Science and Technology Facilities Council

STFC Balance of Programmes 2020

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Introductions from the Science Board Chair

Following on from the first Balance of Programmes exercise in 2017, Science Board were charged in 2019 by STFC's Executive Board with undertaking the second Balance of Programmes (2020) exercise. Specifically, Science Board were asked to review the strategic direction and balance and depth across the various PPAN science programmes (Particle Physics, Particle Astrophysics, Astronomy and Nuclear Physics), alongside the Accelerator Science and Computing programmes which support them, and to make high-level recommendations to Executive Board for a programme for the next five years of excellent science, within a realistic financial planning envelope. The environment of flat cash that has existed since 2013 has placed an enormous pressure on STFC's programmes, and STFC Executive Board needs to be well informed to make necessary decisions.

Excellent, world-leading science was identified across all six programme areas. However, all programme areas have suffered considerably from the previous reduction in funding and there are no longer any identifiable areas for cut backs that would not seriously impact on core science output, and put at risk existing international collaborations and economic returns. In addition, there are few, if any, new opportunities for investment in internationally-leading science. Each of the six programme evaluations identified that an uplift in funding of at least 10% was necessary to start to reverse the damage caused by years of flat cash.

A large number of colleagues have contributed to the preparation of this report, and without whose help the report would not have been written. Within STFC, I would particularly like to thank the various Programme Managers for their openness, Derek Gillespie and Malcom Booy for their patience with our many queries and Karen Clifford and Jackie Hawkins for their helpfulness. Within the STFC core programme, special thanks are due to the chairs and members of the six Programme Evaluations, the various Advisory Panels and, of course, my colleagues on the Panel.

Professor Jayne Lawrence
Science Board Chair

Introduction from STFC

The 2020 Balance of Programmes exercise was commissioned to provide the STFC Executive with a higher-level strategic advice on how to apportion funding across its frontier science programme (the PPAN areas of particle physics, particle astrophysics, astronomy, and nuclear physics, alongside the accelerator science and computing programmes that accompany them) and to provide any associated recommendations that emerged during these considerations. This is an important part of an ongoing three-yearly process that considers the overall funding position and, importantly, advice from the scientific community channelled by the Advisory Panels via a set of six detailed Programme Evaluations.

STFC will respond to the individual recommendations in a subsequent document.

I would like to thank everyone involved in this process, especially the Chair and Deputy Chair of Science Board, the members of the Balance of Programmes 2020 panel, the Advisory Panels, and the teams in Swindon for keeping everything on track during a challenging period.

Professor Grahame Blair
STFC Executive Director, Programmes

Executive Summary

1. The purpose of the Balance of Programmes (BoP2020) review is to define a balanced programme of excellent science within a constrained financial planning envelope. BoP2020 has assessed the strategic direction, balance and breadth within and across the particle physics, particle astrophysics, astronomy and nuclear physics (i.e. PPAN) science programme, alongside the accelerator and computing programmes which support them, over the next five years. Two financial scenarios are considered, namely that of flat real (assumed to be a 1.2% increase per year) and +10% increase or "uplift".
2. **The Panel strongly endorse the key finding from all six programme evaluation reports[1] that at least a 10% funding uplift is required to address the on-going erosion to the programme from many years of flat cash funding.**
3. The 2017 Balance of Programmes exercise found that the programme was under extreme pressure and could not be stretched much further, stating that all programme areas had suffered reductions in the volume of research and that there were no longer any easily identified areas for savings that did not impact on core science output. Since 2017 the funding situation has deteriorated ever further and problems concerning the balance, depth and long-term viability of each of the programmes have become even more acute and, in some areas, critical.
4. The present BoP2020 exercise has taken place after a 7-year period of non-indexed, flat cash imposed on all programme areas. The financial constraints manifest themselves in several ways including as an inability of the UK to deliver a broad and in-depth programme of high-quality science, as well as lost opportunities to maintain and develop the UK's leadership in instrumentation, facilities and exploitation. This lost leadership results in a loss of knowledge exchange and a loss of the opportunity for industrial return.
5. Despite increasingly constrained funds, the exercise identified that the science being performed across each of the programme areas is excellent and world leading. However, the BoP2020 identifies that any further cut back of the programme's volume will cause severe damage to the UK's scientific output, will disadvantage the UK's position and reputation on the international scene, and erode the knowledge-base and any future UK economic and academic returns. The Panel also identified risks to the programme, most importantly the loss without equivalent replacement of EU funding and insufficient computing

[1] https://stfc.ukri.org/about-us/our-purpose-and-priorities/planning-and-strategy/programme-evaluation/balance-of-programme-exercise-ppan/

hardware provision; the Panel makes recommendations to mitigate against these.

6. The BoP2020 Panel believes that in two areas the situation has now deteriorated to the point where urgent action is required to prevent the programmes becoming non-viable over the next 5-year period. The panel recommend the following minimal additional levels of support to mitigate these threats: an increase of £0.6M/yr in support to Nuclear Physics, sufficient to provide a more appropriate level of PDRA funding and to allow involvement in a development project; additional support for Particle Astrophysics in the form of an uplift to £1.5M/yr in the last two years of the time period to allow the UK to play a leadership role in the design and construction phase of a single next generation dark matter experiment. In a +10% scenario, these would be the top priority for receipt of the increased funds. In a flat real scenario, implementing these recommendations would require redistribution of funds from other areas, though this would in turn cause programme damage. Furthermore, in the +10% scenario, it is also recommended that the Project Research and Development (PRD) programme be reinstated, following its temporary suspension in BoP2017; in a flat real scenario the Panel recommend that this suspension continue since reinstatement cannot be achieved without causing unacceptable damage to the rest of the programme, though this will itself cause long term damage.

7. If a funding scenario of significantly less than flat real is realised, then the current programme will fail and a new strategic exercise must be undertaken to define a programme with much more modest aspirations than the current broad, world-class remit.

BoP2020 Process Summary

8. The first STFC Balance of Programmes exercise was published in 2017, with the intent to review the exercise on a three-year cycle. Thus, the second Balance of Programmes exercise ran from February to June 2020, with initial discussions on the topic held by Science Board in late 2019. During the intervening 2017-2019 period, a number of more detailed Programme Evaluations of STFC's research programme areas were carried out and published online in December 2019.

9. The Panel were asked to consider two financial scenarios: 'flat real' (assumed to be an increase of 1.2% per year) and +10% increase.

10. BoP2020 was designed to provide high-level advice on whether there is suitable depth and breadth within each research discipline to provide sustainability and health of the programme, including scope for development and support of future opportunities. Consideration was given to the balance between STFC's frontier science research disciplines over a five-year time horizon, advising on the appropriateness of the relative balance of funding between different disciplines. The exercise aimed to advise on any areas suitable for preferential or prioritised funding allocation in the event of any change in core funding to STFC. The exercise did not comment on the detail of specific projects that comprise a programme's portfolio: such commentary was an output of the detailed Programme Evaluations.

11. The Panel for BoP2020 comprised of Science Board members, along with the remaining chairs of the Programme Evaluations, Professors Ofer Lahav and Don Pollacco (hereafter, 'the Panel'). The Panel were provided with the following evidence to inform the Balance of Programmes 2020:

    - The Balance of Programmes 2017 report.
    - The six Programme Evaluation reports related to the frontier science programmes: particle physics, nuclear physics, particle astrophysics, astronomy, computing, and accelerators.
    - Up to six short updates designed to allow the programme advisory panels an opportunity to provide timely updates to each Programme Evaluation (Annex 1).
    - A structured update from each Programme Evaluation Chair, presenting a summary of key findings and recommendations from the respective review (Annex 2).
    - A structured update from each of the six relevant STFC programmes, presenting a financial summary and a perspective on the programme's existing and future portfolio (Annex 3).

12. BoP2020 was delivered via a series of structured panel meetings that began in February 2020. The original timetable of face-to-face meetings was amended in light of the COVID-19 pandemic, and a revised series of video conference meetings were implemented in March 2020. In total, there were three full meetings of the Panel (February, March, and April 2020), a number of supplementary working group meetings in March and April, and focused updates during scheduled Science Board meetings.

