Dark Matter Strategic Review 2020

Contents

The Dark Matter Strategic Review panel proposes a series of recommendations for STFC investment in dark matter research over the next five to ten years. Based on the submissions to our community consultation, we present an overview of UK leadership in a vibrant dark matter community that spans all areas of the STFC remit. The evidence of growth in the community and the range of diverse future opportunities on the horizon reflects the widening landscape of viable dark matter models. STFC should maintain and develop this diversity. The review pays special attention to UK presence at the cutting edge of the field of direct dark matter detection recommending a focus on synergies in research and development in the path towards a future next generation experiment. If the UK Boulby Underground Laboratory is shown to be a suitable site, it should be STFC's ambition to host a large scale direct dark matter detection experiment in the UK.

Introduction

"STFC's research seeks to understand the Universe from the largest astronomical scales to the tiniest constituents of matter, yet creates impact on a very tangible, human scale." The search for dark matter is at the very heart of this STFC vision, addressing far-reaching questions about the evolution of our Universe, the formation of galaxies and the properties of the fundamental constituents of matter. Public and academic interest in identifying this elusive invisible particle is high and research spans the full STFC spectrum with astrophysics, cosmology, particle physics, nuclear physics, and space science all playing a role.

Numerous astrophysical and cosmological measurements require the existence of a non-luminous substance to explain how gravity works at large scales in the Universe. The nature and properties of this "dark matter" remain unknown to us, but it accounts for ~27% of the energy/matter content of the Universe. Particle theory applied to the dark matter conundrum reveals that the characteristics of known elementary particles do not match with those of dark matter. Therefore, there is a breadth of well-motivated ideas of what dark matter could be. Possible solutions cover a vast range of masses, from weakly interacting massive particles (WIMPs) to axions, dark photons, new neutrino species, primordial black holes, superfluids and more. Researchers are also using data to confront alternatives and extensions to standard gravity theories. It could be argued that all the dark matter in the Universe is unlikely to reduce to a single particle species. Furthermore the lack of discovery of non-standard model particles at the Large Hadron Collider (LHC) at CERN, ruling out some of the simplest supersymmetric (SUSY) theory models, has somewhat weakened the previously strong theoretical prior towards SUSY-like WIMP dark matter particles. Whilst WIMPs, nevertheless, remain the favoured candidate, it is vital to search for dark matter in every possible way to fully explore the landscape of potential dark matter models.

Experimental approaches can be broadly split into four complementary routes to probe the dark sector: direct searches, indirect detection, production at particle accelerators, and observation of large and small-scale astrophysical effects. The UK is recognised as a world leader in all four of these areas.

The UK Dark Matter Landscape

The wide range of viable dark matter models necessarily leads to many varied approaches to dark matter research. This scope is reflected in the numerous different projects pursued and led by the UK community. Based on the responses to our community consultation, we summarise the impressive breadth of the overall experimental and theoretical dark matter programme in the UK. STFC was listed by the majority of respondents as their primary funding resource with additional support from UKRI, the Royal Society, Leverhulme, local University funding and the European Research Council. We recommend that the current breadth and diversity in the UK dark matter programme should be maintained, supported and encouraged to grow with suitable levels of funding to exploit UK access to the many world-leading facilities in this key science area.

Accelerator-based Experiments

A direct way to measure the properties of dark matter is through the creation of dark matter candidate particles at colliders. The general-purpose LHC detectors, ATLAS and CMS, have already constrained the existence of a wide range of new physics scenarios, including supersymmetry. In these studies both missing-energy and long-lived particle signatures are explored. We expect significant improvements in the LHC Run 3 and during its future operation at higher luminosity.

There is growing interest in dedicated accelerator-based experiments probing the dark sector by searching for decays, or transitions into Standard Model particles, of long-lived dark sector particles. Some experiments additionally may be sensitive directly to scattering signatures of produced dark matter particles, via electron or nuclear recoil. Examples of UK involvement in these LHC experiments are the approved FASER experiment. This is also UK interest in projects such as CODEX-b and MATHUSLA. These are sensitive to potential production of dark long-lived particles which decay in their detector volumes. Beyond the LHC, existing fixed-target experiments at CERN have some sensitivity to dark sector particles. For example UK physicists are proposing a beam-dump run (NA62++) with dark sector sensitivity beyond existing limits.

