

Particle Astrophysics Advisory Panel

submission to the

Balance of Programme Exercise

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Science Roadmap

Q1. *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.*

In September 2016 the **Particle Astrophysics Advisory Panel (PAAP)** completed a revision of its science roadmap for UK particle astrophysics. For convenience we include a summary of the prioritisation below.

Particle astrophysics (PA) has seen enormous advances over the last few years. These include the first observation of gravitational waves from binary black hole mergers, by Advanced LIGO, with its subsequent opening of a new field of astrophysics. Construction has begun on second generation dark matter (DM) detectors including LUX-ZEPLIN (LZ), which will probe the WIMP parameter space for masses above a few GeV down to cross-sections near the irreducible neutrino coherent scattering background. The Cherenkov Telescope Array (CTA), the first global observatory for very high-energy photons with sensitivity an order of magnitude better than any previous facility, has entered its pre-construction phase. The first detector strings of the KM3NeT high-energy neutrino observatory have been deployed in the Mediterranean, following the first observation of PeV-energy astrophysical neutrinos by IceCube.

The UK has particularly large and influential communities in three PA areas: **gravitational wave astronomy**, **γ -ray astronomy**, and **direct dark matter detection**. Figure 1 shows the expected evolution of projects with significant UK involvement. The coming years will see exciting science from these areas, including the observation of many more binary black hole mergers, the potential direct detection of WIMPs, and the expected discovery of a thousand or more new high-energy gamma-ray sources. For example, the detection of gravitational waves in the first months of Advanced LIGO operation indicates that the scientific potential of future observations will be far larger than previously anticipated. The first detections demonstrated the existence of stellar-mass black holes many tens of times the mass of the sun, with wide-ranging implications for astrophysics. It is expected that the masses of >100 black holes will be measured in observations over the next five years; by contrast, decades of observations have yielded the masses of ~ 60 neutron stars. The study of stellar-mass black holes will emerge as an active observational as well as theoretical field and will be the focus of intense activity over the next decade.

Looking ahead, planning has already begun for upgrades to Advanced LIGO, and for third-generation gravitational wave observatories such as the Einstein Telescope, as well as for third-generation direct

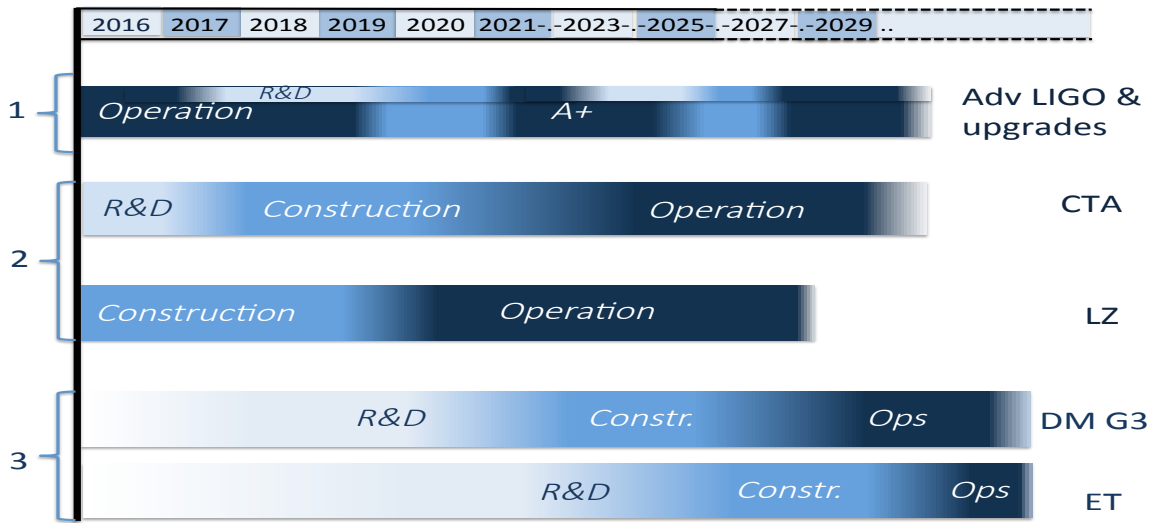


Figure 1: Anticipated roadmap for UK particle astrophysics, showing the global R&D, construction/installation, and operations phases of each project. Numbers on the left indicate the prioritisation bands.

dark matter detectors. UK groups have recognised international leadership in key areas for these projects. These include suspensions and materials technology vital to the low-frequency sensitivity of gravitational-wave detectors, and analysis techniques and the science case for future ground- and space-based detectors. For CTA the UK provides the spokesperson for the largest set of telescopes, the so-called Small Size Telescopes, and is leading the development of the ground-breaking silicon photomultiplier-based camera to be used by all dual-mirror SSTs. UK capabilities for the processing of low-radioactive-background materials will be important for any third-generation DM detector, irrespective of the chosen technology, and have applications well beyond PA. The UK also has world-leading expertise on noble liquid characteristics and engineering for up-scaling. The UK is therefore extremely well-placed to exploit upcoming opportunities given sufficient funding.