13. The February 2020 meeting served to familiarise the Panel with the key recommendations and supporting evidence for each programme area. Following this meeting, the Panel were sub-divided into working groups, each of which was assigned a programme area. These working groups then examined the evidence available for each programme area in accordance with a set of specific questions (Annex 4) and recorded their initial conclusions.

14. The March 2020 meeting allowed the working groups to report back to the Panel and discuss their initial conclusions for each programme area. Group discussion allowed the Panel to understand the rationale for a working group's initial conclusions and identify areas where further information was required, or investigation needed. Following this meeting, the Panel worked with staff from STFC's Programmes Directorate to clarify necessary points of information, which were communicated by email and video conference to the Panel.

15. The April 2020 meeting allowed the Panel to review all the evidence and information considered during BoP2020 and the discussion was structured around a series of questions related to the STFC frontier science programme as a whole (Annex 4).

16. The output of the April meeting was an agreed set of recommendations that were used as the basis of the Balance of Programmes 2020 report, as prepared by a report drafting group drawn from a sub-set of the Panel. Drafts of the report were considered by the Panel during the drafting process. The recommendations of the report were presented to STFC's Executive Board during their June 2020 meeting.

Scope of Exercise

17. The Panel considered the Programme Evaluations for Accelerator Science, Astronomy, Computing, Nuclear Physics, Particle Astrophysics and Particle Physics, along with any up-dates submitted by the Advisory Panels along with roadmaps. Further material, background information and financial data were provided by the programme managers. The Panel considered the strategic direction, balance and breadth within and across the science areas for two financial scenarios (flat real, assumed to be a 1.2% increase per year, and +10% increase) but did not review individual projects.

18. Significantly, a number of assumptions were made during the BoP2020 discussions:

- That the pre-2016 level of EU funding is restored, or else, is directly replaced at a comparable level.
- That the recent UKRI uplifts (such as for the Particle Physics programme) are incorporated into the baseline of the resource programme funding going forward.
- That there is no long-term impact of the COVID-19 pandemic.
- That the current exercise will align with the forthcoming European Strategy for Particle Physics and Accelerator Science[2].

19. If one or more of these assumptions are not met, it is recommended that another Balance of Programmes exercise is undertaken with full community consultation and involvement to determine how best to sustain the STFC programmes.

[2] https://cerncourier.com/a/european-strategy-update-postponed/

Programme Overview

20. STFC supports research in the programme areas of Accelerator Science, Astronomy, Computing, Nuclear Physics, Particle Astrophysics and Particle Physics. Support is primarily provided by project grants, which support projects of high scientific priority in the programme areas, and consolidated grants, which provide funds for exploitation, core support for projects and some research and development to university and institute research groups. Consolidated grants are awarded for three years; the duration of project grants is typically 3-4 years.

21. The available resource budget for the programme areas is approximately £112M. The breakdown between areas is shown in Figure 1. Astronomy and Particle Physics receive most of the support (£48M and £45M respectively), while the budgets for other areas are much smaller (Accelerators £6.9M, Nuclear Physics £5.9M, Particle Astrophysics £3.7 M, Computing £3.2 M).

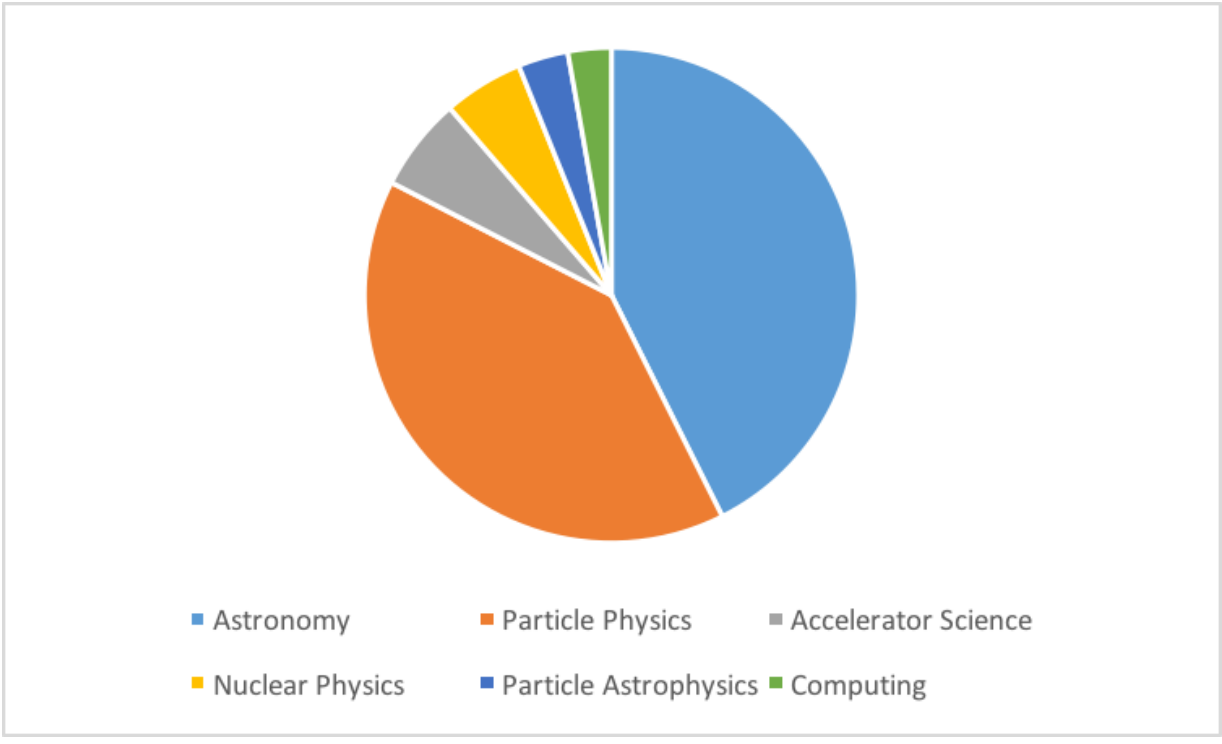

Figure 1: Breakdown of the 2019/2020 resource budget between programme areas.

22. The funding level has been held at flat cash since 2013, which follows significant cuts made after the financial crisis**.** It has been augmented by an annual £3.2M uplift in 2018 by UKRI, to enable STFC to fulfil international particle physics project commitments and to provide additional, urgent support across the programme (primarily to Particle Astrophysics and Computing). This current exercise assumes that the uplift is baselined, i.e. it will be an integral part of the available resource budget for the programme areas from 2020.

Summary of Programme Areas

Accelerator Science

23. Accelerator Science (AS) enables advanced facilities that underpin nuclear and particle physics, and physical and life sciences, in addition to developing novel techniques that could revolutionise future research with potential for a wealth of novel applications.

24. The UK performs world-leading accelerator science and is a valued and sought-after international partner. UK scientists lead international collaborations, develop innovative techniques, produce high impact papers, and attract international investment in projects[3].

25. The STFC funded programme supports the accelerator institutes (the Cockcroft and John Adams Institutes), ASTeC, and three projects in the areas of Frontier Machines, Novel Accelerators and Light Sources. The institutes, ASTeC and universities provide the expertise (technicians, PhD students and PDRAs) necessary to carry out projects and support a broad range of activities including research and development (R&D). STFC funding supports 49 academics[3].

26. Accelerator science community activities are further supported by BEIS, the EU (critically important for supporting training networks and the EuPRAXIA and EuroCircCol collaborations), and other external funds. The accelerator institutes raise at least 100% of their STFC investment again through external funds.

27. The strength of UK research has opened many opportunities for leadership. However, constrained programme funding has seriously limited the breadth of the programme. Only a subset of activities can be fully supported and there is insufficient funding to support the development of applications (or to exploit the future opportunities offered by EPAC).

28. Furthermore, some areas (plasma wakefield acceleration, free electron lasers and the Diamond-II upgrade), have insufficient depth and a skills pipeline which is maintained only through other income streams, representing risk to the sustainability of these areas.

29. The recent programme evaluation judged the current funding level to be sub-optimal. Should funding reduce further, the income of the accelerator institutes is likely to be eroded as the development line is committed until 2022, and this would magnify the impact through the loss of leveraged funding.

