeds into the subject area review.

242. The following reviews, noting any time constraints, have been highlighted in order to aid scheduling before the next Balance of Programme exercise. STFC should consider how best to structure this so that the reviews are completed by spring 2019.

- Particle Physics Programme Evaluation (2017/18)

  Recommendation R12: “We recommend a programme evaluation be carried out in late 2017, with a view to ensuring that the programme is optimal, balanced, coherent and sustainable.” The evaluation should be used to inform subsequent funding decisions.

  A decision on the construction phases for DUNE and Hyper-K is needed by December 2018.

- Radio Astronomy Review (2017)

  Recommendation R5: “We recommend an immediate review of UK involvement in all on-going, and planned, radio facilities and experiments…”

  In March 2018, the contract between STFC and Jodrell Bank in respect of e-MERLIN operations comes to an end, and a decision on bridging funds will be needed by then. STFC will also need to decide on the continuation of LOFAR by mid-2018. Over the next two years, there will be significant milestones for the SKA, including convention signing (Q1 2017), construction phase approval (July 2018) and CDR for Phase 1 R&D (Q1 2018).

- Particle Astrophysics Programme Evaluation (2018)

  This review should include the Particle Astrophysics review as per recommendation R15.

- Accelerators Programme Evaluation (2017)

  Institutes have been given one year of bridging funding ahead of a review. A strategy review is already underway.

- Computing Programme Evaluation (2018)

Part of the planned review before the next BoP exercise in 2019.

- Astronomy Programme Evaluation 2018

  Part of the planned review before the next BoP exercise in 2019.

- Nuclear Physics Programme Evaluation (2018)

  Part of the planned review before the next BoP exercise in 2019.

R28: **Recommendation: We recommend that STFC reflects on the lessons learnt from this BoP exercise in order to enable a more effective process in future and to ensure the process is communicated in a timely fashion.**

243. During the BoP exercise period, the need for size of community data was highlighted. However it was difficult to obtain the desired data that was consistent across the programme, and this was an area of significant concern for the Sub Group. It is important to understand the relative sizes, vibrancy and productivity of the different communities of the PPAN disciplines in the UK. These are important elements of current and future strategies and the balance of the PPAN programme and should be monitored in a consistent way. STFC also needs to understand the level and origin of all sources of community funding and any associated strategic implications, for example, the impact of the loss of European funding on the PPAN communities which is expected to become more significant in the future, the Global Challenge Research Fund and other sources of research funding.

R29: **Recommendation: We recommend that STFC must consider how best to acquire and monitor community size information accurately and consider what other data might be helpful in future.**

244. Adequate timescales to prepare the report to Science Board should also be taken into consideration. Preparation of this report fell over the Christmas period, which resulted in little time for iteration. An exercise which starts earlier in the year and is able to circulate the draft for several iterations would be more effective.

245. After the BoP exercise is reviewed at Science Board, the timescales and steps of completing the exercise through STFC's internal review and procedures need to be clarified. Furthermore, the details of how and when the findings will be communicated to the PPAN community, and how much of the report will be public, needs to be determined.

9. Conclusions and General Comments

246. The STFC PPAN programme provides the strategic funding for the UK's high-profile and world-class research communities in astronomy, nuclear physics, particle

astrophysics and particle physics, and the associated areas of computing and accelerator physics. The balance of funding between the disciplines should be assessed periodically, along with the health and progress within the different disciplines. This process will recognise the evolution of the research environment and of the financial environments and ensure the most effective application of available resources. Thus, this BoP activity has allowed us to consider the current programme and, through a process of consultation, discussion and assessment to make a set of recommendations, including the application of a set of funding scenarios in today's constrained financial environment.

247. The exercise focused on the detailed assessments of each discipline, which are given in section 4 of this report, and the overall balance and financial scenarios, which are detailed in section 5. We present this to Science Board, the STFC Executive Board, STFC Council and the community at large as a rational plan that allows the PPAN programme to function in the most effective way for the UK's scientific community at this time. That plan does not demand major changes or sweeping cuts, but focuses on modest, strategic activities to best balance the programme for today's scientific needs.

248. We note that, by their very nature, the global research environment and the overarching financial environment, change with time; we are always in a transient state that makes it very difficult to find the best time to assess the programme. For example, the uncertainties of the UK's exit from the EU, the wait for decisions in response to requests made for the 2016 Autumn statement, the establishment of UKRI in 2018, and the impacts of new funding opportunities such as the Global Challenges Research Fund and the Industrial Strategy Challenge Fund can all have an influence on the PPAN programme in ways that are not yet known. We note this in our assessments and recognise that future Balance of Programme exercises must consider their impact, both positive and negative.

249. This has been a demanding exercise, requiring dedication and openness from a number of key individuals beyond the Sub Group members, including the STFC Advisory Panel chairs, the STFC Programme Managers and the day to day support from Charlotte Jamieson and Tahmina Aziz from Swindon Office. The Sub Group members wish to thank them all for their efforts.

Appendix 1. Terms of Reference

Balance of Programme Science Board Sub Group

The purpose of the balance of programme exercise is to ensure the balance of STFC's PPAN Research programme is the most appropriate.
The Science Board Sub Group will:
Identify the most appropriate balance between STFC's key research areas

- Astronomy
- Nuclear Physics
- Particle Physics
- Particle Astrophysics
- Accelerators for the above
- Computing for the above

Ensure there is appropriate breadth within each research area including development for future opportunities and scale of projects.

Identify the most appropriate balance between R&D, construction and scientific exploitation both across the programme and in each subject area.

Recommend financial planning that will ensure provision for STFC's highest strategic priorities.

Recommend the appropriate balance of programme for the following financial scenarios

- Flat cash
- Flat cash + / - 5%

Appendix 2. Members Biographies

Chair: Professor Richard Harrison (RAL Space)

I am Chief Scientist at RAL Space, the space department of the STFC Rutherford Appleton Laboratory. I am a solar physicist, of 37 years experience, specialising in the physics of the solar atmosphere and solar impacts on Earth. I have led space-borne instruments aboard NASA and ESA spacecraft for the last 24 years, involving extreme-UV spectroscopic plasma diagnostic measurements of the solar atmosphere, and coronal and heliospheric imaging. So, I fall into the Astronomy part of PPAN, but with heavy involvement in the UKSA programme. I am a member of Science Board and previously served on AGP.

Deputy Chair: Professor Tara Shears (Liverpool)

I am an experimental particle physicist at the University of Liverpool. My focus is testing the Standard Model at the high energy frontier, with the LHCb experiment at the Large Hadron Collider (in the electroweak and strong sectors; I have worked in heavy flavour physics previously). I lead our local Liverpool LHCb group. With regard to STFC, I have served as ETCC chair (finishing September 2016) and ex-officio member of SEAB, and am now a member of Science Board.

Professor Gary Barker (Warwick)

I am Professor of Particle Physics at the University of Warwick where I head the Experimental Neutrino Group. My focus is the measurement of CP-violation in the neutrino sector and we are contributing to three long-baseline neutrino oscillation projects: T2K (Japan), DUNE (USA) and Hyper-Kamiokande (Japan). I am also involved with aspects of neutrino detector and beam line development and the search for new physics from the Hidden Sector with the SHIP project. I have contributed to several STFC committees/reviews and was a member of the Particle Physics Grants Panel from 2007-2012.

Professor Stewart Boogert (Royal Holloway, University of London)

I am deputy director of the John Adams Institute for Accelerator Science at Royal Holloway. I have an early background (PhD/post-doc) in analysis of particle physics experimental data. Over the last 10 years (as a lecturer/reader/professor) I have worked in accelerator science developing experimental beam instrumentation systems at CERN, DESY, SLAC and KEK. The focus has been on high energy frontier machines such as the linear collider, LHC and high luminosity LHC. I am a member of the STFC Accelerator Strategy Board (ASB) and the UK representative to the European Committee for Future Accelerators (RECFA).

Professor Peter Clarke (Edinburgh)

I am a particle physicist at the University of Edinburgh and Chair of ‘eScience’. I was previously head of the particle physics research group at UCL. My last three experiments were OPAL/LEP (e+e-), ATLAS, and now LHCb, and also an attachment to LSST.