Looking further ahead, new beam-dump experiments have been proposed. The largest of these, SHiP (Search for Hidden Particles), has UK leadership and a broad dark sector search programme in the accessible mass range. SHiP proposes to use a new 400 GeV proton beam-dump facility at the CERN SPS. It would be sensitive to a wide range of new physics models with new particle masses below about 10 GeV. The main aim is to search for very weakly interacting long lived particles such as heavy neutral leptons, vector, scalar, axion portals to the hidden sector, and light supersymmetric particles. A wide variety of such models can be explored due to the high energy and intensity of the proton beam. Direct searches for dark matter produced in decays of dark photons can be made via electron and nuclear scattering, made easier because any dark matter particles would be highly relativistic. If a positive decision is taken to proceed with the new beam dump and experiment, SHiP could start operating after the CERN Long-Shutdown 3, i.e. in 2026 or soon after.

Astrophysics

Decades after its discovery through astronomical observations of galaxy clusters, astrophysical observations provide the only direct measurements of the properties and influence of dark matter. Improving the characterisation of dark matter serves as a primary motivation for a number of large international astrophysics projects with strong UK interest.

Astrophysical studies generally take the form of statistical analyses of the two- or three-dimensional distributions and dynamics of celestial objects, from groups of stars through to the largest scale structures in the Universe. Three ongoing projects with significant UK involvement will revolutionise the astrophysical study of dark matter.

The Large Synoptic Survey Telescope (LSST) is a US DOE/NSF-funded telescope that will survey the entire southern sky in multiple optical bands to unprecedented depth and with a temporal cadence that enables detailed studies of optical variability over the next decade. The UK is involved through the STFC-funded LSST:UK consortium which comprises ~100 senior astronomers with additional involvement from postdocs and students. A substantial part of its science case is focussed on dark matter, with ~30 LSST:UK members actively engaged in LSST dark matter research. It will measure the radial density profiles and shapes of the dark matter halos of objects over a range of mass scales, from the smallest galaxies to the largest clusters (a mass range of ~5 orders of magnitude). The detailed shapes depend upon the nature of dark matter, in particular how strongly it self-interacts through non-gravitational channels. Its repeated observation of the entire sky over its decade-long mission will allow for sensitive micro-lensing searches that will place exquisite limits on the fraction of dark matter that is in the form of primordial black holes. The entire data set will result in a detailed map of structure on the largest scales, probing its growth and evolution over the majority of the history of the Universe. The statistics of the matter distribution is a sensitive probe of the amount of dark matter and on the amount that is present in light relic particles including massive neutrinos. In combination with observations sensitive to the effect of dark energy, any coupling between the two main components of the dark sector will be elucidated.

A prime driver for the ESA Euclid mission, to be launched in 2022 on a 6-year mission, is to map the distribution of dark matter on scales ranging from individual galaxies to the largest clusters of galaxies across a large fraction of the extragalactic sky. The mission benefits from a close to Hubble-like spatial resolution in the optical and near-IR enabling the determination of dark matter halo shapes to high accuracy through weak gravitational lensing. In this it is complementary to LSST, trading its better spatial resolution for the greater depth of the LSST data. The UK has major leadership roles in both the instrumentation and data analysis of Euclid, supported through the UKSA. The Euclid:UK group represents 240 astronomers within the international Euclid consortium with ~30 members actively engaged in Euclid dark matter research.

Over the next two decades the Square Kilometer Array (SKA) will complement these optical/near-IR probes of dark matter. This two-continent radio telescope interferometric array will be the world's largest with an unprecedented sensitivity to radio emission from cosmic sources. It will generate samples of radio sources covering a large volume of extragalactic sky, sources whose clustering statistics depend strongly on the amount and nature of dark matter. Additionally, the SKA can probe dark matter haloes of a huge range in mass in a very different way to the optical/near-IR probes. If certain types of dark matter annihilates, it may well eventually produce radio emission from the halos, any detection or limit will constrain the annihilation cross section to several orders of magnitude better than currently possible from gamma-ray measurements. The wide eventual frequency range of the array allows it to probe the composition and mass of the dark matter particles undergoing annihilation as the shape of the spectrum produced depends on the mode of annihilation and decay.

In addition to probing dark matter using data from these telescopes alone, combining their results with each other and those from other facilities and projects, will significantly enhance the strength of an astrophysical approach. The UK is in a very strong position for future astrophysical dark matter studies given that few other nations have membership of and direct access to the data of these three observatories. Its user community should be able to capitalise on this to ensure leadership in the field well into the coming decades.