30. An uplift of at least 10% is essential to reverse the damage already caused by flat cash funding. A 10% uplift would enable the volume of research to be

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[3] Table 3, Accelerator Science programme evaluation, https://stfc.ukri.org/files/accelerator-programme-evaluation/

maintained in the institutes and allow some applications funding, protecting breadth and maintaining key skills. In such a scenario the Technology and Accelerators Advisory Board and Accelerator Advisory Panel could consider how best to support applications and maximize economic impact.

31. Should funding remain at flat real over the next five years, then no new development funding will be possible until 2022. It is also clear that programme depth and breadth cannot be restored in this scenario. Applications are unlikely to be supported and risks due to loss of external funding cannot be mitigated.

Astronomy

32. UK Astronomy delivers quality and productivity assessed internationally as second only to the US over a wide breadth of science, but there are indications that the programme may be over tensioned[4] which even a small uplift may not address.

33. STFC Consolidated Grant (CG) funding supports 312 academics from the 759 total applicants, awarding 227 PDRAs and cross-community core effort across the latest 3-year cycle (currently £29M/year). The rest of the £48M/year STFC funding line supports development projects, subscriptions and experiment maintenance and operations.

34. The breadth of the research within astronomy is a key area of strength, resulting in its world-leading reputation. This diversity of scientific and technical expertise has arisen from the strategy of "excellence" as the driving criterion for STFC grant support with little ring-fencing of resources. This approach has led to a community that is flexible and able take full advantage of a range of world-wide opportunities. Evidence of the competitiveness of UK astronomy is apparent from its success in winning EU funding (see Point 38. below).

35. In recent years astronomy projects have delivered return to the UK through the award of multi-million-pound contracts to industry (e.g. Teledyne e2v for the supply of detectors for the ELT, Euclid, GAIA, PLATO, the LSST and NASA's Kepler space craft; €80M of SKA construction contracts in addition to £149M of SKA related output for the UK economy[5]).

36. A critical issue is pressure on the exploitation consolidated grants line. The level of science exploitation supported by STFC is now at the point where, on average, applicants may expect to be awarded only one PDRA every ten years. Only one in three proposed projects receives funding, meaning that only 40%

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4 Astronomy Programme Evaluation Report, 2019, https://stfc.ukri.org/files/astronomy-programme-evaluation/

5 SKA Economic Impact Assessment and Outline Evaluation Framework, WECD, 2018

of all applicants get any staff time, and those not successful are frozen out for a three-year cycle.

37. The UK has contributed to a significant uplift in the ESA Space Science budget over the next 5 years and the missions being implemented will tackle some of the most important problems in astronomy. UK based scientists have gained leadership and senior roles in all these upcoming missions. In order to capitalise on this investment, further pressure will be placed on an already overheated exploitation line. It is also imperative that STFC and UKSA work closely, effectively and efficiently together.

38. While the future of ERC/EU funding is a significant concern to all the PPAN areas, the issue is particularly acute in Astronomy. UK Astronomy has been very successful in winning ERC/EU support, contributing >40% of programme funding, with the support predominantly going towards exploitation. The absence or reduction of such funding would place even more pressure on the already overburdened STFC exploitation line, as projects that would otherwise have received funding through the ERC route would instead be funnelled back into the consolidated grants funding rounds.

39. The flat cash funding of Astronomy exploitation is already harming the programme. There is a reduced capacity for international leadership, evidenced in publication statistics which show that the rate of UK first-authors steadily declined from 26% in 2006/7, to 18% in 2014/15. In addition, the extremely challenging funding environment has been found by the AAP to be having a disproportionate effect on early career researchers, damaging their prospects for career development into future international leaders.

40. The priority in the Astronomy area is therefore very clearly to protect the exploitation grants line. However, this strategy comes at a cost to future projects and to R&D, which will cause further damage to the programme, loss of future leadership, skills, etc., and to the long-term health of UK Astronomy as a whole. Furthermore, success in ERC grants has brought new communities into Astronomy, which puts further pressure on exploitation, rather than across the R&D/construction/exploitation cycle.

41. Over the next 5-year period, opportunities in exciting new projects (e.g. New Robotic Telescope, Blue MUSE, CUBES, MARVELS, the European Solar Telescope, Simons Observatory, etc.) where the UK is well positioned to play a leading role will be missed.

42. Investment in R&D has already declined, with a corresponding loss in skills and people. This is a concern for the UK's ability to play a leading role in future development and construction projects. The recent lack of the PRD scheme has exacerbated the problem. To avoid long-term negative impact, investment

is now needed to reverse this decline, but this cannot be realised outside of a scenario with an uplift to the programme.

43. Over the next 5-year period, astronomy will truly enter the era of “Big Data” with surveys exploiting LSST, Euclid, PLATO, SKA and Solar Orbiter, so investment in computing will be essential. Significant infrastructure investment is needed, but this must as part of a coordinated UK-wide facility funded by UKRI. While astronomy is well placed to exploit existing big computer infrastructure, there is a need to invest in people to develop domain specific skills and expertise; an example to emulate is the recent successful adaptation of the TOPCAT software to maximally exploit the GAIA data set.

Computing

44. Computing underpins all scientific exploitation across the STFC programme. Data analysis and event-based simulation are carried out using high throughput computing (HTC), and calculations are performed with specialist high performance computing (HPC). GridPP is the primary HTC facility and is used predominately by Particle Physics, although demand from Nuclear Physics, Particle Astrophysics and Astronomy is rising. DIRAC is the primary HPC facility and is used by the theory community across programme areas.

45. Computing coordination across the STFC programme has been aided by the recent establishment of IRIS. IRIS is a welcome initiative to harness the full potential of large-scale computing infrastructure for the benefit of all the STFC science programmes (for example, there has been success in enabling data analysis for astronomy with GridPP hardware). IRIS is funded until March 2022.

46. Current funding levels mean that DiRAC and GridPP are the only major facilities that can be supported at some level, other than university-based facilities, leaving no headroom to adjust the balance. Continued operation of these facilities is a programme priority. The programme also has an obligation to support PRACE, a European HPC infrastructure.

47. There is little opportunity for research and development (the development of hardware and software to improve performance, capability, speed and computational complexity), and construction projects (investment in new hardware and architectures) to maintain future competitiveness, although investment in both are needed. Consolidated grant awards offer very limited support and have been steadily eroded over several grant cycles.

48. The Computing Evaluation report highlighted that HTC demands will increase in the next five years, following the start of high-luminosity LHC. Present capacity will not meet programme needs, and high priority science outputs will be reduced (across the programme) if the necessary additional capacity is not

provided. There are insufficient programme funds to meet these additional demands. This represents a risk to future STFC science output.

49. HPC is also likely to suffer in the same 5-year timescale. The decline will be less severe than for HTC, as it is due to an ongoing need to replace existing machines as units fail over time. However, subsequent phases of DiRAC and its associated power costs cannot be met within current programme funds. STFC are reliant on attracting external funding to support future HPC provision. This represents a risk to future STFC science output.

50. Improvement may only be possible through UKRI-wide initiatives. Discussions are ongoing within UKRI on how best to support large e-infrastructures, and thereby provide a route to enable future HTC and HPC hardware provision.

51. STFC is well placed to lead these UKRI initiatives from its experience running large-scale collaborations and facilities. Further opportunities for building leadership within UKRI include student training through CDT-like schemes; demonstrating to UKRI how to incorporate a range of different computational projects in one framework (based on IRIS); and links with industry to address energy usage in computing facilities.

52. A route to strengthening computing in the longer term within STFC would include supporting career opportunities for Research Software Engineers (RSE). The evaluation report recommends spending any funding uplift on staff/RSE fellowships. Further improvements to the skills pipeline could include continued support of CDTs (in data science or other relevant areas) to supply the next generation of RSEs.

Nuclear Physics

53. Nuclear Physics (NP) aims to elucidate the properties of nuclei and understand the strong nuclear force. The area is broad, ranging from the study of nucleon structure and stability to nuclear astrophysics, and encompasses theoretical and experimental investigation.

54. The UK community is small, yet remarkably productive. The UK has a significant presence at most of the world's leading facilities, a position enabled by technical excellence and sought-after detector expertise, leadership of experiments and large theoretical collaborations, and is a world-leading producer of highly cited papers[6]. However, the programme is unsustainable and at risk due to the funding for development projects and exploitation being severely strained.