My most important previous work was in making the defining measurements of the properties of the Z boson to very high accuracy at LEP. My current physics focus is on measuring CP violating parameters through the decay of heavy beauty mesons at LHCb. I am also involved in computing and data handling provision for the LHC and more recently as an enabler for all of PPAN science through work towards common working and also the work going on with RCUK and BEIS to obtain an investment in eInfrastructure.

I was Chair of the STFC Computing Advisory Panel (CAP) for about 7 years. I am currently a member of Science Board and Deputy project leader of the GridPP project (UK LHC computing).

Professor Antonella De Santo (Sussex)

I am a Professor of Physics at the University of Sussex, where I am Head of Experimental Particle Physics and the ATLAS team leader. My current research focuses on the search for new physics and triggering at ATLAS. Prior to joining ATLAS, for over a decade I had been working on neutrino physics, with focus on short- and long-baseline neutrino oscillation experiments (NOMAD and HARP experiments at CERN; MINOS experiment at FNAL). Within STFC, I have served on PPRP (2007-10, core member from 2008) and the PPGP (2011-15).

Professor Janet Drew (Hertfordshire)

I am a professor of astrophysics working at the University of Hertfordshire. I currently sit on ESA's Astronomy Working Group and the UK Space Advisory Committee, and have recently served a term on STFC's Astronomy Grants Panel. For over 20 years I have been a member of the MNRAS board of editors, handling papers on star formation and multi-wavelength Galactic/stellar astronomy and theory. My main research activity over the last decade has been as PI of two linked optical photometric/imaging broad- and narrowband Galactic Plane surveys. In 2009-10 I chaired an international panel reporting on streamlining the use of Europe's 2-4m class telescopes.

Professor Simon Hands (Swansea)

BA 1983 Cambridge PhD 1986 Edinburgh. I am a theoretical and computational physicist with expertise in lattice field theory, with over 150 publications spanning particle, nuclear and condensed matter physics. After postdocs in Oxford, Illinois, Glasgow and CERN I worked at Swansea University since 1993. I chaired the Scientific Board of the European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT* Trento) 2010-12 and have chaired the STFC Particle Physics Grants Panel (Theory) since 2011. I am also a member of the DiRAC Management Board and the editorial board of the European Journal of Physics A. I was elected Fellow of the Learned Society of Wales in 2013.

Professor David Ireland (Glasgow)

I am a Professor of Physics and head of the Nuclear Physics Group at the University of Glasgow. My area of research interest is in hadron physics, with a particular emphasis on the spectroscopy of light baryons and mesons. The experimental programme is mostly based at Jefferson Lab in the US. In terms of STFC work, I have previously been the chair of the Nuclear Physics Grants Panel, and as a non-core member of Science Board, I served on the PPAN subgroup that carried out the most recent STFC Programmatic Review.

Professor Bob Nichol (Portsmouth)

I am Director of the Institute of Cosmology and Gravitation and Professor of Astrophysics at the University of Portsmouth. I have over 25 years' experience with large astronomical surveys including roles in the Sloan Digital Sky Survey, the Dark Energy Survey and Euclid. Over the years, I have developed a number of interests including cosmological measurements (using multiple probes), galaxy morphology, galaxy evolution as a function of environment, statistics, and public engagement. I have also served STFC as both a chair of the AAP and a member of Science Board.

Professor Alberto Vecchio (Birmingham)

I'm Head of the Astrophysics and Space Research group at Birmingham. My work is primarily in the area of relativistic astrophysics and more specifically gravitational waves. I've been heavily involved in LIGO for 15+ years (ranging from instrumentation to data analysis and science exploitation), and also more recently pulsar timing arrays. According to the STFC classification, I am particle astrophysics and astronomy, and given my long-standing interest in LISA (and Birmingham involvement in LISA-Pathfinder), I have some contact/overlap with the UKSA programme.

Appendix 3. Documentation List

Document
2013 Programmatic Review report
Key Science Questions
Astronomy Advisory Report
Solar System Science Advisory Report
Nuclear Physics Advisory Report
Particle Physics Advisory Report
Particle Astrophysics Advisory Panel Report
Computing Advisory report
Computing Strategic review
Accelerator Review report
LHC upgrade Tensioning Review 2014
ATLAS/CMS Tensioning review*
Long Baseline Neutrino Experimental Strategic Review *
Exoplanet Review
Astronet Science Vision
Astronet Infrastructure Roadmap
Finance: what was spent in each area (top line figure)
Programme Managers Report (6 reports) - High level Summary of current plan, changes in the programme or the funding landscape since 2013 Review. - High level summary of planned programme, changes in the programme or in the funding landscape for the future to consider - Areas overrunning on. Areas STFC are overcommitted on - Critical decision dates for each area, plus financial critical decision dates
Brief overview of projects in areas
Financial summary of the current programme plus 5 years back from last CSR period.
Financial summary of planned programme
Advisory Panels Response to BoP Questions (6 reports)

*The following conflicts of interest were noted:

- ATLAS

Direct (Antonella DeSanto)
Institutional (Tara Shears, Peter Clarke, David Ireland, Alberto Vecchio, Stewart Boogert, Richard Harrison, Gary Barker)

- CMS

Institutional (Richard Harrison)

- DUNE

Direct (Gary Barker, Peter Clarke)
Institutional (Antonella DeSanto, Tara Shears, Richard Harrison, Alberto Vecchio)

- Hyper-K

Direct (Gary Barker)
Institutional (Richard Harrison, Stewart Boogert, Peter Clarke, Tara Shears)

Appendix 4. Advisory Panel Questions

1. Please provide an update on any changes to your most recent science roadmap. Specifically, please ensure that:

   - the scientific priorities of your area are clearly listed, taking into account any recent changes;

   - you list activities/projects to cater for potential involvement in new or emerging opportunities;

   - in order to enable support for new opportunities and the stated priorities, you identify any areas where the level of support could be reduced.

2. The last programmatic review advocated broadening the programme whilst maintaining the most appropriate balance between R&D, construction, operation and scientific exploitation.

   - Do you believe the current programme activities have achieved this?

   - Please highlight any particular successes (or failures).

3. It was recognised at the time of the last programmatic review that should a flat-cash funding environment continue the balance of programmes should be re-examined to ensure sustainability. In the light of this, could you consider the following? (Please note that we recognise that the Advisory Panels do not normally consider financial details of the programme, so the responses must be educated assessments of the situation).

   - What steps should be taken to obtain the appropriate balance of adequately supported projects in your field?

   - How can the field be scientifically sustainable in a continuing flat cash/no inflation environment over the next 5 years?

   - At a strategic level, broadly speaking what would be the impact of reduced/increased funding (+/- 5%)?

4. In addition to supporting our science we recognise that the science programme results in the development of enabling technology that builds capability for UK.

- What are the key technologies in your area where the UK is world leading and how do they generate benefit for the UK?

- How could STFC support the development of critical technologies that will be essential to support the field in the future?

5. Our science programmes depend on a pipeline of skilled people.

   - Do you feel the current balance that exists for students, PDRAs, academic staff, technicians, engineers, software engineers etc. is roughly correct in your field?

   - Are there sufficient skills, experience and leadership for the current and projected future programme or are there areas where these are lacking?

   - Please comment on how this field generates skills impact for the UK.

6. Our science areas are increasingly reliant on mid and high level computing needs (including software development).

   - Is the current computing resource available for the field adequate?

   - What are the foreseen future computing resource needs of the field?

   - Do you have access to adequate computing resources for archive/open data support in your field? Please comment on how you consider this will develop in 5 years.

Computing Advisory Panel specific question

- As part of the computing strategy review you were asked to comment on the balance and level of support of High Performance Computing (for theory) and high throughput computing for data-intensive science. What, if anything, has changed since your response at that time?

Appendix 5. Key Science Challenges

A: How did the universe begin and how is it evolving?

Key Science Questions	Astronomy	Particle Physics	Nuclear Physics	Particle Astrophysics
A:1. What is the physics of the early universe?	X	X	X	X
A:2. How did structure first form?	X	X		
A:3. What are the roles of dark matter and dark energy?	X	X		X
A:4. When were the first stars, black holes and galaxies born?	X		X	X
A:5. How do galaxies evolve?	X			
A:6. How are stars born and how do they evolve?	X			X

B: How do stars and planetary systems develop and is life unique to our planet?