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

1. **Advanced LIGO:** exploitation to profit from major UK investment and leadership in this new field of astronomy, and development and implementation of initial upgrades to the system
2. **LUX-ZEPLIN:** exploitation, building on current investment and substantial UK expertise and leadership
CTA: construction and exploitation, building on current investment and substantial UK expertise and leadership
3. **Einstein Telescope:** support of R&D for future GW detectors, to facilitate future UK participation in ET
G3 Dark Matter: support of R&D to facilitate UK participation in a future G3 experiment.

The current annual PA spend of approximately £3.2M supports gravitational wave R&D, operations and exploitation focussed on Advanced LIGO, targeted R&D for CTA, and construction of LZ. Full

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

There is also potential for significant UK impact in high-energy neutrino astronomy. The PAAP supports the statements made in the [2015 IOP review of UK particle astrophysics](#) that the UK community should seek to coalesce around support for a single project, and we would support such an project's inclusion in a future PAAP roadmap.

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

Breadth and Balance

Q2. *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).*

Breadth

The UK particle astrophysics programme has been enormously successful, both in terms of outstanding science and in international leadership. The detection of gravitational waves from binary black hole mergers was only possible due to critical contributions to hardware, analysis techniques, and source modelling by UK groups. LISA Pathfinder has been an outstanding success as a technology demonstrator mission. In dark matter detection, the UK pioneered the use of noble liquid time projection chambers with xenon targets, the technology that now dominates the field. UK scientists lead many LZ Work Packages, and have made major contributions across nearly all areas, such as the cryostat, phototubes, and low-background assays. For CTA, the UK pioneered the design and adoption of compact dual-mirror Small Sized Telescopes (SSTs), and are producing prototype silicon photomultiplier cameras for them. The UK provides the SST spokesperson, and is in line to provide the complex front-end electronics for all of their cameras.

Continued success at this level is only possible with sustained, long-term investment. After 2009, PA

funding in the UK contracted to the point where only gravitational wave detection was funded at any significant level. The recent expansion to now also include γ -ray astronomy and dark matter restores critically needed breadth to the UK PA programme and is widely appreciated by the community. Our prioritisation recognises this breadth as vital for the long-term health of UK particle astrophysics.

We note, however, that even this minimal healthy breadth is unsustainable at current funding levels: the current PA spend is insufficient for the R&D, construction and exploitation activities needed to maintain current UK leadership in gravitational waves, DM, and γ -ray astronomy. Preserving even the current minimal breadth of the PA programme therefore requires an expansion of the funding envelope in the near future. Specifically, we need commitments to funding for CTA construction, R&D for Advanced LIGO upgrades and future detectors, and R&D for third-generation dark matter detectors. Enhanced investment in these areas will ensure the UK's ability to play leading roles in the exciting science to come over the next decade.

In addition, we note that the UK has not re-established participation at project level in any of the high-energy neutrino or cosmic ray projects (IceCube, KM3NeT, AUGER, *etc.*), despite having active researchers in both of these areas and a history of significant contributions to these projects. UK researchers have also made important contributions to the DM project ADMX. These represent further opportunities that are not currently exploitable due to funding restrictions.

Balance

The prioritisation presented on page 2 combines guaranteed science over both the short and long term (e.g. GWs and γ rays) with high-risk/high-reward science (e.g. WIMPs). The full prioritisation also strikes a balance between basic R&D, experiment construction and exploitation; we note that the current PA spend is relatively heavy on construction (LZ, CTA), with less emphasis on exploitation (mainly in LIGO). We stress that it is essential to fully support the exploitation phase of projects that have been funded by the UK in order to maximise the return on investment.

It is also vital to maintain the health of other activities and infrastructure that support large projects, including the theoretical work and data analysis and computing infrastructure that underpin all particle astrophysics experiments. For example, LZ is able to embark upon a world-class programme of materials testing due to the excellent low-background facilities available at the STFC-funded Boulby Underground Science Lab.