55. STFC consolidated grant funding supports 53 academics, PDRAs and cross-community core effort (currently £4.7M/year). The rest of the £5.9M/year STFC

[6] See the 2017 STFC Impact Report: https://stfc.ukri.org/files/stfc-impact-report-2017/

funding line supports development projects, subscriptions and experiment maintenance and operations. A single project, AGATA, is funded at present.

56. The breadth of the Nuclear Physics programme is narrow and restricted to specific topic areas where the UK community specialise within hadronic physics, nuclear structure, nuclear astrophysics and nuclear theory. The community are also active in developing medical and security skills and applications, often funded outside STFC. Many opportunities exist for the UK to build further leadership in all areas.

57. The balance between development projects and exploitation is severely strained. The level of consolidated grant funding was already critical at the time of the first Balance of Programmes in 2017. Now, combined with a rise in overheads and indirect costs, an acceptable outcome is not possible for the 2020 round.

58. Besides limiting the exploitation of previous STFC investments, constrained consolidated grant funding also impacts the balance between the current and future programme. At risk are: R&D, particularly in the absence of PRD; skills as cross-community support is decreased; future leadership as the UK can no longer build on opportunities currently open to it.

59. A decision on the future level of consolidated grant funding must be taken in summer 2020.

60. As it stands, the programme is unsustainable. A reduced exploitation line will irreparably damage the programme. Moving available development funds to exploitation is insufficient to remedy the shortfall. Furthermore, such a solution is not sustainable and would damage the future programme, UK skills and leadership by limiting development to one project.

61. A modest uplift to maintain research volume and inject a small, but significant amount into new projects is a minimum requirement in moving towards restoring programme health.

62. Alternative funding opportunities exist (potential partners include NPL, MRC, UKAEA, EPSRC and AWE). These represent an addition to, rather than a replacement of, core funding given the potential of the associated activities to further alter programme balance.

63. If a solution cannot be found to the funding crisis, then it will be necessary to have a dedicated review to determine how best to reduce the area, as recommended by the programme evaluation.

Particle Astrophysics

64. The STFC Particle Astrophysics (PA) programme covers ground-based and scientific studies of gravitational waves (GW), direct searches for dark matter (DM), and very high energy gamma rays (VHE). The programme is highly

exciting and has strong synergies with the rest of the frontier science programme, increasing science output and reach.

65. PA is an evolving field of research with support for the community coming from different science areas within STFC, particularly Astronomy and Particle Physics, making it difficult to precisely gauge the community size and overall funding. Using a broad definition of PA that includes all neutrino and non-accelerator research, STFC currently supports 60 academics[7].

66. The PA programme budget covers development and R&D, amounting to 3.6M/year. Exploitation is largely funded by the Particle Physics (DM) and Astronomy (GW, VHE) Grant Panels. Additional funding is provided by UKRI for GW, including £10.5M over 4 years from the Fund for International Collaboration towards aLIGO construction, and £0.5M for 2018-19 & 2019-20 to support LIGO operations. The latter is hoped to be added to the baseline funding level. Funding from all sources is estimated to amount to £7-8M/year. It is noticeable that funding for GW dominates the programme.

67. There is minimal breadth in the programme, with lack of funding preventing other areas of UK expertise to further develop. These include neutrino astrophysics, cosmic rays and aspects of cosmic microwave background (CMB) and theory.

68. There is no depth to the programme, with each of the funded aspects, GW, DM, and VHE, consisting of a single project/experiment. Loss of any of these projects/experiments could well result in a non-viable PA programme.

69. The present level of funding is insufficient to maintain an appropriate balance between R&D, construction and exploitation.

70. While the injection of funds from UKRI to GW makes this area secure in the immediate future, no decision has been made on funding for GW in the longer term and this represents a risk. In particular, R&D for the Einstein Telescope is urgently needed if the UK is to capitalise on its existing enviable position. The scale of funding required is inconsistent with the existing PA budget line and is probably too large for a reinstated PRD scheme. There is risk that absence of new funds for this area on a timescale of 2022-23 will result in minimal scientific return on UKRI investment.

71. The recent PA Programme Evaluation (PAPE) exercise (Section 1.6) noted that even “the current position is unsustainable”. In a flat real scenario, a decision between DM and VHE seems inevitable, with the consequences to the PA programme that entails.

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[7] The breakdown of support between project and Astronomy, Particle Physics experiment and theory consolidated grant support is given in paragraphs 4.4-4.7 of the Particle Astrophysics programme evaluation.

72. There is huge potential for future growth, with opportunities for expansion in each of GW, DM and VHE, as well as new opportunities in cosmic rays, astrophysical neutrinos, CMB and novel quantum technologies. In addition, Boulby, the UK's only deep-underground-science laboratory, has already established a strong science programme and is a potential site for an international 3rd generation dark matter experiment. Present funding levels mean opportunities are already being missed and R&D is insufficient to ensure major future roles.

73. The PA & Particle Physics Programme Evaluations and the PAAP update agree that a 10% increase in funding (in addition to the UKRI uplift being baselined) is the minimal viable funding level to maintain the current programme. An uplift beyond this level would enable some depth and breadth to be restored.

74. CMB is an area of high interest and importance. Currently, support for the UK CMB community is through astronomy consolidated grant funding, non-STFC funding and fellowships (especially EU). Loss of EU funding without an equivalent replacement would be particularly severe in this area. Presently there are no CMB development projects. If the Simons Observatory, or other CMB development projects, receive support, it is recommended that they should be part of the PA programme, although exploitation should be retained within the Astronomy Grants Panel.

Particle Physics

75. Particle Physics (PP) aims to identify, study and understand the fundamental particles and forces that ultimately comprise the universe. The area has strong synergies with accelerator science, which enables major experimental facilities, and is critically reliant on computing, which underpins data analysis and the calculation of theoretical predictions. There are also scientific overlaps with particle astrophysics in the areas of dark matter, aspects of neutrino physics, and cosmology.

76. The UK Particle Physics community is internationally respected and performs world-leading research[8]. The UK programme aligns strongly with the European Strategy for Particle Physics, and members of the community play leading roles in current and future experiment international collaborations and lead the development of new detector technologies.

77. STFC supports activities in five main areas: frontier physics, flavour physics, neutrino physics, non-accelerator physics and particle physics theory. Consolidated grant rounds (currently £23.3M/year), support a community of

[8] See the particle physics programme evaluation, the recent STFC review of particle theory, and the citation analysis in the 2017 STFC Impact report for examples.

360 academics, post-doctoral research associates (PDRAs) and core effort. The funds are delivered in two consolidated grant rounds; experiment, which also includes some support for Accelerator Science and Particle Astrophysics exploitation, and theory. Consolidated grant funds also support international maintenance and operations and very limited early stage research and development (in total, currently £23.3M/year). The rest of the STFC funding line supports development projects, RAL PPD and GridPP.

78. The community are further supported by non-STFC funds, including EPSRC (supporting the Isaac Newton Institute and part-funding eEDM), BEIS (which supports DUNE), UKRI and the ERC. Theory is particularly reliant on ERC income, which over 2009-2019 has corresponded to 60% of STFC consolidated grant income. Over the same period, experiment ERC income corresponds to 25% of consolidated grant income.

79. Constrained funding, and the recent increase in university overheads, have placed the programme under pressure. The most recent experiment consolidated grant round required additional funding (provided by the UKRI uplift) to allow the UK to meet its international LHC Upgrade project commitments. It has only been possible to award PDRA posts at the low level of 0.2 FTE per investigator in the most recent theory consolidated grant round, which directly impacts scientific output.

80. R&D support, enabled through consolidated grant funding, is low and has been impacted by the cessation of the PRD scheme. This is an issue of concern to the community and should be addressed if the UK is to retain intellectual and technical leadership at future experiments.

81. A shortfall in experiment computing provision is foreseen on a timescale of 5 years, when HL-LHC computing requirements cannot be met by GridPP. This cannot be resolved within current funds. The theory community relies on access to high performance computing through DiRAC, and the quantity of science output will erode if the next phase of DiRAC is not invested in.