Key Science Questions	Astronomy	Particle Physics	Nuclear Physics	Particle Astrophysics
B:1. How common are planetary systems and is ours typical?	X			
B:2. How does the Sun influence the environment of the Earth and the rest of the Solar System?	X			
B:3. Is there life elsewhere in the universe?	X			

C: What are the fundamental constituents and fabric of the universe and how do they interact?

Key Science Questions	Astronomy	Particle Physics	Nuclear Physics	Particle Astrophysics
C:1. What are the fundamental particles?		X	X	X
C:2. What is the nature of space - time?	X	X		X
C:3. Is there a unified framework?		X		X
C:4. What is the nature of dark matter?	X	X		X
C:5. What is the nature of dark energy?	X	X		
C:6. What is the nature of nuclear and hadronic matter?		X	X	X
C:7. What is the origin of the matter - antimatter asymmetry?		X		

D: How can we explore and understand the extremes of the universe?

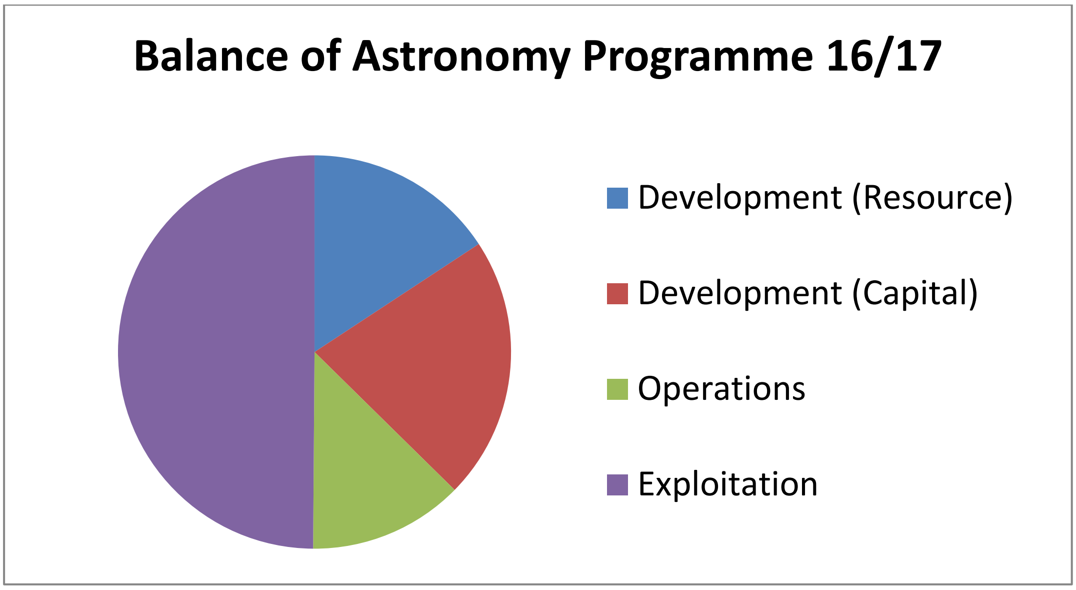
Key Science Questions	Astronomy	Particle Physics	Nuclear Physics	Particle Astrophysics
D:1. How do the laws of physics work when driven to the extremes?	X	X	X	X
D:2. How can high energy particles and gravitational waves tell us about the extreme universe?	X	X	X	X
D:3. How do ultra-compact objects form, what is their nature and how does extreme gravity impact on their surroundings?	X			X

To note: Computing underpins all PPAN science areas and accelerators provide necessary facilities for a significant proportion of PPAN science.