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

Funding Scenarios

Q3. *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 ($\pm 5\%$)?

Scientific sustainability of the UK particle astrophysics programme can only be achieved with an increase of the funding envelope. The UK PA community is still recovering from the crippling restriction of funding brought on by the global financial crisis. We have only recently restored a minimal viable breadth to the PA programme, and it is crucial that support for our top-priority projects be enhanced. Quoting one consultation response, “*We are now at a point where senior world-leading experts are funded at the same (or lower) level as junior faculty in other countries. This is clearly not sustainable and will inevitably lead to a loss of expertise.*” Even in the relatively well-supported area of gravitational waves, flat funding has produced a decrease in real-terms support at a critical time, that if not corrected will irreparably damage the UK. Any further decline in funding would be disastrous, leaving the UK behind in an entirely new field that we’ve helped to create. In dark matter, LZ construction and near-term exploitation (to 2019) is currently funded, but participation in third-generation experiments requires R&D investment on the same timescale. UK funding of CTA construction can begin as LZ construction funding winds down, but provisions for exploitation are needed very soon: the first CTA science data will be available in 2017, and will flow in increasing volumes for several decades.

Even flat PA funding is therefore likely to involve the loss of significant UK scientific capability (and reputation). Options include:

- foregoing the exploitation of Advanced LIGO at the birth of the new field of gravitational-wave astronomy;
- relinquishing our position for leading roles in next-generation gravitational-wave observatories;
- loss of leadership in the realisation of the CTA observatory in a science area initially established by the UK; or
- failing to secure a leading role in any third-generation dark matter experiment.

Each of these options brings the loss of UK leadership in a key science area, and failure to capitalise on current and past investment and UK expertise.

At the same time, we note that despite the highly diverse nature of the PA community, the total yearly spend in PA – £3.2M – is small compared to the particle physics and astronomy budgets, and **a 5% loss (or uplift) for PA is a tiny correction to the spend in those much larger areas.**

Technology

Q4. *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?*

There are a number of UK SMEs that offer world-leading technologies for PAAP experiments, such as the UK companies that are engaged in developing the mirrors and mirror coatings for CTA. Similarly,

the Boulby BUGS low-background suite of Ge detectors benefits from low background lead shielding supplied by UK industry. UK companies are currently demonstrating world-leading know-how in the fabrication of large scale structures for liquid argon TPCs. ET Enterprises Ltd continue to build and distribute world-class photosensors at their Uxbridge facility in the UK.

STFC provides valuable funding mechanisms to enable knowledge transfer from PAAP activities to UK-based SMEs, e.g. the mini-IPS and IPS schemes, we support this and advocate the continuation of this scheme.

Finally, we note the importance of basic research done at the university level, as the technical challenges underlying new PA projects are often beyond a typical industry-led development program. For example, the key technologies which made Advanced LIGO possible were developed in university groups. Previous successful instrument development in this field was achieved with a now well established route, starting with proof-of-principle experiments, followed by meter-scale prototype systems, and after a down selection, demonstrations on 10 m scale prototype interferometers and eventually the further development for large-scale observatories. This process, spanning decades, is intertwined with the theoretical design work and the development of advanced numerical modelling tools.

It is crucial that STFC continues to provide support for university-based instrument development with close interaction between blue-skies R&D, that advances the state-of-the-art in precision measurement, and the work for integration and application of new systems into the infrastructure of large PA instruments.

Skills

Q5. *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.*

Balance

Particle astrophysics is by its nature frontier physics, addressing big questions with often exotic detectors, and excites and inspires young people. A PA PhD typically involves not only pure physics/astrophysics research, but also in-depth experience in commercially valuable activities such as experiment design, data handling & IT, and mathematical modelling. As a consequence PA produces a steady stream of highly trained people with sought-after technical skills who find employment in academia, high-tech industries, IT, finance, and government.

Our consultations have noted a lack of the PDRA support that is crucial for driving progress in any research group or project. Both our Roadmap and consultation responses point out how the number of PDRAs per academic in PA is very low, with one group noting *“the UK will progressively struggle in keeping leaders in the field who will prefer to move abroad to work in better conditions.”* There is also a general desire for increased numbers of studentships.

Another specific concern is the shortage of software engineers. All large PA projects increasingly rely on large-scale computing. Unfortunately, it is often very difficult to fund the software engineers who

enable the scientists to make optimal use of these facilities – it’s “easier to buy hardware than people”. Cutting support for the personnel who are needed to efficiently exploit the available computing infrastructure is a false economy.