Indirect Detection

Indirect detection strategies rely on the identification of the products (photons, neutrinos, anti-matter) resulting from the decay, conversion or annihilation of dark matter particles in space. Future satellite, neutrino telescopes, and ground-based gamma-ray observatories will have enhanced sensitivity in important regions of the parameter space.

The Cherenkov Telescope Array (CTA) consists of two arrays of more than 100 gamma ray telescopes, one in each hemisphere, sensitive to energies between 20GeV to 300TeV. It is run by a world-wide consortium including scientists from 13 UK institutions. Construction will begin in 2020 and observations in 2022. CTA will have the sensitivity to detect gamma rays from the self-annihilation of a wide range of dark matter particles, reaching the expected cross-section for thermal relic particles. It will target emission from the Galactic halo, close to, but avoiding, the Galactic Centre in the first three years of operation. Continuing through the first decade of operation, further targets will include dwarf spheroidal satellite galaxies of the Milky Way, the LMC, galaxy clusters and those that arise as potential dark matter rich targets from ongoing optical and near-IR surveys.

The Chinese DArk Matter Particle Explorer II (DAMPE-II) will search for the decay signal of a range of WIMP candidates through the characterisation of the resulting charged particle's (electrons and positrons) energy spectra in the GeV-TeV range. The UK is expected to be involved through the development and operation of particle tracking detectors.

Direct Detection

For masses around and above the GeV scale, the best sensitivity to WIMPs is provided by tonne-scale direct-search experiments based on liquefied noble gases. UK leadership in the xenon and argon direct-detection experiments forms the main focus of the second half of our review. In this section we therefore summarise other techniques to explore lower masses and the direction and time dependence of the dark matter signal.

UK physicists contribute to all of the following direct detection GeV-TeV WIMP experiments. COSINE-100 uses sodium-iodide to test the long-standing claimed detection of a dark matter annual modulation made by the DAMA/LIBRA collaboration, that has so far been unconfirmed by any other experiment. SuperCDMS is a long-standing collaboration using cryogenic Ge detectors with good sensitivity to GeV dark matter. NEWS-G, in contrast, is a new collaboration using Spherical Proportional Chambers with sensitivity to GeV and sub-GeV dark matter. The UK Boulby Underground Laboratory is developing plans to support NEWS-G and also DAMIC, a future experiment, sensitive to scattering of MeV-TeV dark matter with electrons.

Directional detectors that measure the directions of nuclear recoils as well as their energies, offer a theoretically powerful way of confirming the Galactic origin of a WIMP signal and probing the local dark matter velocity distribution. The UK has leadership in CYGNUS, a proto-collaboration aimed at developing a global network of directional detectors. The UK part of the programme includes DRIFT, hosted at the Boulby Underground Laboratory, and R&D on low threshold directional readout technology

In addition to the WIMP-arena, there is intense activity on direct searches for axions and axion-like-particles. The main actors in the field rely on mature techniques (helioscopes, haloscopes, light-shining-through-walls) to enhance the discovery potential. UK physicists are active in both ADMX and ALPS. ADMX is a long-standing experiment searching for QCD axions in the micro-eV mass range via their resonant conversion to microwave photons in a magnetic field. It has excluded axions making up 100% of the dark matter for most of the mass range (2.7-3.3) micro-eV and a larger range of masses will be probed in future runs. ALPS (Any Light Particle Search) is a 'light shining through a wall' experiment and is sensitive to axion-like particles with a range of (sub-eV) masses.

Many new ideas are emerging and the detection of sub-MeV dark matter will require significantly different techniques and technology in the future. An excellent example is AION (Atomic Interferometric Observatory and Network; 22 core members), a proposed experiment that will have sensitivity to ultra-light dark matter within a large mass range (10-13 - 10-23) eV. It was selected as a priority project in the 2018 'Big Ideas' call, and is a lead programme in the open call for Quantum Technologies for Fundamental Physics which includes other Quantum Sensors work packages that will have a wide range of sensitivity to various light dark matter candidates.