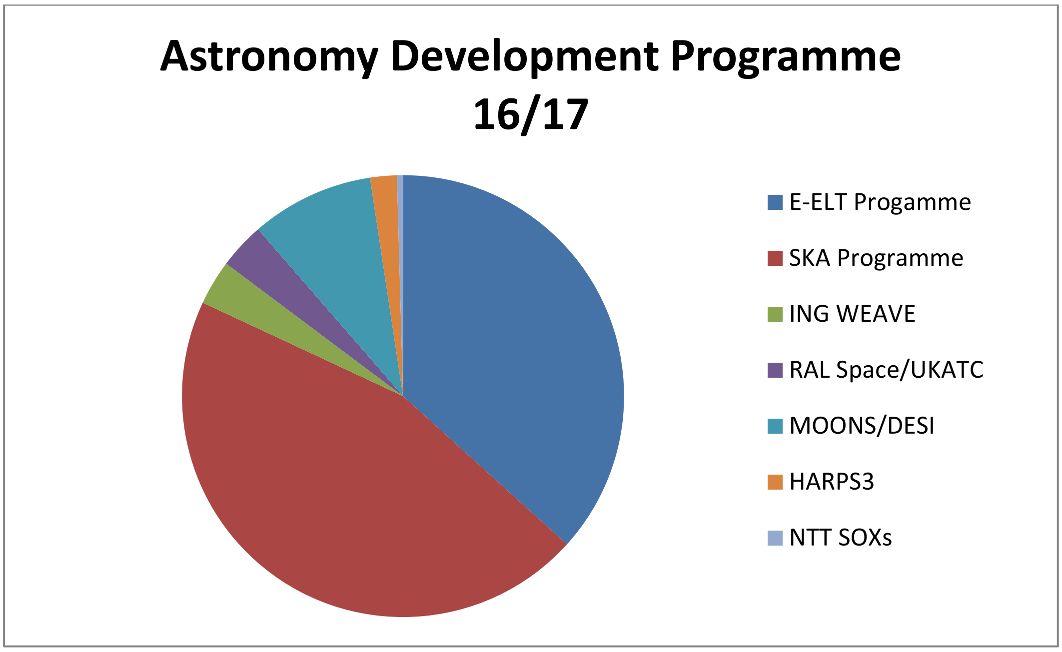
Appendix 6. Pie charts of Subject areas

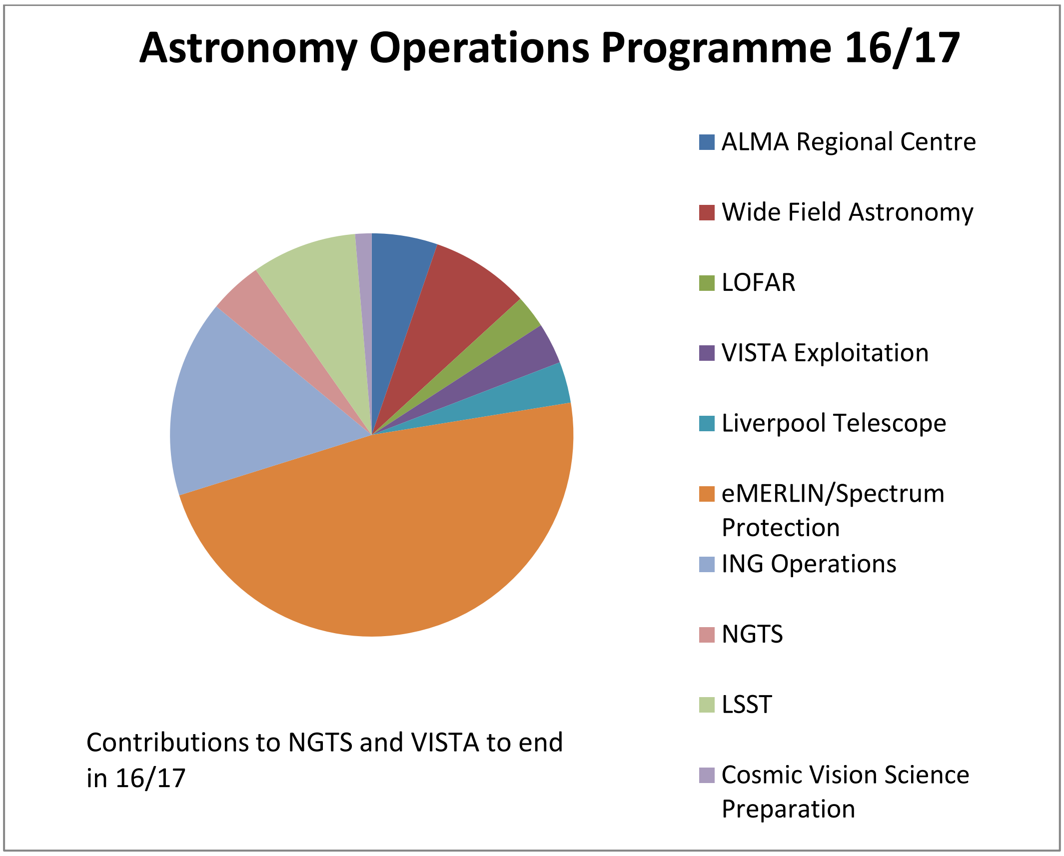
Astronomy

Astronomy programme balance and breadth - based on 2016/17 budget



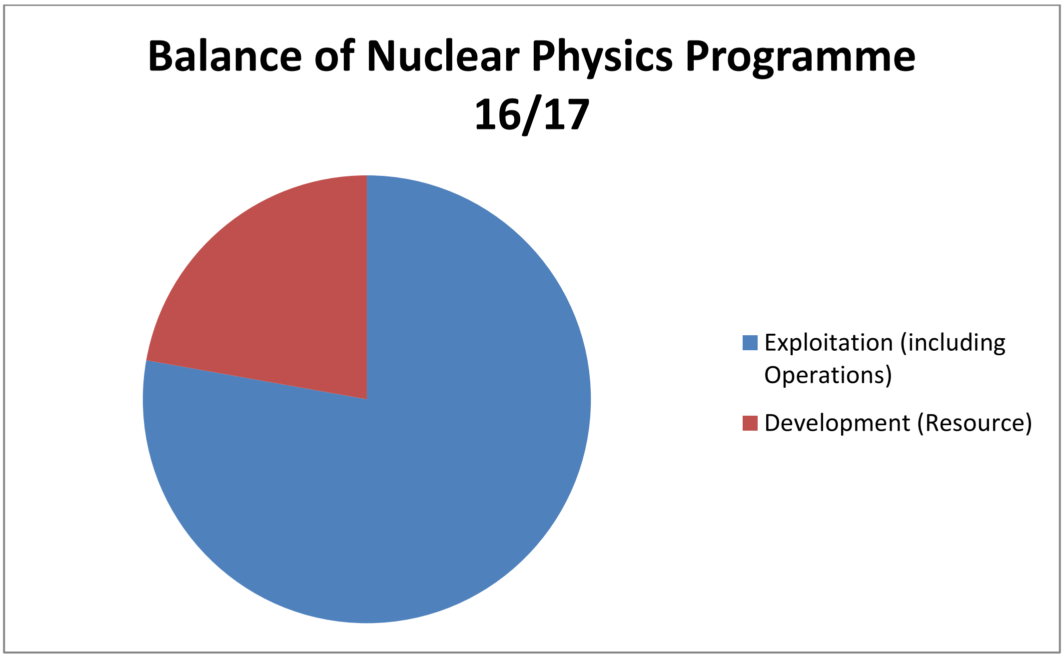
The below graphs show the breakdown of the development and operations spend within the Astronomy programme.

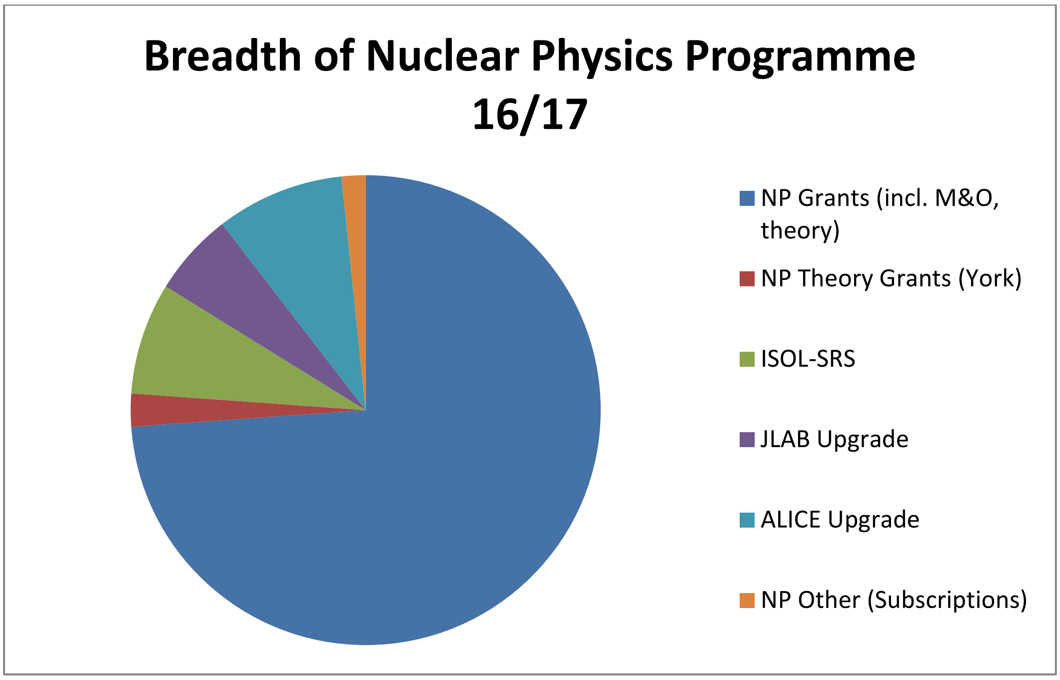



Astronomy Operations Programme 16/17
ALMA Regional Centre
Wide Field Astronomy
LOFAR
VISTA Exploitation
Liverpool Telescope
eMERLIN/Spectrum Protection
ING Operations
NGTS
LSST
Cosmic Vision Science Preparation
Contributions to NGTS and VISTA to end in 16/17

Nuclear Physics

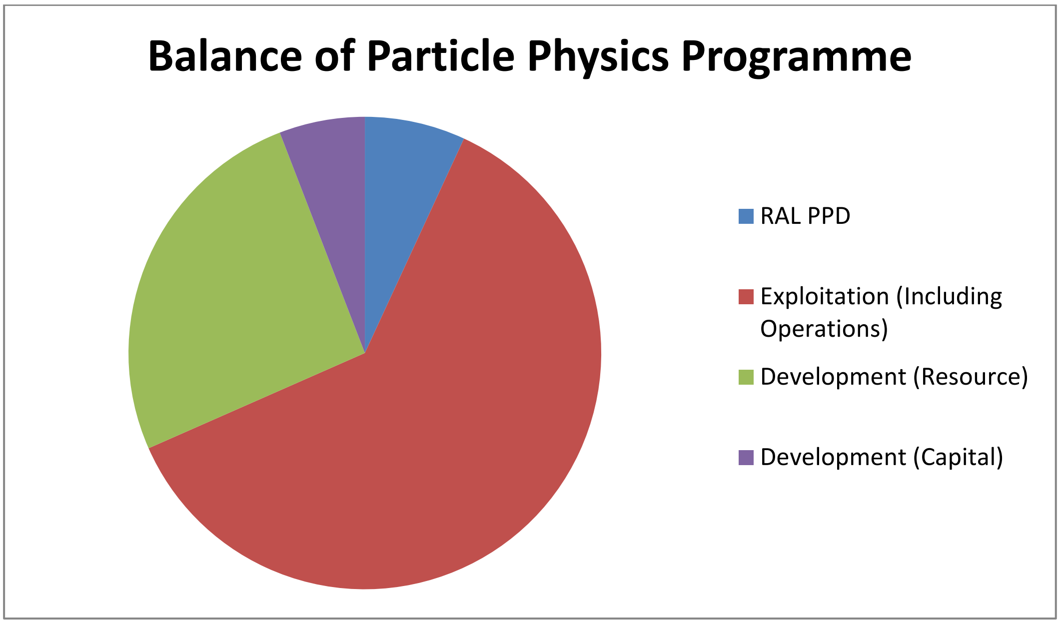
Nuclear Physics programme balance and breadth - based on 2016/17 budget