82. The recent programme evaluation recommended that a 10% uplift in funding was the minimum necessary to sustain the current programme. Priority should be given to preserving support for exploitation and R&D. It is also imperative that the UKRI uplift is baselined, to avoid further pressure on the programme.

83. Should funding remain at flat real over the next five years, then difficult decisions will need to be made. It will not be possible to maintain programme depth and breadth due to above-inflationary pressures (future increases in overheads and increasing operations costs as new experiments start up).

84. Reduced consolidated grant funding is likely to lead to a loss of support for neutrino astrophysics, neutrinoless double beta decay, and potentially some groups. Reduced development funding could potentially lead to the loss of a

high priority science area (flavour physics)[9], which will lead to reputational damage should the UK need to withdraw from international commitments. If this occurs, it will be important to find alternative mechanisms to support some research diversity to maintain the health of the discipline.

85. The strong alignment of the programme with the European Strategy for particle physics makes it imperative that the updated, and at the time of writing unknown, European Strategy recommendations are taken into account in any future decisions.

[9] Particle Physics Programme Evaluation Report, 2019, https://stfc.ukri.org/files/particle-physics-evaluation/

Current Programme Balance

86. Successive years of flat cash funding have resulted in a programme that is successful and of high quality but is also lean and lacking the necessary flexibility to respond to opportunity or challenge. The programme has been exposed to additional pressure by rising overheads costs, which have decreased the volume of funding available to support activities. The inability of core funds to now meet existing commitments is evidenced by the necessity for UKRI uplifts.

> **RECOMMENDATION 1**: STFC should maintain pressure for an uplift to its core programme as part of the next CSR to underpin core capability and leadership for development and exploitation, and to ensure a future pipeline for future technology and skills development and impact.

87. These pressures have left the programme underfunded and unbalanced, with areas that are already or will be unsustainable in their current form within a five-year timescale. Nuclear Physics will not be able to fund a minimal consolidated grant round even if all free development funding is routed to exploitation. Within Particle Astrophysics, contribution to the construction of aLIGO has only been possible through a substantial FIC award, and even with this injection the programme area is in danger of losing the ability to support developments in dark matter at a critical stage of community growth. Computing provision is insufficient to meet the needs of HL-LHC in five years, and unless upgrades can be secured for DiRAC from non-core funding then science areas reliant on high performance computing will erode in leadership and quality.

88. It is therefore urgent, regardless of the financial scenario, to mitigate the risks facing the programme and perform some measure of programme rebalance.

Risks Confronting the Programme

89. **Flat cash settlements in the PPAN area since 2013** have caused years of considerable erosion to the scientific programmes across all six programme areas, resulting in loss of balance within each programme area and a significant and quantifiable damage to the science as detailed in the specific area reports above. This negative impact is despite tranches of additional funding from UKRI for specific projects. All six programme evaluation reports note as a key finding that a 10% uplift was required **to start** to reverse the damage that flat cash has caused.

> **RECOMMENDATION 2**: In anything deviating significantly from either a flat real or +10% settlement, another Balance of Programmes exercise must be

undertaken with full community consultation and involvement to determine how best to sustain the various PPAN programmes.

90. **Loss of European Union (EU) funding to support the STFC programmes:** The full extent of the UK's exit from the EU on the net effective income to UK science and, in particular, STFC's community, is not yet known. Since 2008 ERC grants have provided an average of over €20M/yr of additional (to STFC) funding across the PPAN areas, so any reduction in funding will result in a significant loss of research volume and opportunities for UK leadership. To avoid this, it is essential that an equivalent amount of new funding is made available. Any replacement scheme for distributing the funding should use excellence as the principle criterion. This exercise assumes that funding will be provided at pre-2016 levels, either through continued access to EU funding or through a replacement scheme. If this does not happen, a strategic review of the programmes must be triggered.

RECOMMENDATION 3: STFC, together with UKRI and its other research councils, must strongly urge the government to either maintain access to pre-2016 levels of European funding or else replace the funding in full, with new money to maintain the breadth and balance of the current programme. Any replacement for EU funding should also be allocated according to scientific excellence. If funding is not made available then a strategic review of the programmes must be undertaken to determine how to minimise and mitigate the damage to the programme, which is predicted to be considerable.

91. **Increasing overhead recovery by universities is leading to a reduction in the fEC recovery or PI time in the consolidated grants** and placing extreme pressure on the opportunity for research volume and leadership within the PPAN programme. This problem is well evidenced by the 2015 and 2018 PPGP rounds, where the combination of flat cash and overhead/indirect cost rises translated to a 20% cut in the programme[10] from one round to the next. This is a reduction that cannot be accommodated within existing programme funds.

RECOMMENDATION 4: STFC should take measures to ensure appropriate levels of fEC/PI time are available within the consolidated grant round.

92. **There is a need to ensure viability of computing needs.** Large-scale HPC and HTC computing underpins an increasingly large part of all PPAN science

[10] 2018 PPGP Consolidated Grant Review: "The effects of flat cash funding together with the increase in indirect costs equates to a ~20% cut in the programme relative to 2015."

output. Computing provision needs a substantial uplift to ensure the international competitiveness and full exploitation of the PPAN programme. Hardware/e-infrastructure should be provided as part of wider e-infrastructure within UKRI, as needs can no longer be met within core funds. In contrast, some element of software support should be provided within the programmes (for example, supported within consolidated grants and/or projects). Some activities (e.g. data archiving) and staff (research software engineers) could and should be shared between programme areas. If external (non-STFC) funds are not forthcoming, PPAN science will be seriously impacted on a 5-year timescale. The IRIS scientific communities have estimated necessary future costs as £10M (£4M) per year for hardware (research software engineers)[11].

RECOMMENDATION 5: STFC should seek additional funds to support the long-term software needs of the PPAN programmes.

RECOMMENDATION 6: Hardware/e-infrastructure should be provided as part of wider e-infrastructure within UKRI. Hardware infrastructure needs to be accompanied by sufficient staff provision to give local support e.g. for data access issues, software compatibility, etc. The support for this resource should be shared between UKRI and STFC.

RECOMMENDATION 7: STFC should investigate the possibility of playing the lead role in a potential UKRI-wide hardware infrastructure.

93. **There is a need to baseline the recently awarded UKRI uplift (2018/2020)**, used to support the ATLAS and CMS upgrades (Particle Physics) and the growing gravitational waves area (Particle Astrophysics) which could not be provided for within core funds. Without this £3.2M uplift being incorporated into the base line going forward this would represent a significant cut to the area.

RECOMMENDATION 8: The existing UKRI uplift needs to be incorporated into the base line.

94. **No funding is currently available for the research and development (R&D) of new technologies for future projects and to maintain hardware/technical leadership.** The 2017 Balance of Programmes exercise recommended a temporary suspension of the 'PRD programme to create some headroom in the PPAN programme' stating that this 'does not negate the clear need for development of new technologies for future projects.' Continuing this

[11] Estimates given in "STFC Data e-Infrastructure requirements 2020-2025", prepared by the IRIS scientific communities and submitted to STFC in June 2019.

temporary (short term) suspension will result in damage to the UK's ability to play a meaningful role in novel international projects across the PPAN area, as well as impacting across areas through technical synergies. Consequently, it is proposed that a 'PRD-style' scheme is reinstated to support R&D, with consideration being given to themed calls.

RECOMMENDATION 9: In the case of a 10% uplift the Panel support the re-introduction of a 'PRD-style' funding scheme which should be targeted at demonstration-level technology development.

95. **There is a need to ensure regular horizon scanning to avoid opportunity loss.** The programme evaluations have revealed many exciting opportunities open to the UK that build upon community expertise and intellectual and technical leadership. It is important that every area have a process (via a roadmap, or otherwise), to regularly consider and record (and update) these opportunities. Such a process would avoid opportunity loss, particularly if new funding calls requiring rapid response arise. The process should involve the relevant Advisory Panels, community and Science Board.

RECOMMENDATION 10: Every area should ensure that there is a defined process (roadmap or otherwise) for regular horizon scanning involving Science Board, the Advisory Panels and the wider community, to avoid accidental loss of opportunity. This should be an ongoing exercise to avoid accidental loss of potential opportunity.