Context for the Review

The 2019 Particle Astrophysics Programme Evaluation

The recent Particle Astrophysics Programme Evaluation (PAPE) highlighted the particularly strong history and track record of dark matter direct detection research in the UK. The UK has led and contributed to numerous world-leading results and innovations with a range of scintillator, semiconductor and gas based detectors. The UK is also playing a leading role in the current construction of the LUX-ZEPLIN experiment. A number of future opportunities for UK involvement in direct dark matter detection have been proposed, including R&D for next generation liquid xenon experiments; participation in the construction of DarkSide, a liquid argon instrument; the potential for Boulby Underground Laboratory to host a next generation dark matter experiment. These focused direct detection experiments are highly complementary to the proposed alternative approaches for dark matter searches, as summarised above. Given these opportunities to add breadth to the dark matter programme, the PAPE recommended that "*STFC conduct a focused review of the dark matter subfield to establish a clear strategy for longer term investment that maintains a UK presence at the cutting edge of the field, takes into account future opportunities, and possibly leads to hosting a 3rd Generation instrument.*"

The PAPE recommendation forms the basis for this Dark Matter Strategic Review. The panel's schedule and membership can be found in Appendix 2. The panel had cross-membership with Science Board, the Projects Peer Review Panel and the STFC community. It also included an international expert.

The 2012 Science Board Sub-Group Dark Matter Strategy Report

In 2012, a Science Board Sub-Group conducted a strategic review of the dark matter programme. They proposed a coordinated strategy for supporting direct dark matter search experiments that could potentially position the UK for leadership in this area. Since the strategy report was published, the majority of the recommendations have been implemented.

Direct Dark Matter Detection

In the medium-term, the Strategy recommended: support for development and design work contributing to the next generation of world-leading tonne-scale experiments and building UK capability and leadership for the long-term.

STFC provided (£640k) support for the 'UK Involvement in Direct Dark Matter Searches' project which focused on R&D and design development for next generation liquid xenon experiments.

Since 2012, there has also been a small amount of funding for liquid argon activities through the particle physics consolidated grant. DEAP/CLEAN liquid argon activities have also been supported through STFC Project Research and Development funding (£165k in 2012).

In the longer-term, the Strategy recommended: capital-phase support for construction of the next generation of world-leading tonne-scale experiment(s). Given the similarities between the technologies used in liquid xenon and liquid argon detectors the Strategy recommended that in all funding scenarios support should be allocated to at most one noble liquid target. The noble liquid community was encouraged to consolidate behind one such proposal when feasible.

Due to financial constraints the Review recommended that the UK dark matter community converge on a single experiment, for possible future funding at the construction phase. The formation of the Dark Matter UK (DMUK) Collaboration facilitated the consolidation on a single future experiment with members of the EURECA project joining LUX-ZEPLIN (LZ) in 2013. As a result, the DMUK Institute Board selected LZ as the experiment that would seek significant construction funds in the UK. In the close out report for the LZ project, the Collaboration and the Oversight Committee recognised that the UK contribution to LZ was stronger and more impactful as a result of the consolidation of the UK dark matter community.

Following the convergence of the DMUK on LZ as the choice of project for a capital phase construction project, STFC funded 'LUX-ZEPLIN Dark Matter Search' from April 2015 to September 2019 at a level of £4M. The panel noted that the level of UK funding was relatively low in comparison to other international partners. Despite this restriction, the UK's scientific leadership and expertise in the titanium cryostat, low background testing, and the xenon detector have resulted in the UK playing a leading role in the construction of LZ. It is anticipated that LZ will begin operating in mid 2020.

The Strategy recommended that more direct collaboration with the theory community in the planning and data-analysis phases of the experiments should be encouraged. The formation of the DMUK collaboration clearly facilitated interactions and direct collaborations between theorists and experiments, and based on the responses to the community consultation, it is clear that this recommendation has largely been realised.

Whilst the Strategy recommendation led to the consolidation towards a single xenon dark matter community, there was not a consolidation across the whole UK community behind one noble liquid target. In retrospect this diversity should be viewed as a benefit to UK dark matter research, with growth in the UK community working towards the DarkSide liquid argon detection through the inclusion of both theorists and experimentalists. Research for DarkSide in the UK has primarily been supported through European Research Council grants.

Directional Dark Matter Detection

The Strategy noted that the UK has significant international leadership in the area of directional detectors. Although such experiments do not currently compete in terms of spin independent scattering cross-section sensitivity, they provide the best means of definitively identifying a Galactic dark matter signal. As recommended in the Strategy, STFC considered proposals for research and development for directional detectors through the Project Research and Development (PRD) funding line up until the scheme was paused in 2017.