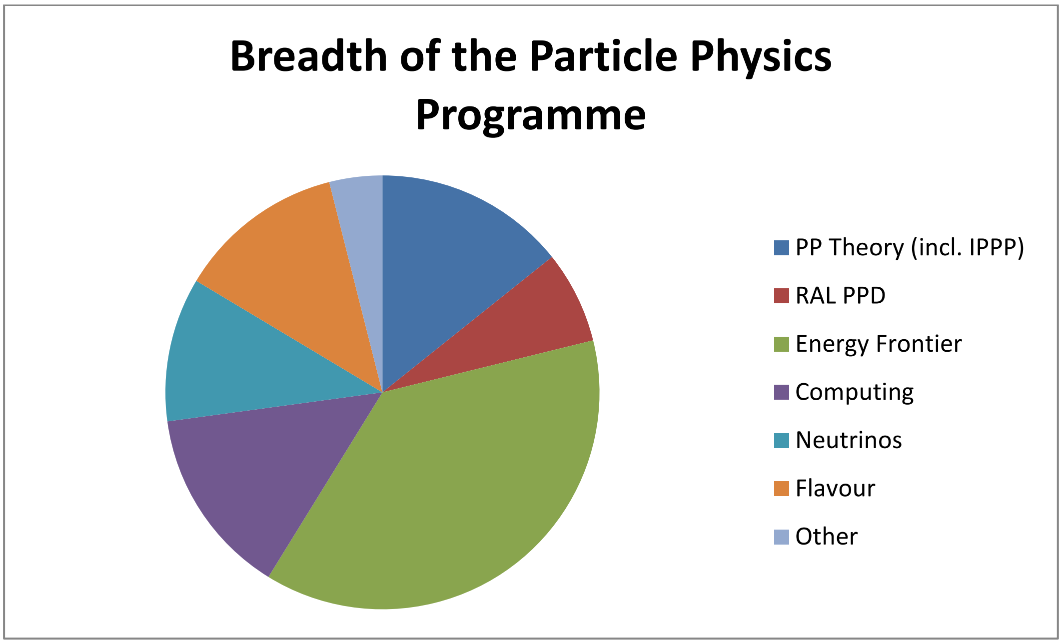




Particle Physics

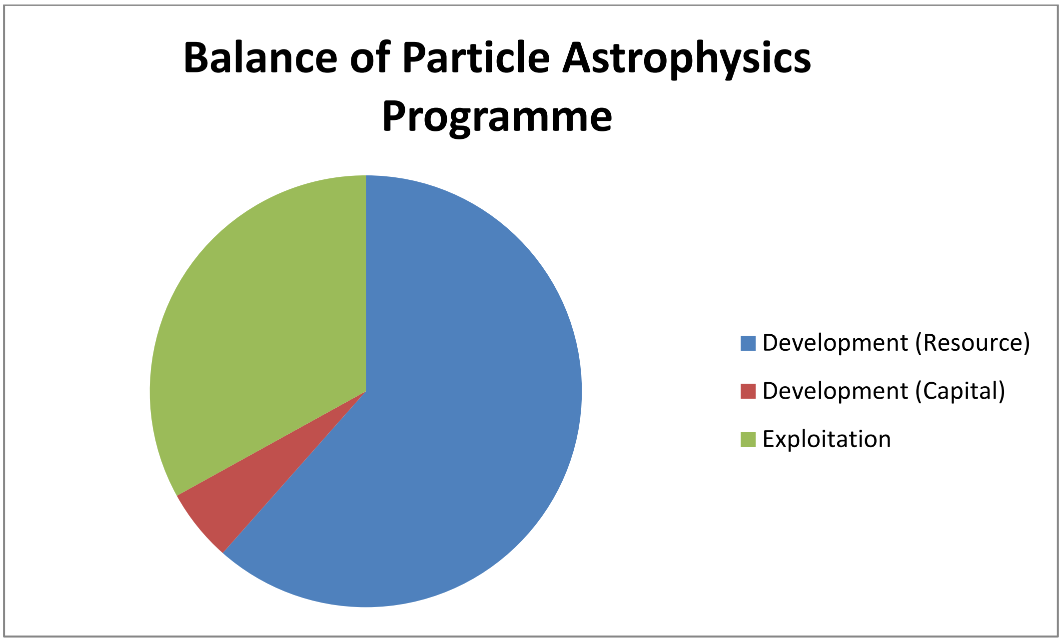
Particle Physics programme balance and breadth - based on 2016/17 budget

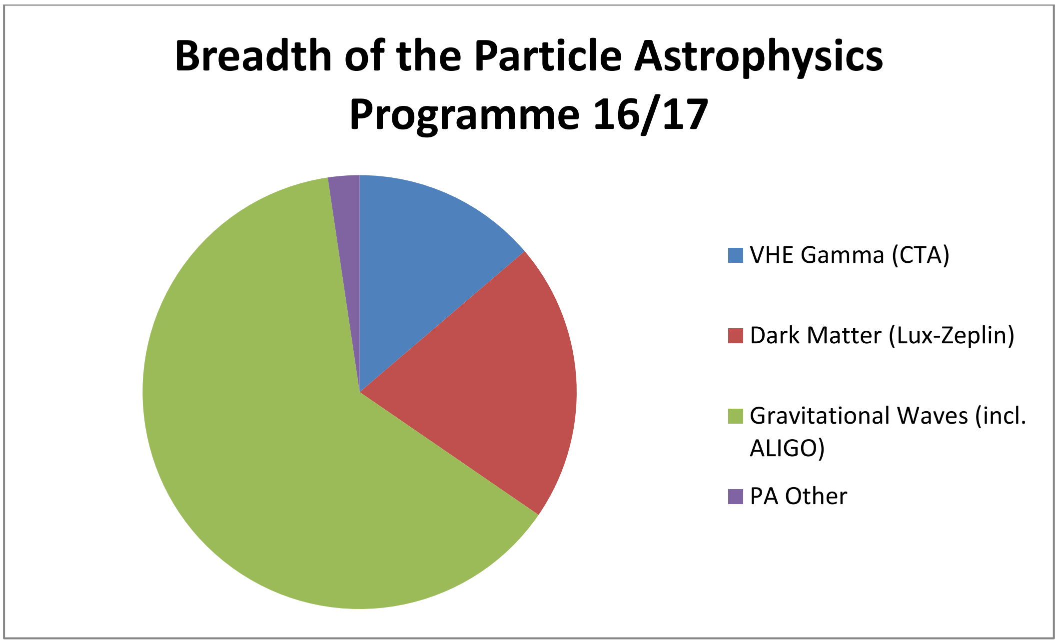




Particle Astrophysics

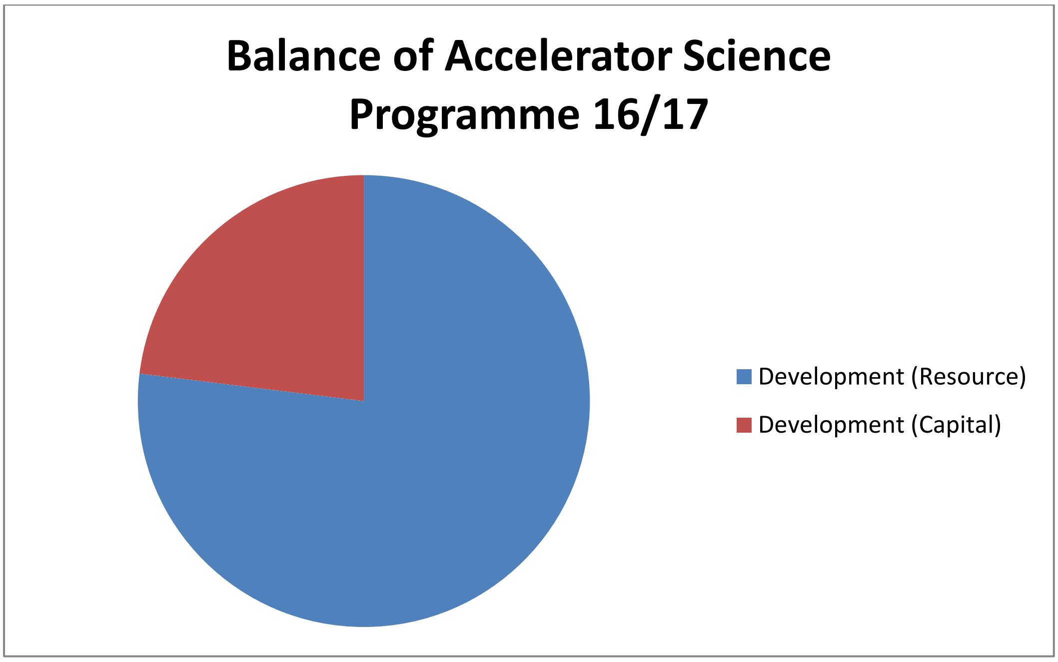
Particle Astrophysics programme balance and breadth - based on 2016/17 budget