96. **The lack of an ability to access cross-PPAN funding for small, high priority projects.** Constrained funding over many years has eroded the agility of areas to respond to new opportunities. This is an issue across the whole of the PPAN programme with smaller programme areas in particular, for example Nuclear Physics and Particle Astrophysics, lacking the capability to seize *any* new opportunity. Furthermore, novel approaches employing a cross-PPAN approach are disadvantaged in the absence of such a scheme, meaning that some areas (e.g. gravitational waves) may not be able to grow, despite increasing interest in the area. Such projects are unlikely to obtain funding under the Developing a World Class Research Programme scheme due to their size and interdisciplinary nature. Any new scheme would need to respond quickly to timely opportunities; have a high risk – high gain aspect; explore/prototype new areas to allow formulation of a future larger scale experiment; avoid overlap with existing calls. To mitigate the opportunity loss the Panel propose that STFC investigate the creation of a **cross-PPAN funding line** for small, high priority experiments.

RECOMMENDATION 11: STFC should explore opportunities for responsive mode funding calls targeted at the support of small high risk – high gain projects.

97. **There is a need to ensure environmental sustainability within the programme.** As yet, the programme has not considered environmental sustainability and will need to do so in the near future. It is anticipated that UKRI will provide guidance shortly. One course of action could be to introduce a question into grant applications on how a project intends to address environmental sustainability.

RECOMMENDATION 12: All projects should be requested to provide high levels details of their efforts to make their research as environmentally friendly as possible.

98. **The effect of forthcoming strategic reports.** A number of crucial strategic reports are expected later in 2020 (e.g. European Strategy for Particle Physics, which affects Particle Physics and Accelerator Science). As yet the influence of up-coming strategic reports such as the ESPPU[12] on the various PPAN areas is unknown. Indeed, should the findings of these reports diverge from current strategy and require an altered balance, this must trigger another Balance of Programmes exercise.

RECOMMENDATION 13: Considering the strategic reports expected in mid-late 2020, any divergence from current strategy and/or any requirement for an altered balance must trigger another Balance of Programmes exercise.

99. **A sustainable career structure** is needed at all levels; a clear career structure should be apparent for everyone.

RECOMMENDATION 14: Fellowships are needed to bridge the gap between PhD graduation and existing schemes, for researchers with clear leadership potential to establish a strong, independent research programme.

RECOMMENDATION 15: STFC should explore developing and enhancing links with industry through fellowships, thus supporting skills development.

RECOMMENDATION 16: A clear career structure for research infrastructure and software engineers and project managers should be established by

12 https://www.ukri.org/skills/policy-and-frameworks/review-of-the-concordat-to-support-the-career-development-of-researchers/

STFC, in analogy to the Concordat to Support the Career Development of Researchers[12].

Programme Balance in Future Financial Scenarios

100. Two funding scenarios, i.e. flat real and + 10%, have been considered. Given that the PPAN programme has a current budget of approximately £112M, the + 10% scenario amounts to an overall increase of approximately £11M.

101. In both scenarios the projected outlook for the subject areas and priorities for uplifts are given, and the risks identified with rebalancing funding between areas are discussed. The Panel are clear that rebalancing in either scenario will not achieve a programme with the ability to fully exploit previous investment, grasp the vibrant new opportunities for UK leadership that exist and mitigate external risks. **A larger uplift to core funds is necessary** to achieve that. Both scenarios do require a rebalancing of funds to sustain the future health of the programme.

Summary: In the case of a Flat Real settlement, the Panel recommends a rebalancing of the programme to provide a rescue package of £0.6M per year to the Nuclear Physics area to prevent imminent programme-wide, severe and irreversible damage; the cost of this will be equally borne by the Astronomy and Particle Physics areas as the two largest PPAN components, though the Panel note that this will cause damage to these programmes. The Panel further recommends that in years 4 and 5 of this period an uplift to £1.5M per year be allocated to Dark Matter within the Particle Astrophysics area to develop limited breadth in the programme; this would be paid for from the inflationary uplift afforded by Flat Real and so the other areas of the programme would effectively revert to flat cash in these years.

Programme Balance: Flat Real

Projected Outlook

102. **Nuclear Physics** has inadequate funding to support the programme in this scenario. Urgent support, estimated to be approximately £0.6M per year (an uplift of about 10%), is required to maintain the programme throughout the time period by: (i) supporting consolidating grant funding at constant volume, mitigating the effects of rising overheads costs and allowing PDRAs to be funded for the full grant period; and (ii) increasing development funding sufficiently to allow a second project to be funded, and to maintain some level of programme depth. The Panel agreed that Nuclear Physics is the highest priority for an uplift.

103. **Particle Astrophysics** is also considered to become critical within the next five years. In this scenario there is a risk of losing an entire science area, reducing programme breadth and impacting the Astronomy or Particle Physics communities who wish to exploit it. The limited breadth and depth of the Particle Astrophysics programme resulted in the Panel finding it necessary to consider each of the programme elements separately, so that the relatively stable position of the largest element, GW, would not unduly affect the smaller areas of DM or VHE. An uplift to £1.5M per year in the last two years of the time period is necessary to mitigate the risk to UK involvement and leadership in direct detection of dark matter[13]. The Panel agreed that Particle Astrophysics is the second highest priority for an uplift.

104. **Computing** has inadequate funding to meet programme demands on a five-year timescale. GridPP must be upgraded to meet HL-LHC demands and DiRAC must be upgraded to counter ageing and non-replacement of equipment, to maintain scientific competitiveness. The uplifts necessary to purchase this hardware are beyond the capacity of core funding to provide and are not considered here. In this scenario staff/engineers cannot be supported as computing funding lines are already fully committed. Insufficient funds for computing will damage science across the whole of the STFC programme.

105. **Accelerator Science** will suffer damage under flat real due to above-inflationary pressures. Reductions in institute funding will result in a loss of skills and programme breadth and risk a greater impact to the community because of the institutes' ability to leverage external funding. There are insufficient funds to mitigate the loss of EU funding.

[13] See the 2020 Dark Matter strategic review, https://stfc.ukri.org/files/2019-dark-matter-strategic-review/

106. **Astronomy** will suffer damage under flat real due to above-inflationary pressures and additional calls for exploitation coming from the PA and UKSA areas. Constrained consolidated grant funding will be damaging and result in loss of international competitiveness as less of the community can be supported. Reduced funding is likely to lead to a loss of future programme opportunities with exciting projects where the UK could take a leading role being missed. Astronomy is particularly exposed to the risks to EU funding.

107. **Particle Physics** will suffer damage under flat real due to above-inflationary pressures. It is likely that diversity and breadth will reduce with constrained consolidated grant funding, return on existing investment (such as the LHC experiments) will reduce and support for smaller activities will be lost, although with careful management it should be possible to avoid losing an entire science area. There are insufficient funds to mitigate the loss of EU funding.

Rebalancing the Programme in this Scenario

108. The Panel considered that Nuclear Physics and Particle Astrophysics need additional funding to prevent programme-wide, severe and irreversible damage over the next five years.

109. Computing will require additional funding on a five-year timescale to prevent damage to the wider scientific programme. The Panel considered that the necessary investment needed to meet demands is beyond this exercise to provide. Any reduction in funding now would result in direct damage to scientific output across the programme and should be avoided.

110. The Panel noted that rebalancing the programme in this scenario has insufficient funds to meet the cost of computing hardware upgrades in five years and to mitigate against external pressures.

111. The Panel felt that any gain obtained by moving funds away from Accelerator Science, to resolve the situation, would be outweighed by the disproportionate effect this would have on the community with the loss of leveraged funding. The programme is very constrained and lacks flexibility to respond to changing circumstance. Reducing funds should be avoided.

112. Only the larger programme elements, Astrophysics and Particle Physics, have sufficient flexibility to redirect funds. However, reducing either will cause more damage to large sections of the STFC community and involves a number of risks.

113. While the suspension of the PRD scheme was put into place by the previous Balance of Programmes exercise as a temporary measure, the Panel believe that it cannot be reinstituted into the overall programme without an uplift of funding to pay for it. The Panel noted that this will result in long term damage to development of new technologies and reduce the scope for knowledge

exchange and collaboration with industry. In addition, the Panel note that the PRD provided an opportunity for early career researchers to develop their own research and the lack of such a scheme will limit development of future UK leaders.