Funding and Support

The Strategy recommended that the funding model for this area should evolve to match more closely that used in other parts of the STFC programme. Specifically funds for exploitation of direct dark matter detection experiments, including dedicated RA effort, should be awarded via Consolidated Grants, with project funds reserved for R&D, design and construction. Exploitation funding for dark matter experiments is now requested, reviewed and supported on the particle physics consolidated grants. For example, following the completion of the LZ construction project, support was reviewed and allocated in the 2018 particle physics consolidated grant for LUX-ZEPLIN exploitation.

The Strategy recommended that STFC RAL Particle Physics Department continue to support this area in cases where staff possess unique expertise of value to the UK direct detection community and consistent with the agreed SB strategy. STFC RAL PPD has continued to support this area of research during this period, in particular providing support to the LUX-ZEPLIN project.

As with other areas of STFC supported science, European Research Council grants have enabled the dark matter community to maintain diversity in its programme; in particular providing significant support for liquid argon research and development and other dark matter searches (e.g. axion/ultra-light detectors). It is therefore a source of concern that access to this significant EU funding resource remains uncertain at this time.

The panel noted that currently, in the absence of the PRD programme, UK scientists have no opportunity to bid for low-level seedcorn capital and resource investment to deploy in future experiments. We recommend that a PRD-like programme is reinstated as this would allow for R&D in multiple diverse dark matter experiments, beyond the larger-scale WIMP experiments that form the main focus of this review.

UK WIMP Detection with Noble Liquids

Noble liquid based detectors, and in particular liquid xenon, have dominated the sensitivity for typical WIMP mass candidates for the last decade. The UK pioneered the use of xenon for dark matter detection, including the highly successful ZEPLIN programme. By developing key technologies in the UK, the limits on the dark matter cross-section continued to improve with the LUX experiment. The UK also contributed to the development of argon for dark matter detection through the single phase DEAP/CLEAN experiment. As a consequence of these major contributions to the field, the UK has scientific leadership in both LUX-ZEPLIN (LZ) and DarkSide, two of the leading second-generation direct detection experiments under construction. The primary difference between these two experiments is the choice of target material.

LUX-ZEPLIN (LZ) is a dual-phase xenon time projection chamber, with an active target mass of 7 tonnes, surrounded by additional instrumented shielding consisting of 2 tonnes of liquid xenon and a further 17 tonnes of liquid scintillator outside the xenon cryostat. Key features include low energy electron background rejection via the ratio of the scintillation and ionisation signals, and accurate 3D reconstruction of interaction sites. STFC has supported LZ through R&D and construction grants and the project has run to schedule, building heavily on the proponents' experience from the LUX and ZEPLIN programmes. Underground installation in the SURF facility in South Dakota is underway, with operations planned to start in 2020. With a 1000-liveday exposure over 5 years, LZ will reach an optimal sensitivity of $1.4x10^{-48}$ cm^2 for the spin independent WIMP nucleon cross section at 40 GeV mass (or equivalently 2.5 x 10^{-47} cm^2 , 2.1 x 10^{-48} cm^2 and 1.8 x 10^{-47} cm^2 at 10, 100 and 1000 GeV masses respectively). It also has sensitivity to spin dependent reactions and to astrophysical neutrinos via coherent nuclear scattering.

DarkSide is a dual phase detector with a target mass of 50 tonnes, sitting inside an instrumented 700 tonne liquid argon veto. Key features include the excellent electron rejection via pulse shape discrimination, and the relatively lower costs of argon, although the intrinsic ^{39}Ar has to be removed. DarkSide will be sited at the Gran Sasso Underground Laboratory in Italy, and represents the merger of four existing argon dark matter collaborations. Construction is starting now with physics running planned from 2023. With 6 yrs running, the optimal projected sensitivity on the spin independent nucleon cross section is 1.0 x 10^{-48} cm^2 at 100 GeV mass (or equivalently 1.1 x 10^{-45} cm^2 and 4 x 10^{-48} cm^2 at 10 and 1000 GeV masses respectively). It has sensitivity to sterile neutrinos in nuclear decay processes and to neutrinos from astrophysical sources.

There is already extensive discussion worldwide concerning the next generation of dark matter detectors. These will reach the irreducible ‘neutrino floor’ provided by the coherent neutrino-nucleus interactions. At these scales there is likely to only be a single xenon and a single argon based next generation detector. The global argon community has already coalesced with a long-term vision to construct the “Argo” detector (~400 tonne argon mass) to start operations around 2028. With three collaborations worldwide working to deploy tonne-scale liquid xenon detectors in 2020 (LZ 7 tonne, XENON 6 tonne and PANDA-X 4 tonne), the global xenon community is formally less well united, although DARWIN (60 tonnes) represents a possible next generation xenon observatory. Based on the LZ design cycle, 4 years of R&D, 2 years of pre-construction, and 4 years of construction would see a next generation xenon experiment start operations in 2029.