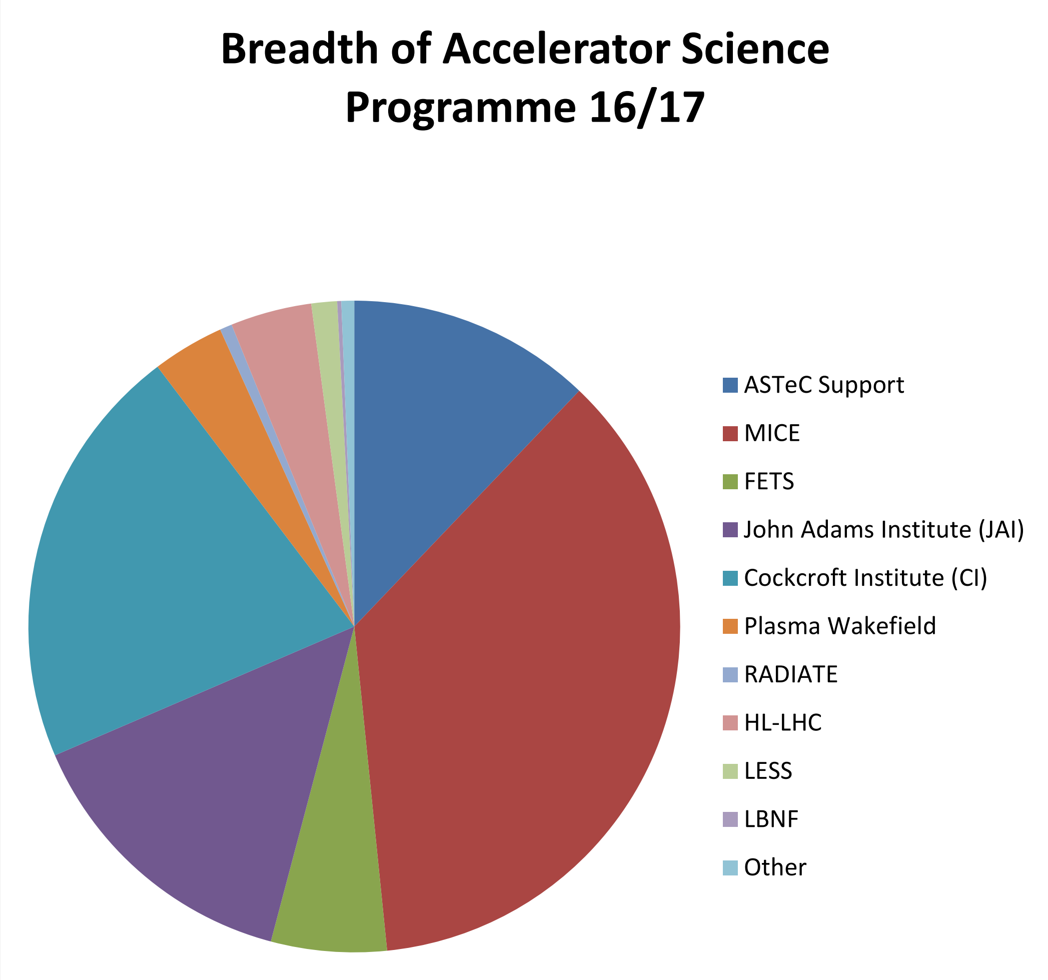




Accelerator

Accelerator Science programme balance and breadth - based on 2016/17 budget (do not include ASTeC core funding)

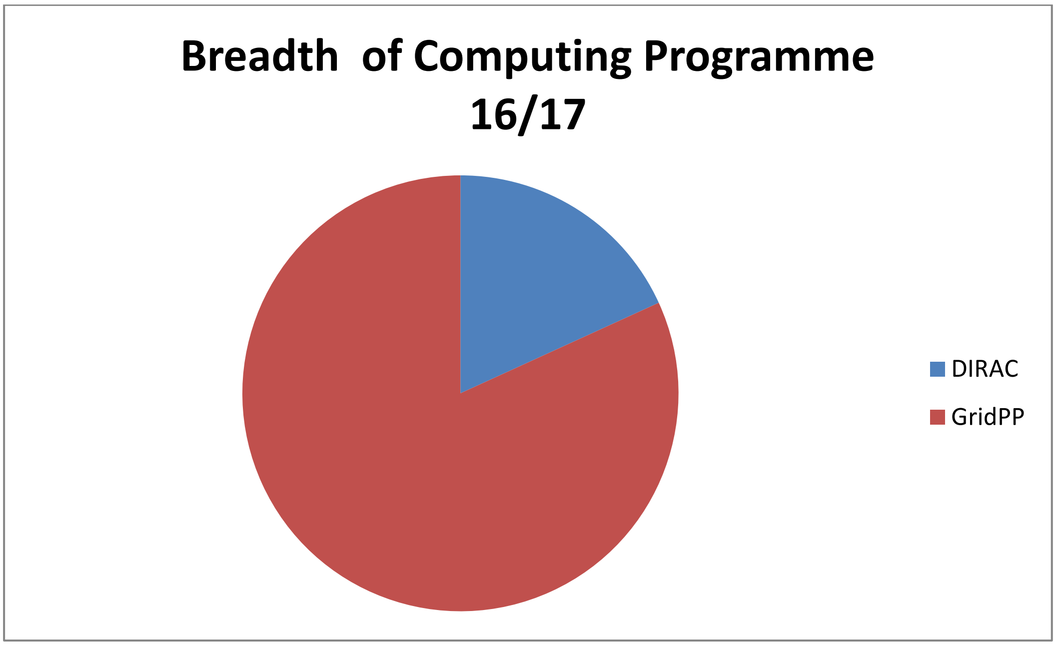




Contributions to RADIATE to end in 16/17

Computing

Computing breadth - based on 2016/17 budget



The pie chart above does not include any computing elements which are embedded within the astronomy programme.

There is no pie chart regarding the balance of the computing programme as the majority of the programme resides in exploitation.

Appendix 7. Glossary of Acronyms

AAP – Astronomy Advisory Panel. Provides a link between the Science board and the astronomy community and represents the needs of the community to STFC

ACPA – Advanced Charged-Particle Array. An EU-funded electron accelerator under construction at STFC's Daresbury Laboratory

AGATA – Advanced Gamma Tracking Array. A collaborative European project to construct and operate a gamma-ray tracking spectrometer.

AGP – Astronomy Grants Panel. The panel assess and make recommendations to the STFC Executive on all research grant applications in astronomy

ALICE – A Large Ion Collider Experiment. One of the seven detector experiments at the LHC at CERN which focuses on understanding the physics of strongly interacting matter at extreme energy densities.

A (Advanced) LIGO – Advanced Laser Interferometer Gravitational-Wave Observatory. A second generation gravitational wave laser interferometer, expected to routinely observe and study gravitational waves from cosmic sources

ALMA – Atacama Large Millimeter/Submillimeter Array. A radio interferometer in the Atacama Desert in Chile designed to study the Universe at millimeter and submillimeter wavelengths

ARIEL - Atmospheric Remote-sensing Exoplanet Large-survey, is one of the three candidate missions selected by ESA for its next medium class science mission

ARCHER - Advanced Research Computing High End Resource

ASKAP - Australian Square Kilometer Array Pathfinder

ASTeC – Accelerator Science and Technology Center. A facility that studies all aspects of the science and technology of charged particle accelerators

ATLAS – A Toroidal LHC Apparatus. One of two general-purpose detectors at the LHC investigating the research of particle physics beyond the Standard Model.