Finally, we note that large projects (in PA or any other field) require skilled management to ensure the efficient use of funds and timely progress toward objectives. Good management also helps to safeguard leadership in international collaborations. In practice, however, it is very difficult to get support for project managers. Furthermore, experienced managers for large projects are few in number and tend to be over-stretched. We recommend that STFC review panel support for project management, to ensure allocated funds are well-spent.

Leadership

The UK PA community punches well above its weight in terms of international leadership. UK scientists occupy a large fraction of leadership roles in the LIGO Scientific Collaboration, including co-chairs of 2 of the 4 international GW search groups, and lead the science case for the Einstein Telescope. UK development of mechanical and optical technology for Advanced LIGO gained the UK partnership in this major project and ensured data access for UK scientists, and the UK was a major contributor of flight hardware for the LISA Pathfinder mission. In CTA the UK provides the spokesperson for the largest set of telescopes, the Small Size Telescopes, and is leading the development of the ground-breaking silicon photomultiplier-based camera to be used by all dual-mirror SSTs. UK scientists occupy significant leadership roles in the LZ construction project, with co-leadership of 3 of the 11 Work Packages, and membership in both the project Technical and Executive Boards. The UK holds responsibilities for delivery of the LZ titanium cryostat, a fraction of the phototubes, low-background assays for material selection and background modelling, one of two project Data Centres, internal sensors, and contributions to calibration systems.

Stable, long-term investment is absolutely necessary to maintain this leadership in an international context. Acknowledged leadership such as that demonstrated by UK scientists is built up only gradually, via sustained commitments to support research across the gamut of activities, from blue-skies investigations, through experiment conceptualisation, instrument design, construction, exploitation, data interpretation, and source modelling. UK groups have clearly demonstrated that they are exceptionally well placed to continue leadership if they are provided with adequate support for the construction and exploitation of current instruments and the forward-looking R&D that ensures UK roles in future projects.

Computing

Q6. *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?

Particle Astrophysics research requires both high-performance and high-throughput computing resources due to the very large datasets it produces, and to the multi-scale, multi-dimensional and non-linear domains to be explored in building model simulations. For example, the CTA archive growth is expected to be ~ 25 PB/year; accurate data interpretation requires extensive Monte-Carlo

simulations of the γ -ray particle shower interactions in the atmosphere. The analysis of gravitational wave observations (~ 100 TB/year for Advanced LIGO) for signal detection and source characterisation relies heavily on filtering the data streams against banks of theoretical waveform templates.

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

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

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

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

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.

Large PA projects typically plan for the capacity to store and serve their data for the project's needs. However, the field is developing rapidly: gravitational-wave sources are expected to become numerous as LIGO moves to its design sensitivity, and CTA was explicitly established to be the first very high-energy observatory, having public data and the aim of enlarging the VHE community. Experience in astrophysics has shown that project-provided archives have performed well in their core roles, but users have often seen a need for specific added-value science capabilities (e.g. XMM-Newton, and more recently LSST). The increasing scientific utility of the PA facilities argues for their widest possible exploitation, and thus the development of highly-functional user-facing services. Meeting this need will require significant resources because of the compute-intensive nature of the analysis tasks involved. CTA and Advanced LIGO have specific plans for their community support. These efforts require support, while significant UK roles in this can help to optimise them for UK benefit.

Gravitational Wave Funding

Q7. *The STFC planning line for gravitational waves had been considered as part of the 2013 Programmatic Review; however, the context has now changed. Given the recent gravitational waves detection, the role of the UK in this detection and the opening of a new field of gravitational wave astronomy; what are the future plans for involvement in gravitational wave astronomy and what is the level of funding required?*

The detection of gravitational waves (GWs) has opened a new window on the Universe, and given birth to a completely new observational science: gravitational-wave astronomy. Explorations have only just begun and already Nature has surprised us, as even the first black hole masses inferred exceeded those of all previously known stellar-mass systems. Further GW measurements of the coalescence of black holes and neutron stars will reveal the mass and spin distributions of these objects, and provide insights into their formation mechanisms and their impact on the astrophysical environment. GWs will also provide a precision probe of strong-field dynamical gravity, help us further understand the evolution of galaxies, and give an independent handle on the nature of dark energy. Joint GW – electromagnetic observations of binaries containing neutron stars will be a particularly rich source of information, revealing the nature of short gamma-ray bursts and constraining the neutron star equation of state; this is testified to by the dozens of astronomy groups worldwide now following up candidate signals from LIGO and Virgo. Other possible sources include GW pulsars, supernovae, cosmic strings, and even a stochastic GW background from the Big Bang. Perhaps most excitingly, unexpected discoveries are always the hallmark of opening new channels on the universe, and the most interesting science to come may be from systems as-yet totally unknown to us.