UK presence at the cutting edge of the field

The panel considered cases for making significant UK contributions to both the construction of DarkSide and research and development for a next-generation xenon experiment. Direct searches for dark matter aim to initially confirm the existence of a WIMP dark matter particle. Once detected, a second experiment with an alternative target provides the crucial cross-check and the combined data analysis allows for the characterisation of the WIMP. An observation of a dark matter particle would be a scientific breakthrough of great importance and have huge implications across frontier science from particle physics to astronomy. It is clear that the UK has the world leading experience, skills and knowledge to make major impacts in both the argon and xenon experiments and that there would be a clear benefit to UK dark matter research to follow this path.

The European Astroparticle Physics Strategy 2017-2026 report demonstrates that no one technology is considered to be superior to the other with clear pros, cons and uncertainties identified with each approach. The panel understands that APPEC is in the process of setting up a committee of experts to review technology options for future next generation experiments. The US particle physics community aims to increase international partnership and support one or more next-generation direct detection experiment, with strategic plans guided by the results of the preceding searches expected in ~2021.

Given the international uncertainty in the future path for direct dark matter detection, the panel concluded that it would be premature for the UK to downselect to any single preferred option for the R&D of a future next generation experiment, at this time. The panel instead recommend that the areas of synergy in technological developments should be pursued in a R&D phase that remains agnostic to the final target material. Synergies included increasing low mass dark matter sensitivity through the Migdal effect, the development of Silicon photomultiplier technology, and the potential to host a future next generation rare event observatory in the UK at the Boulby Underground Laboratory.

Silicon Photomultiplier Technology leadership and development

There is an increasing global interest in moving towards silicon photomultiplier technology (SiPM) for future argon/xenon detectors searching for dark matter as well as measuring neutrino interactions. SiPMs promise a higher effective quantum efficiency, higher reliability at liquid noble gas temperature, and a much higher radiopurity than photo-multiplier tubes. A smaller material budget helps to reduce background. Work on SiPMs is performed with a small number of world-wide leading institutions and companies (e.g., FBK, Hamamatsu). The SiPMs need to be sensitive to VUV light (Xe=175 nm; Ar=128 nm) either directly or via the use of wavelength shifting material (e.g. TPB). Furthermore, the cryogenic electronics need to be designed to meet stringent low-background requirements.

The development of SiPMs for future large-scale direct-dark matter searches using noble gases provides the opportunity for the UK to invest in early R&D in order to achieve technological leadership in any future next generation experiment. R&D would focus on the design, production and testing of large SiPM tile arrays including electronics. The creation of a common R&D SiPM UK dark matter consortium with an integrated and coherent programme, would avoid duplication of effort. It is expected that this would result in cost savings and a more efficient use of resources for the two noble-gas technologies based on argon and xenon. A single entity would also likely boost collaboration with UK industry.

Hosting a Next Generation Dark Matter Detector in the UK

The UK Boulby Mine hosts one of a small number of internationally recognised underground laboratories. Although at intermediate depth, Boulby has a number of distinct advantages including very low-levels of radon gas and the relative ease with which new underground spaces can be excavated. Historically it has supported world-leading direct dark-matter detection programmes; it still hosts the DRIFT directional detection experiment and an ultra-low background screening facility comprising HPGe detectors and an alpha-spectrometer. Boulby will be the site of an Advanced Instrumentation Testbed associated with the WATCHMAN reactor monitoring project.

Given these advantages, Boulby is now under consideration as a host laboratory for a next-generation direct dark-matter detection experiment. Funding for a scoping study was awarded through the 2019 STFC Opportunities call. The outcome of the study will present the experimental requirements and expectations for the construction and operation of a host facility for rare event search experiments. If the scoping study findings are promising for direct dark matter searches, the panel recommends that STFC strongly advocate for Boulby to be the host for a next-generation experiment as this would be a unique opportunity for the UK. The level of funding required is an order of magnitude above what is traditionally spent in this area in the UK, but the expectation is that hosting such a major international experiment would unlock significant extra resources from the UK government. This development would be beneficial for many research areas beyond dark matter detection. For example Boulby would be expected to play an important role as a centre of expertise for low-background detector development, including SiPM technology.