BEIS - Department for Business, Energy and Industrial Strategy

BepiColombo – A European mission to Mercury set to launch in 2018

BIS - Business, Innovation and Skills

BoP - Balance of Programme

CDR - Critical Design Review

CDT - Centre for Doctoral Training

CERN – European Organisation for Nuclear Research. A European research organisation operating the largest physics laboratory in the world

CGPS - Capital Grants to the Private Sector

CHIPS - CHerenkov detectors In mine PitS. Uses a unique concept in neutrino oscillations physics as it aims to build megaton neutrino detectors cheaply and flexibly

CI – Cockcroft Institute. An international center for Accelerator Science and Technology in the UK

CLASP – Challenge Led Applied Systems Programme

CLIC – Compact Linear Collider. A proposed collider which will collide electrons and positrons at energies of several TeV to study the underlying physics between these interactions

Cluster - An ESA Cornerstone mission launched in 2000 with the primary aim to make major breakthroughs in the understanding of how the Earth's magnetosphere works and the Earth's response to the ever changing solar-wind and the influence exerted by the ionosphere

CMB - Cosmic Microwave Background

CMS – Compact Muon Solenoid. A general purpose detector at the LHC with a broad physics programme ranging from studying the Standard Model to dark matter

COMET – Coherent Muon to Electron Transition. An experiment which aims to measure muon to electron conversion in the presence of a nucleus with unprecedented accuracy. This process is forbidden by the Standard Model of particle physics, however models beyond the Standard Model predict this to exist

COSMOS - Super Computer located in the Stephen Hawking Centre for Theoretical Cosmology (CTC) at Cambridge University, is dedicated to research in cosmology, astrophysics and particle physics

CPU - central processing units.

C-RSG - Computing Resources Scrutiny Group. The purpose of the C-RSG is to inform the decisions of the Computing Resources Review Board (C-RRB) for the LHC experiments

CSR - Comprehensive Spending Review

CTA – Cherenkov Telescope Array. A project to build the next generation ground-based very high energy gamma-ray instrument providing a deep insight into the non-thermal high-energy Universe

DAQ - Data acquisition

DEAP - The DEAP-3600 experiment is located 2 km underground at SNOLAB

DESI – Dark Energy Spectroscopic Instrument. An instrument which will measure the effect of dark energy on the expansion of the Universe

Diamond Light Source - UK's national synchrotron science facility, located at the Harwell Science and Innovation Campus in Oxfordshire.

DiRAC – Distributed Research utilising Advanced Computing. The integrated supercomputing facility for theoretical modelling and HPC-based research in astronomy, particle physics and cosmology

DKIST – Daniel K. Inouye Solar Telescope. A collaboration of 22 institutions in which the construction phase of the project to build the next ground-based solar telescope is now underway

DUNE – Deep Underground Neutrino Experiment. A proposed international experiment for neutrino science and proton decay studies

eEDM experiment – Electron Electric Dipole Moment Experiment. An experiment looking to measure the electric dipole moment of the electron

E-ELT – European Extremely Large Telescope. A telescope under construction which will have a 39-m main mirror and will be the largest optical/near-infrared telescope in the world. First light is targeted for 2024

ELI-NP – Extreme Light Infrastructure Nuclear Physics. ELI-NP will consist of both a very high intensity laser system and a very intense brilliant γ beam both of which will create a new European laboratory with a broad range of science covering fundamental physics, nuclear physics and astrophysics

e-MERLIN – Multi-Element Radio Linked Interferometer Network. A radio interferometer consisting of seven radio telescopes run from the Jodrell Bank Observatory by the University of Manchester

EPSRC - Engineering and Physical Sciences Research Council

ERC – European Research Council. A public body for the funding of scientific and technological research conducted within the European Union

ESA – European Space Agency. An international organisation that comprises programmes designed to research the Earth, its space environment, our Solar System and the Universe and which develops satellite-based technologies and services

ESO – European Southern Observatory. ESO provides research facilities to astronomers and astrophysicists by building and operating powerful ground-based telescopes enabling important scientific discoveries

ESS – European Spallation Source. A research facility currently under construction that will contain the world’s most powerful neutron source

ET – Einstein Telescope. A proposed third-generation ground-based gravitational wave detector that will test Einstein’s theory of general relativity and build on precision gravitational wave astronomy

EU - European Union

Euclid - A planned joint ESA/NASA project space telescope, its goal is to map the large scale distribution of dark matter and characterise properties of dark energy

FAIR – Facility for Antiproton and Ion Research. A new international accelerator facility for the research using antiprotons and ions. It is currently under construction.

FCC – Future Circular Collider. The FCC study explores the feasibility of different particle collider scenarios with the aim of significantly expanding the energy and luminosity of future detectors

FEC - Full Economic Costing

FEL – Free Electron Laser. A type of laser in which the medium consists of very high speed electrons moving freely through a magnetic structure

FNAL – Fermi National Accelerator Laboratory, USA

FP - Framework Programmes. Funding programmes created by the European Union/European Commission to support and foster research in the European Research Area

FTE - Full Time Equivalent

G3 - Generation-3

GAIA – An ESA mission to map the three-dimensional view of our Galaxy revealing its composition, formation and evolution.

GeV - gigaelectronvolt

GR - Einstein's General Theory of Relativity

GW – Gravitational waves. Ripples in the curvature of spacetime which propagate as a wave, travelling outward from the source

GridPP – Grid for UK Particle Physics. A collaboration of particle physicists and computer scientists based in the UK and at CERN who contribute to the development of new open source software and applications needed to power large-scale distributed computing for particle physics and beyond

H2020 - Horizon 2020. The biggest EU Research and Innovation programme with nearly €80 billion of funding available over 7 years (2014 to 2020)

HIC - Heavy Ion Collisions

HiRES – High Resolution Echelle Spectrometer. A spectrograph which operates between 0.3 and 0.1 microns at the Keck Observatory and has been used for the detection of exoplanets and to test our model of the Big Bang theory

HL-LHC – High-Luminosity Large Hadron Collider. An upgrade to the LHC which aims to increase the luminosity by a factor of 10 beyond the LHC's design value

HPC – High Performance Computing. The use of parallel processing for running advanced application programmes efficiently, reliably and quickly

HTC - High Throughput Computing

Hyper-K – **Hyper-Kamiokande detector**. The detector consists of a megaton scale water tank and ultra-high sensitivity photosensors. Neutrinos are used to make observations of elementary particles and also the Sun and supernovae

IAB - Innovation Advisory Board

ISIS Neutron Source - world-leading centre for research in the physical and life sciences at the STFC Rutherford Appleton Laboratory near Oxford in the United Kingdom

ILC – International Linear Collider. The proposed ILC would complement the LHC at CERN and would consist of two linear accelerators to further our understanding of the nature of dark matter and dark energy

IoP - Institute of Physics

IPPP – Institute for Particle Physics Phenomenology. An international center for research in particle physics phenomenology – the bridge between theory and experiment in the study of the tiny building blocks of all matter in the universe and of the fundamental forces that operate between them

IPS - Innovations Partnership Scheme

IR - Infrared

ISOL-SRS – ISOL Beam Storage Ring Spectrometer. A proposed spectrometer which will aid in precision studies of the reactions and properties of unstable nuclei across the vast range of masses and isotopes produced by the ISOLDE radioactive beams facility at CERN

JAI – John Adams Institute. The John Adams Institute for Accelerator Science provides expertise, research, development and training in accelerator techniques, promoting advanced accelerator applications in science and technology

JAXA – Japan Aerospace Exploration Agency. Japan's national aerospace agency

JLab – Thomas Jefferson National Accelerator Facility (Jefferson Lab). One of 17 national laboratories funded by the US Department of Energy. Its mission is to conduct basic research of the atom's nucleus using the lab's accelerator

JUICE – Jupiter Icy Moon Explorer. A planned ESA spacecraft to visit the Jovian system, focussed on studying Jupiter's Galilean moons

JWST – James Webb Space Telescope. The successor to the Hubble Space Telescope, the JWST is a major space observatory currently under construction and scheduled to launch in 2018. It will operate at wavelengths ranging from 0.6-27μm

Kaon - Any of a group of four mesons (subatomic particles made of one quark and an antiparticle version of a quark)

Lattice QCD - A non-perturbative (see Perturbation Theory) approach to solving the QCD

LBNE - Long Baseline Neutrino Experiment. A high energy physics project, currently in its design phase that will combine the world's most intense long-distance neutrino beam and world's largest particle detector to reach unprecedented sensitivity and precision in measuring quantum mechanical mixing in the neutrino sector

LCLS - Linac Coherent Light Source

LHC – Large Hadron Collider. The world's largest and most powerful particle collider located at CERN

LHCb – Large Hadron Collider beauty. A study undertaken at CERN's LHC to investigate b and anti-b quark decays

LHCC – LHC Experiments Committee. A committee created to interact with LHC collaborators to discuss detector designs and to review the construction, installation and commissioning of the experiments

LHeC –Large Hadron Electron Collider. A project under design for combining the intense hadron beams of the LHC and possible future Circular Hadron Collider with a new electron accelerator at CERN