Risks of Reducing Astronomy Funding

114. While the exploitation line is scalable, it is already overstretched and will face increased future pressure as exploitation requests for projects from UKSA and PA bid for this same resource. Any reduction in exploitation would reduce programme breadth and be very damaging to the international competitiveness of UK astronomy. The priority is therefore protecting the exploitation line, which implies that a reduction in Astronomy funding will result in a cut to development and operations.

115. Such a cut could be implemented through either a top-down or bottom-up approach. The former of these would require a cut to the UK contribution to a significant international project such as ELT or SKA. This would result in significant and immediate reputational damage to the UK and raise doubts for international partners in the UK community's ability to deliver on commitments. There would also be adverse impact on the UK technology and instrumentation sector coupled with a loss of UK industrial return from construction contracts.

116. A bottom-up cut would result in the closure of a large number of projects in order to realise a substantial saving, damaging the diversity of the Astronomy programme. There would be knock-on harm to technological development and building capabilities together with a loss of capacity and expertise within the community for the future.

Risks of Reducing Particle Physics Funding

117. Consolidated grant funding is committed until 2023/24. Reduced funding after this point will restrict programme breadth by removing support for neutrino astrophysics, neutrinoless double beta decay and electron dipole moment experiments. Exploitation for Particle Astrophysics and Accelerator Science (which both have groups funded by PPGP), will be impacted. Return on existing investment (such as the LHC experiments) will reduce. It is likely that groups will be lost, and that this will lead to a loss of ability to participate in future activities (with consequent loss of skills, leadership and knowledge exchange).

118. Restricting development project funding, which is very limited, would lead to the loss of project(s) graded as alpha-5 by the Particle Physics Programme Evaluation that are of high international strategic priority. In this scenario it is possible that an entire science area is lost from the programme (flavour physics, if the LHCb Upgrade cannot be supported), and/or that the UK

withdraws from an established and longstanding programme of internationally leading neutrino physics research with Japan (if Hyper-K cannot be funded).

119. A settlement corresponding to a funding reduction below flat cash would necessitate a new review of Particle Physics.

RECOMMENDATION 17: Funding for Nuclear Physics should be increased by £0.6M per year, with the cost being met by reducing funding for Astronomy and Particle Physics equally. The Panel further recommend that funding for Dark Matter in Particle Astrophysics is increased to £1.5M per year in the last two years of this time period, with funds coming from the inflationary increase across the whole programme. The Panel recommend that the relevant programme managers distribute the funds according to the best interests and health of the programmes.

Programme Balance: + 10% Increase in Funding

Summary: In the case of a +10% uplift to funding, the Panel recommends that the £0.6M/year rescue package for Nuclear Physics and the increase to £1.5M/year in years 4 and 5 for Dark Matter to build breadth in Particle Astrophysics (see Flat Real recommendation) are both implemented as a top priority. As a second priority the Panel recommend the reinstatement of the PRD programme (or equivalent) at a level of £1.4M/year. The remainder of the uplift funds should then be distributed pro rata amongst the six areas.

Projected Outlook

120. **Nuclear Physics** funding is considered to be at threshold in this scenario. The Panel considered this level of funding to be the minimum necessary to re-establish a level of health for the next five years; an optimal level of support would be higher.

121. **Particle Astrophysics** funding is also considered to be at threshold in this scenario. The Panel regarded this funding to be the minimum necessary to ensure some level of programme health over the next five years.

122. **Computing** would be able to support a number of research software engineers in this funding scenario, which would benefit science across the programme. The funding scenario is insufficient to meet the cost of hardware upgrades needed in five years.

123. **Accelerator Science** would be able to fund the accelerator institutes at least at constant volume in this scenario, ensuring the full value of leveraged income is available to the community. The scenario would also allow some (small) investment in new opportunities, allowing strategically directed thematic funding calls.

124. **Astronomy** would use an increase in funding to bolster consolidated grants in this scenario, somewhat mitigating the pressure on the exploitation line and guarding the UK's international position. This would provide capacity to support the expected increase in the number of future ESA missions, and return greater value for investment through increased exploitation. It will be possible to support the highest-priority, novel developments and bid for UK leadership in these projects.

125. **Particle Physics** would be able to support consolidated grant funding at constant volume in this scenario. Any additional funds could be used to support programme breadth; supporting experiments where the UK has leadership, or

makes key contributions, that would otherwise be lost, and allowing research and development to prepare future experiments.

Additional Candidates for Financial Uplift

126. The Panel noted that the cessation of the PRD scheme in 2016 had impacted the amount of research and development possible across the programme. This has damaged the balance between developing future opportunities and exploiting existing investment. The loss of support has been highlighted as a problem by the programme evaluations. The Panel considered the introduction of a **PRD-like scheme** to be a high priority and recommended that this be funded at £1.4M/year, i.e. at a volume consistent with the last year of PRD operation.

Rebalancing the Programme in this Scenario

127. The programme evaluations have all recommended that a +10% funding scenario is necessary to repair at least some of the damage caused by long term constrained funding.

128. The Panel identified as a first priority that the measures identified under the Flat Real scenario to make Nuclear Physics and Particle Astrophysics sustainable over the next five years be implemented. A second priority is the reinstatement of a PRD-like scheme, which the Panel considers affordable in this financial scenario.

129. With these uplifts assigned, the Panel consider that all programme areas will benefit equally from any subsequent uplifts. The Panel recommend that remaining funds are distributed pro rata between the programme areas.

130. In this financial scenario there are insufficient funds to meet the cost of computing hardware upgrades and to mitigate the effects of external pressures such as loss of EU funding. However, investment in the future programme can be reinstated and damage caused by constrained funding can be partially repaired.

131. The Panel note that this scenario has insufficient finances to create a cross-PPAN funding line and recommend that STFC maintain sufficient flexibility between areas to allow very high priority projects to be considered regardless of area.

Conclusions

132. The STFC programme provides the strategic funding for the research communities in Astronomy, Nuclear Physics, Particle Astrophysics and Particle Physics, and the associated areas of Computing and Accelerator Physics. The purpose of the Balance of Programmes 2020 review was to define a balanced programme of excellent science within a constrained financial planning

envelope. During the current exercise, the Panel considered each of the programme areas and, through a process of consultation, discussion and assessment made a set of recommendations. The report is presented as a plan that will allow the STFC programme to function in the most effective way for the UK's scientific community.

133. **The Panel strongly endorse the key finding from all six evaluation reports that at least a 10% funding uplift is required to address the on-going erosion to the programme from many years of flat cash funding.**

134. The plan and associated recommendations do not propose any major changes or sweeping cuts, but instead focus on modest, strategic activities to best balance the programme and to ensure the continued viability of the programme areas.

135. The Panel acknowledge that the exercise was performed in a time of great uncertainty, not least due to the effect of EU Exit on the level of funding available for the STFC programmes, and the consequences of the COVID-19 pandemic. To perform the exercise several assumptions had to be made. If one or more of these assumptions are not met, it is recommended that another Balance of Programmes exercise is undertaken with full community consultation and involvement to determine how best to sustain the STFC programme areas.

136. The Panel would like to thank all those involved in facilitating and supporting the process, including the chairs and members of the six Programme Evaluations, the Accelerators Advisory Panel, the Astronomy Advisory Panel, the Computing Advisory Panel, the Nuclear Physics Advisory Panel, the Particle Astrophysics Advisory Panel, the Particle Physics Advisory Panel and the Solar System Advisory Panel, STFC Programme Managers, and Derek Gillespie, Malcom Booy, Karen Clifford and Jackie Hawkins from the Swindon Office. The Panel wish to acknowledge them all for their hard work and openness during the process.

List of Recommendations

RECOMMENDATION 1: STFC should maintain pressure for an uplift to its core programme as part of the next CSR to underpin core capability and leadership for development and exploitation, and to ensure a future pipeline for future technology and skills development and impact.

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Glossary

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

AccPE - Accelerator Programme Evaluation.

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.

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.

ASTeC – Accelerator Science and Technology Centre. 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.

AWE – Atomic Weapons Establishment.

BEIS - Department for Business, Energy and Industrial Strategy.