Funding Scenarios for Direct Detection

The review panel found a strong history and track record for direct dark matter detection research in the UK, and a great potential to build on this leadership in a number of different future projects. In the current severely constrained funding climate, the planned budget for this research area is significantly less than the optimal level of funding sought by the direct detection dark matter community to participate in either argon or xenon searches, and more broadly the wide range of non-WIMP searches. We therefore recommend that STFC consider a funding uplift in this area to ensure the UK benefits from its existing expertise and leadership. Without increasing levels of support for the next generation of direct detection experiments the UK community risks being marginalised in these global projects.

Our community consultation considered the optimal distribution of support for direct detection in a constrained funding climate. The majority of respondents supported providing significant funding, and hence scientific leadership, in a single experiment over lower-level funding and scientific involvement in multiple experiments. Based on this community view, the panel considered UK involvement in WIMP direct detection experiments for a range of funding scenarios. In all the following scenarios, however, the panel recommends that STFC should be ready to react to significant developments in the non-WIMP arena.

a. **Current Funding**

The current STFC budget projection for dark matter research is at the level of £1M per year from 2023 onwards, and £300k per year resource in total before this date. This permits limited R&D work toward a next generation experiment, ramping up to a moderate role in the design and construction phase of a single next generation experiment.

b. **Increased Funding 1**

Raise the funding to £1.5M per year from 2023 onwards and the UK could play a significant leadership role in the design and construction phase of a single next generation experiment. Assuming that Boulby Underground Laboratory proves to be a suitable host, the panel recommends that the goal to host a next generation experiment in the UK Boulby mine is prioritised, as this has the potential to provide additional benefits to the UK and unlock additional resources.

c. **Increased Funding 2**

Raise the funding to £3M per year and the UK could play a significant leadership role in the construction of multiple dark matter direct detection experiments.

Conclusions and Recommendations

In this review we have taken a snapshot of the vibrant UK dark matter research community at the very start of the 2020's, a decade that is expected to yield great advances in our understanding of the mysterious dark matter in the Universe. We have highlighted UK participation, leadership and capability spanning the full STFC remit, based on the responses to our community consultation. With a focus on direct dark matter detection experiments we have highlighted the progress made since the recommendations of the 2012 Dark Matter Review and propose a long term strategy for future investment to maintain UK presence at the cutting edge of the field. Our recommendations are summarised as follows.

Continued funding to support dark matter research across the full STFC remit is essential in order to exploit UK access to the many world-leading facilities in this key science area. At a minimum, current levels of support through STFC fellowship schemes and the exploitation grants line must be maintained and ideally expanded.

Since the 2012 review we have seen evidence of growth in the community and a diverse range of future facilities and opportunities on the horizon reflecting the widening landscape of viable dark matter models. We recommend STFC maintains and develops this diversity providing the opportunity for projects to bid for low-level seedcorn capital and resource investment. This would allow for R&D in multiple diverse dark matter experiments, beyond the larger-scale WIMP experiments.

There is a strong history and track record of direct dark matter detection research in the UK, despite the challenging funding environment and relatively low levels of funding compared to those provided by other international partners. STFC should maintain and capitalise on this strong expertise and experience. In a limited funding climate, significant investment should only be made in a single next-generation experiment.

The panel recommends that in the short-term the UK focuses on synergies and areas of commonality in R&D in the path towards either an argon or xenon next generation experiment, for example a common R&D SiPM UK dark matter consortium.

Boulby Underground Laboratory represents a world-class facility and the possibility of hosting a next generation experiment should be fully investigated on a short timescale.

Proposals for the optimal technology for a future construction will require a strategic decision which should be taken on a similar timescale to the global prioritisation exercise in Europe and the US, with the ambition to host this next generation experiment at Boulby.

Appendices

Appendix 1- Terms of Reference

The main purpose of the review is to conduct a strategic review of the dark matter subfield, to establish a clear strategy for longer term investment over the next five to ten years.

The panel is asked to:

- Consider the recommendations of the 2012 Dark Matter Review and assess progress against these recommendations.
- Review the UK dark matter landscape, highlighting current UK participation, leadership and capability.
- Identify and prioritise future opportunities in dark matter research.
- Develop a long term strategy for future investment that:
    - takes into account future opportunities,
    - maintains a UK presence at the cutting edge of the field,
    - could possibly lead to the hosting of a 3rd generation instrument.