LIGO – Laser Interferometer Gravitational-Wave Observatory. A national facility for gravitational wave research comprising two interferometers, one in Washington and one in Louisiana. The detectors use laser interferometry to measure the ripples in space-time caused by passing gravitational waves from astrophysical sources

LINAC - Linear accelerator

LISA – Laser Interferometer Space Antenna (NASA/ESA). A proposed ESA mission designed to detect and accurately measure gravitational waves. It has been re-named to eLISA

LOFAR – Low Frequency Array. A radio telescope working at the lowest frequencies accessible from Earth. The array is currently under construction and, when completed, will be able to survey wide areas of sky simultaneously

LSST – Large Synoptic Survey Telescope. Currently under construction in Chile, the LSST will be used to image the sky at optical wavelengths and will be able to detect faint astronomical objects with unprecedented resolution

LT - Liverpool Telescope. A 2-metre fully robotic Ritchey–Chrétien telescope that observes autonomously

LZ – Lux Zeplin. Large Underground Xenon (LUX) ZonEd Proportional Scintillation in Liquid Noble gasses (ZEPLIN). A next generation dark matter experiment to search for Weakly Interacting Massive Particles (WIMPS)

M&O - Maintenance and Operation

MeerKat - Karoo Array Telescope. Radio telescope under construction in the Northern Cape of South Africa, will be an array of 64 interlinked receptors

MICE – Muon Ionization Cooling Experiment. A high-energy physics experiment designed to demonstrate ionisation cooling of muons

MicroBooNE - a liquid argon time projection chamber (LArTPC) at Fermilab in Batavia, IL

MINOS – Main Injector Neutrino Oscillation Search. A long baseline experiment designed to study neutrino oscillations in a controlled accelerator experiment and to measure the oscillation parameters

MOONS – Multi Object Optical and Near-infrared Spectrograph. A large field, multi object instrument proposed for the VLT, which will conduct research into galactic structure and galaxy evolution up to the epoch of re-ionisation

MOS – Multi Object Spectrograph. Used to obtain the spectra of many objects simultaneously

Mu2e/Mu3e – Muon to Electron conversion experiments. Two experiments designed to observe muon-to-electron conversion which will better our understanding of why particles in the same family decay from heavy to lighter and more stable mass states

Muon – One of the fundamental particles of nature, essentially a short-lived heavier version of the electron

NA62 - An experiment focused on precision tests of the Standard Model by studies of rare decays of charged kaons

NASA - National Aeronautics and Space Administration

nEDM – Neutron Electric Dipole Moment. A measure for the distribution of positive and negative charge inside the neutron

NGTS – Next-Generation Transit Survey. A wide-field photometric survey designed to discover transiting exoplanets

NOvA - NuMI Off-Axis ν_e Appearance. An experiment designed to detect neutrinos in Fermilab's NuMI beam

NP - Nuclear Physics

NPGP - Nuclear Physics Grants Panel

NuSTAR – Nuclear Structure, Astrophysics and Reactions. A collaboration with the aim of exploiting the beams of short-lived radioactive species to study how the properties of nuclei and nuclear matter vary over a wide range of properties

NuSTORM – Neutrinos from Stored Muons. A proposed storage ring facility designed to provide measurements of neutrino and antineutrino nucleus scattering cross sections

PA - Particle Astrophysics

PAAP - Particle Astrophysics Advisory Panel. To provide a link between Science Board and the particle astrophysics community, and represent the needs of the community to STFC

PB – Petabyte

PD- Programmes Directorate

PDFs - Parton Distribution Functions

PDRA - Postdoctoral Research Assistant

PhenoGrid - LCG virtual organisation dedicated to developing the phenomenological tools necessary to interpret the events produced by the LHC

PINGU - Precision IceCube Next Generation Upgrade

PP - Particle Physics

PPAN - Particle Physics, Astronomy & Nuclear Physics

PPD - Particle Physics Department at RAL

PPE - Particle Physics Experimental

PPGP - Particle Physics Grants Panel. Responsible for assessing and making recommendations to the STFC Executive on research grant applications in particle physics covering scientific exploitation of facilities and projects, 'blue skies' technology research, theory, modelling, data handling and HPC access

PPRP - Projects Peer Review Panel. Responsible for the assessment of projects that are considered to have significant scientific priority in particle physics, nuclear physics, astronomy and particle astrophysics

PPT - Particle Physics Theoretical

PRACE - Partnership for Advanced Computing in Europe. 25 member countries creating a pan-European supercomputing infrastructure, providing access to computing and data management resources and services for large-scale scientific and engineering applications.

PRD - Project research & development grants

PSI - Paul Scherrer Institute, Switzerland

QCD – Quantum Chromodynamics. A theory of the strong interaction.

QFT - Quantum field theory

RAC - Resource Allocation Committee

RAL - Rutherford Appleton Laboratory. One of the national scientific research laboratories in the UK operated by the Science and Technology Facilities Council

RCUK - Research Councils UK

ResearchFish –service for the collection and reporting of outcomes to enable research impact tracking.

RIKEN – Institute of Physical and Chemical Research. A large research institute in Japan which conducts research in many areas of science including physics, chemistry, biology, engineering and medical science

RRB - Resources Review Boards

SBND – Short Baseline Near Detector. One of three liquid argon neutrino detectors at Fermilab as part of the Short-Baseline Neutrino Program which will perform searches for neutrino oscillations

SEAB - Skills and Engagement Advisory Board

SHiP – Search for Hidden Particles. A new general purposed fixed target facility located at CERN used to search for hidden particles such as very weakly interacting long lived particles

Solar Orbiter - a planned Sun-observing satellite, under development by the ESA

SKA – Square Kilometre Array. A radio interferometer currently under construction in Australia and South Africa which will address key topics in astrophysics, fundamental physics, cosmology and particle astrophysics

SNO – Sudbury Neutrino Observatory. Decommissioned in 2006, the SNO was an underground neutrino observatory located in Sudbury, Canada

SNO+ - Sudbury Neutrino Observatory +. A new kilo-tonne scale liquid scintillator detector that will study neutrinos

SoLiD - Short baseline Oscillation search with Lithium-6 Detector

SPECT/CT Scan - Single Photon Emission Computed Tomography / Computed Tomography

SSAP - Solar System Advisory Panel

STA - Scintillator Tracking Array

STFC – Science and Technology Facilities Council. A UK government body that carries out research in science and engineering and funds research in particle physics, nuclear physics, space science and astronomy

SuperNEMO – Super Neutrino Ettore Majorana Observatory Demonstrator. A next generation experiment to search for Neutrinoless Double Beta Decay, the only way to investigate the fundamental nature of the neutrino

SUSY - supersymmetry

T2K – Tokai to Kamioka (collaboration). A long-baseline neutrino experiment in Japan to study neutrino oscillations

TDRs - Technical Design Reports

THOR - Turbulence Heating ObserveR

UKATC – UK Astronomy Technology Centre. The national centre for astronomical technology and part of the STFC. UK ATC designs and builds instruments for many of the world's major telescopes and carries out observational and theoretical research in astronomy and astrophysics

UKMHD - Consortium Super Computing facilities

UK FEL - UK Free Electron Laser community

UKSA – UK Space Agency. UKSA are responsible for all strategic decisions on the UK civil space programme

UKT0 - UK-T0 is an evolving self-organised collaboration of the STFC science and facilities communities who use compute resources. The collaboration was founded though computing work being an overlapping and shared environment, with many interdependencies between all STFC areas. UK-T0 promotes working together, sharing of resources, avoidance of duplication, and shared expertise and support. It also serves as a hub to aggregate computing requirements across STFC.

VIRGO - Consortium for Cosmological Supercomputer Simulations

VLA - Very Large Array

VLT – Very Large Telescope. A telescope facility operated by ESO in the Atacama Desert in Chile. It comprises four optical telescopes used together to achieve very high angular resolution

WEAVE – WHT Enhanced Area Velocity Explorer. A concept for a new wide-field spectroscopy facility for the 4.2-m Herschel Telescope

WIMPs - Weakly Interacting Massive Particles

XFEL – European X-ray Free Electron Laser. A subterranean X-ray research laser facility currently under construction which is planned to start operation in 2017

XMM-Newton – X-ray Multi-Mirror Mission – Newton. An ESA space mission which comprises three X-ray telescopes used to conduct research including the study of black holes and the origins of the Universe