Blue MUSE – a blue-optimised, medium spectral resolution, panoramic integral field spectrograph based on the MUSE concept and proposed for the Very Large Telescope.

BoP - Balance of Programmes, review which looked at the balance of funding between the PPAN research disciplines.

CDT - Centre for Doctoral Training.

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

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

CSR – Comprehensive Spending Review.

CUBES – Cassegrain U-Band Efficient Spectrograph. A high-resolution, near-UV spectrograph to be deployed on the VLT.

DM - Dark Matter.

Diamond II - 4th generation light source.

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

DTC – Doctoral Training Centre.

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

ECR – Early Career Researcher.

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

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.

EPAC – Extreme Photonics Applications Centre. A partnership between UKRI, MoD, academia and industry to bring together world-leading interdisciplinary expertise to develop and apply novel, laser based, non-conventional accelerators and particle sources.

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.

ESPPU – European Strategy for Particle Physics Update.

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 characterize properties of dark energy.

EuPRAXIA – European Plasma Accelerator with superior Beam quality.

EuroCircCol – European Circular Energy-Frontier Collider Study. A conceptual design study for a post-LHC research infrastructure based on an energy-frontier 100 TeV circular hadron collider.

European Solar Telescope – European Solar Telescope (EST). A next generation large-aperture solar telescope.

fEC - Full Economic Costing.

FTE - Full Time Equivalent.

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

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.

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.

IRIS - is an image processing software for astrophotography. IRIS is free for non-commercial usage.

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

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.

MARVELS - A system of 4 telescopes feeding a high-resolution spectrograph on La Palma with the aim of supporting ARIEL and PLATO.

MRC - Medical Research Council.

New Robotic Telescope – New Robotic Telescope (NRT). A 4-m-diameter telescope with fully robotic operation.

NP - Nuclear Physics.

NPL – National Physical Laboratory. The national measurement standards laboratory for the United Kingdom.

NPAP – Nuclear Physics Advisory Panel.

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.

PAPE – Particle Astrophysics Programme Evaluation.

PDRA – Postdoctoral Research Associate.

PI – Principal Investigator.

PLATO - PLAnetary Transits and Oscillations of stars (PLATO) is a space telescope under development.

PP - Particle Physics.

PPAN - Particle Physics, Astronomy & Nuclear Physics.

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.

PRD – Project, Research and Development grant.

Solar Orbiter – a mission dedicated to solar and heliospheric physics.

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

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.

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.

TOPCAT - software package widely used in astronomy with a worldwide user base.

UKAEA – United Kingdom Atomic Energy Authority. A UK government research organisation responsible for the development of nuclear fusion power.

UKRI – UK Research and Innovation.

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

VHE – Very high energy.

Annex 1: Advisory Panel Programme Evaluation Update Questions

We recognise that the various programme evaluations were completed at different points in time during 2018 and 2019. It is important, therefore, to provide programme advisory panels with the opportunity to submit a short update to the Panel in order that any important changes in the research discipline landscape have been captured.

To this end, we are inviting each advisory panel to **submit up to two sides of A4** that capture key developments, changes, opportunities or risks in their discipline since the completed their programme evaluation.

The questions to be addressed by each advisory panel are as follows. In each case, panels should confine themselves to providing updates only if, in their view, there have been noteworthy changes since the publication of the programme evaluation.

Programme Evaluations Advisory Panel Update Questions

1. Have there been any significant changes or developments that would cause the panel to alter their ranking and prioritisation of the various projects within the programme evaluation report?
2. Have there been any major scientific developments within the field since the time of the programme evaluation that should affect STFC's consideration of future support of relevant UK research?
3. Where applicable, have there been any significant updates to relevant community roadmaps?
4. Is there any cause to amend the programme evaluation recommendations regarding the choices that need to be made under the different funding scenarios considered?
5. Have any significant new opportunities or risks emerged for the health of discipline that were not included in the programme evaluation, or that need to be expanded upon in more detail?
6. Do any of the recommendations in the programme evaluation require a significant update or revision?

Annex 2: Programme Evaluation Summaries from Panel Chairs

STFC will invite the Chairs of the programme evaluations, or an agreed deputy, to attend the February 2020 meeting. These individuals will be asked to present a brief summary of the content of the programme evaluation report, to aid Science Board members as they familiarise themselves with the evaluations before the March 2020 meeting.

Given that Science Board members will have time to read the full programme evaluation reports in detail, these summaries are not intended to be comprehensive.

The slides presented by the programme evaluation Chairs will cover the following topics:

Summary of key opportunities uncovered (1 slide): providing a summary of key opportunities within the programme area identified by the evaluation, based on the evidence gathered.

Summary of key challenges uncovered (1 slide): providing a summary of key challenges faced within the programme area identified by the evaluation, based on the evidence gathered.

Highlighting key recommendations (1-2 slides): in the view of the panel Chair, which recommendations within the programme evaluation are particularly important, and why?

Annex 3: Programme Evidence Summary Questions

STFC team members with responsibility for each of the six programme areas in scope for the Balance of Programme 2020 exercise are invited to attend the February 2020 meeting. They will present a set of slides that cover an agreed range of topics related to their programme, providing the Panel with important contextual information as part of their evidence base.

The slides provided by STFC team members will cover the following topics:

Programme Financial Headlines (1 slide): providing a summary of the programme budget projection, based on STFC's current budget, for the period covering financial years 2019-2020 through to 2024-2025. Where possible, the information will detail both resource and capital funding, and indicate 'committed' funding and 'headroom' for each within the programme budget.

Programme 'health of discipline' (1 slide): providing a summary of the programme manager's view on the current 'health of discipline' of the programme, taking into account factors such as depth vs. breadth, balance of R&D/exploitation etc.

Response to Programme Evaluation (1 slide): containing the programme manager's views on the output of the relevant programme evaluation, and a summary of any actions undertaken, and associated outcomes. If relevant, programmes should provide a short commentary on what they see as the key recommendations from the programme evaluation.

Key opportunities and risks: flat or reducing budget (1 slide): from the perspective of the programme, a summary of the key areas of opportunity and risk facing the programme over a time period until 2025, based on the assumption of a flat real budget.

Key opportunities and risks: increasing budget (1 slide): from the perspective of the programme, a summary of the key areas of opportunity and risk facing the programme over a time period until 2025, based on the assumption of a moderately increasing budget (no more than +10%).

Annex 4: Balance of Programme 2020 Questions

In line with the terms of reference, the Balance of Programmes 2020 exercise will advise on the following questions.

With reference to each individual programme area:

- Is there an appropriate balance between R&D, construction, and scientific exploitation within the programme area?
- Can the programme maintain an appropriate depth and breadth, ensuring that key areas of research are supported?

- Based on current funding projections, is the programme area sustainable scientifically, balancing construction, exploitation, and key future opportunities?
- If the answer is negative to any of the above, please indicate how the programme could be rebalanced to address the issue.

With reference to STFC's PPAN, computing, and accelerator programme as a whole:

- Is there an appropriate balance of funding between the different areas of the programme? Assuming the current STFC funding scenario continues over the coming five years, is there a case to recommend a re-balancing of funding to ensure a viable portfolio?
- In the event of moderate changes to STFC's funding, are there areas of the programme that should be considered to be preferential areas for increased financial support relative to others? Are there areas of the programme that should be given a measure of protection against a budget reduction in the case of reduced overall funding for the programme?
- Can the programme provide sufficient opportunities for scientific exploitation, theory, or experimental R&D as part of the portfolio, assuming the current STFC funding scenario continues over the coming five years? Is there a case to recommend that such opportunities are prioritised for increased funding in the current funding scenario, or in the event of a moderate funding increase to the programme?

Annex 5: Terms of Reference

The terms of reference for the Balance of Programmes 2020 are as follows:

With reference to each individual programme:

7. To provide high-level advice on whether there is suitable depth and breadth within each research discipline to provide sustainability and health of programme, including scope for development and support of future opportunities.

With reference to STFC's PPAN programme as a whole:

8. To consider the balance between STFC's PPAN research disciplines over a five-year time horizon, advising on the appropriateness of the relative balance of funding between different disciplines.
9. To advise on any areas suitable for preferential or prioritised funding allocation in the event of any change in core funding to STFC.