The review will report to the STFC Science Board who will advise the Programme Directorate Executive on future funding.

Appendix 2 - Panel Schedule and Membership

The membership of the panel has cross-membership with Science Board, PPRP, PAAP and the STFC community. It also includes one international expert.

- Catherine Heymans (University of Edinburgh and Ruhr Universität Bochum) – Chairperson – Previous PPRP Member
- David Waters (UCL)
- Malcolm Bremer (University of Bristol) – PPRP Member
- Gavin Davies (Imperial) – Science Board Member
- Anne Green (University of Nottingham) – Previous PAAP Member
- Stefan Soldner-Rembold (University of Manchester)
- Antonio Bueno Villar (University of Granada)
- Dave Charlton (University of Birmingham)

The Panel held an initial half-day videoconference on 11th July 2019 to introduce the review, identify the information required to carry out the review and formulate the community consultation questions. This was followed by a two month community consultation in order to involve the UK dark matter community in the review process and to understand the current dark matter landscape and potential future research programme. The consultation was carried out via an online survey and responses were sought from both individuals and groups. Further information on the consultation can be found in Appendix 3. The Panel held a two day meeting on the 3rd and 4th October 2019, where a long-term strategy for STFC investment in dark matter was discussed. The review document was then collaboratively drafted with contributions from all panel members, with a final videoconference to finalise the Strategic Review on the 15th November 2019.

Appendix 3 - Community Consultation

We thank the community for their detailed responses to our consultation. The panel received 20 group submissions and 21 submissions from individuals. The respondents represented LZ, DarkSide, SHiP, CYGNUS, Boulby Laboratory, AION, Experimental and Theoretical Particle Physics and Astrophysics. Taking into account the overlap between the responses, the panel estimates that the consultation reflected the opinions of over 200 UK dark matter researchers. STFC was found to be the primary funding resource for UK dark matter research (CG, ERF, PPRP, GCRF), with additional support from UKRI, the Royal Society, Leverhulme, local University funding and the ERC.

The responses were used to form an overview of the breadth of dark matter research in the UK, as reported in the main body of the review. On the question of the highest priority future opportunity for UK participation in direct dark matter detection, submissions were unsurprisingly often partisan with conflicting statements regarding the pros and cons of different experiments. On the question of prioritizing leadership in a single direct dark matter experiment over smaller roles in multiple experiments in a limited funding environment, group submissions were almost unanimous (18/20) in prioritising a single experiment, disagreeing on which experiment to prioritise. The individual submissions were split 50:50 in support of multiple experiments vs a single experiment. Weighted by the number of respondents, the majority of respondents supported prioritising leadership in a single experiment.

Many noted that the landscape was shifting and broadening away from WIMP-SUSY particles as the most likely candidate, presenting a situation in which no one technology could address all of the possible models. Some argued that it was worth waiting to see the first results from LZ before continuing investment in this area, but given the long procurement and construction time for a next-generation experiment, the panel concluded that supporting R&D in the lead-up to the first LZ results was a necessary investment in order to maintain the UKs presence at the cutting edge of the field.

Consultation Questions

1. Are you responding to this questionnaire on behalf of a group or as an individual?
    a. Group response results in one version of the questionnaire with a 400 word limit per question.
    b. Individual response results in the same questionnaire with a 200 word limit per question.
2. Name and email:
    a. Group Name and email contact:
    b. Individual name and email:
3. If you are a member of a direct dark matter detection collaboration, please state your collaboration affiliation. If you are not a direct dark matter detection collaboration member please state your broad research area (e.g Dark Matter Theory, Particle Physics, Astrophysics….)

4. How important is UK participation in dark matter research, in the context of the wider STFC programme?
5. Please outline [your groups (a)][your (b)] current involvement in dark matter research, highlighting leadership and capability.
6. [In your group, how many UK researchers are directly involved in dark matter research? (a)] Where possible, please identify current and previous funding sources for your dark matter research.
7. What are the future opportunities for UK participation in dark matter research? What do you consider to be the highest priority future opportunity for UK participation in direct dark matter detection?
8. Related to this highest priority opportunity, please outline existing or potential UK capability in specific technologies for direct detection experiments.
9. In a limited funding environment would you prioritize leadership in a single direct dark matter experiment over smaller roles in multiple experiments?
10. If limited funding was such that only a single large or next-generation direct detection dark matter experiment could be supported, please state which experiment should take priority, giving reasons for your answer.
11. Are there any other points that you would like to raise?