The detection of GWs has also significantly accelerated interest globally in planning for future detector upgrades and new instruments – an area in which the UK holds unique strengths. The Advanced Virgo detector is expected to join LIGO’s next observing run in spring 2017, the KAGRA detector is under construction in Japan, and the LIGO-India project has been approved. Plans are already in place for upgrades to Advanced LIGO. The A+ upgrade would increase the distance reach by a factor of 1.7 and be operational by 2022. LIGO Voyager is a proposed larger upgrade giving a further factor of 2 increase in distance reach 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 the Einstein Telescope in Europe. The ESA gravitational-wave mission LISA is scheduled to fly by 2034, opening the low-frequency (mHz) waveband for observations of systems such as supermassive black hole binaries.

Given these developments, it is no surprise that the detection of GWs has led to an explosion of interest. Our consultation responses show that Birmingham, Cardiff, Glasgow, Imperial, Sheffield, and possibly Cambridge and Portsmouth, are recruiting additional GW faculty leading to a likely ~50% expansion of UK permanent staff in the field over the next three years. These recruitments cover the full spectrum of research from experiment design, to data analysis and interpretation, and source modelling. At the same time, the expertise of the UK experimental groups is being sought to play a major role in Advanced LIGO upgrades. For example, A+ will include new mirrors with coatings of lower thermal noise, and thinner suspension fibres, both areas of core UK expertise, while Voyager will be a low temperature upgrade. These technologies are highly relevant for the Einstein Telescope and pursuing them would ensure full UK partnership in the ET and Voyager experiments.

Given the demonstrated spectacular successes of the UK GW programme, **we strongly recommend**

an increase in funding for gravitational-wave research. Estimates (provided by the UK GW community) are that the baseline research budget would require a $\geq 50\%$ increase. Required capital investments will be of the order of £10M over 2018-21 for A+ and similarly for Voyager over 2023-27; these are consistent with the **community response** to BIS capital consultation in 2014. **To allow the UK to maintain its current position at the forefront of the field, ensure future UK influence, and capitalise on STFC’s strategic investments in GW research, it is vital that STFC expand its support for appropriate experimental and theoretical GW research.**

We stress that **expansion of GW funding cannot come at the expense of γ -ray astronomy or dark matter research**; the UK PA programme has only recently recovered to a minimal sustainable breadth and this diversity must be protected. We envision the GW uplift as part of a broader expansion across the discipline.

LISA

ESA has selected GWs as the theme for its L3 mission for launch in 2034. The community is now focussed on the LISA laser interferometer mission. The LISA mission is dedicated to studies of GW sources emitting at lower frequency, and provides science return complementary to that delivered by the ground based observatories. For example, LISA will give access to much longer lived and higher signal-to-noise ratio events from both nearby Galactic stellar mass objects out to supermassive black hole mergers at the very edge of the Universe. UK scientists have long been a major presence in all aspects of LISA, including contributing hardware (such as the optical bench) to LISA Pathfinder, establishing the LISA science case, and developing analysis techniques. UK scientists have responded enthusiastically to the recent UKSA solicitation of expressions of interest in LISA.

We strongly recommend that UKSA fully support the L3/LISA mission: UKSA funding for hardware developments should enable science return to the UK in the 2030+ timescale. LISA exploitation will eventually be supported by STFC in the long term (beyond the horizon of the current BoP exercise) and is synergistic with the exploitation work of the ground-based observatories.

Funding Structures

Particle Astrophysics does not have a dedicated grants line. The majority of GW research is funded through a special consortium grant encompassing a number of universities, while the remainder is funded through the astronomy grants panel. This piecemeal approach makes it difficult to ensure that all research challenges (and opportunities) will be adequately addressed, or that proposals can be meaningfully tensioned against each other. For example, GW observations now have direct impact and application in astronomy and astrophysics, raising the question of how to properly fund GW-related astronomy research. A number of different solutions are possible; the fundamental requirements are that the bidding structure is 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). **We recommend that STFC review the current funding structure with the goal of a smooth transition to a solution that is sustainable in the longer term as the field grows.** The issue is complicated, but it needs to be addressed if the STFC is to maintain a competitive world-leading strategy in gravitational wave astronomy.