

The background of the document is a cosmic scene. It features a dark, star-filled space with a prominent purple and blue streak that curves across the upper half of the image. In the upper right, there is a bright, glowing nebula or galaxy core. The lower half of the image transitions into a deep blue gradient.

**UK Research in Particle Astrophysics
Strategy Document, September 10, 2009**

Particle Astrophysics Advisory Panel

Table of Contents: UK Particle Astrophysics Strategy

1. INTRODUCTION	3
1.1 What is particle astrophysics?	3
1.2 Previous reviews and international roadmap	3
1.3 Science questions	5
2. CURRENT PROGRAMME AND UK EXPERTISE.....	7
2.1 Particle astrophysics theory	7
2.2 Gamma rays	7
2.3 Dark Matter	8
2.4 Gravity Wave Interferometers.....	9
2.5 Neutrinos	9
2.6 Cosmic rays	10
2.7 CMB polarisation.....	11
2.8 Small projects	12
3. FUTURE OPPORTUNITIES	13
3.1 UK facilities needed	13
3.2 Prioritisation	14
4. TECHNOLOGY AND OUTREACH.....	16
4.1 Relevant technologies.....	16
4.2 Outreach and public engagement	17

1. Introduction

This document presents a summary of the current state of UK particle astrophysics research and a strategy for prioritisation of research areas for the future. This prioritisation is based on a PA community consultation exercise carried out from June – August, 2009.

1.1. What is particle astrophysics?

The field of particle astrophysics encompasses projects measuring and characterizing the properties of *particles and radiation from space* apart from standard electromagnetic radiation. These projects often lie at the intersection between Cosmology, Astrophysics and Nuclear and Particle physics. Many of the fundamental science questions considered to be in these fields are also addressed in particle astrophysics. In practice, there are two types of particle astrophysics projects:

1. Direct detectors of particles from space or 'particle telescopes':
 - Gravity wave telescopes
 - Neutrino detectors and telescopes
 - Cosmic ray telescopes
 - Gamma ray telescopes
 - Dark matter detectors and telescopes
 - Other exotic particle searches – e.g. axions, magnetic monopoles, etc.
2. Indirect detection of the effects of particles on astronomical objects:
 - Binary pulsars and pulsar timing measurements for gravity waves
 - CMB measurements for dark matter, dark energy, neutrinos, gravity waves, etc.
 - Timing of gamma ray and TeV emission for Lorentz invariance tests
 - Non-accelerator methods for measuring/constraining the properties of fundamental particles

Many of the particle telescopes listed above represent new 'windows on the universe' which have either been recently opened or are expected to be opened in the near future. Historically, whenever a new window on the universe has been opened, e.g. by observations in a previously unexplored electromagnetic waveband, it has led to high impact scientific results. For this reason, the international scientific community has made it a priority to increase the research activity in these areas over the next decade.

1.2. Previous reviews and international roadmap

There have been a number of reviews of particle astrophysics over the last few years. The two reviews which we feel are the most relevant to the UK strategy are:

- ASPERA – A European review and strategy document for astroparticle physics: <http://www.aspera-eu.org>
- 2008 STFC programmatic review: <http://www.stfc.ac.uk/resources/pdf/FinalProgRevOutcome.pdf>

The ASPERA roadmap lists 6 key *science questions* for astroparticle physics:

1. What is the universe made of? In particular: what is dark matter?
2. Do protons have a finite lifetime?
3. What are the properties of neutrinos? What is their role in cosmic evolution?
4. What do neutrinos tell us about the interior of the sun and earth and about supernovae explosions?
5. What is the origin of cosmic rays? What is the view of the sky at extreme energies?
6. What will gravity waves tell us about violent cosmic processes and about the nature of gravity?

Corresponding to these science questions, ASPERA describes 7 key facilities for the next decades (the 'Magnificent 7'):

1. Ton-scale detectors for dark matter search
2. A ton-scale detector for the determination of the fundamental nature and mass of neutrinos
3. A Megaton-scale detector for the search for proton decay, for neutrino astrophysics and for the investigation of neutrino properties
4. A large array of Cherenkov Telescopes for detection of cosmic high energy gamma-rays
5. A cubic kilometre-scale neutrino telescope in the Mediterranean Sea
6. A large array for the detection of charged cosmic rays
7. A third-generation underground gravitational wave antenna

The total European funding required for this activity is roughly envisioned in the graph below:

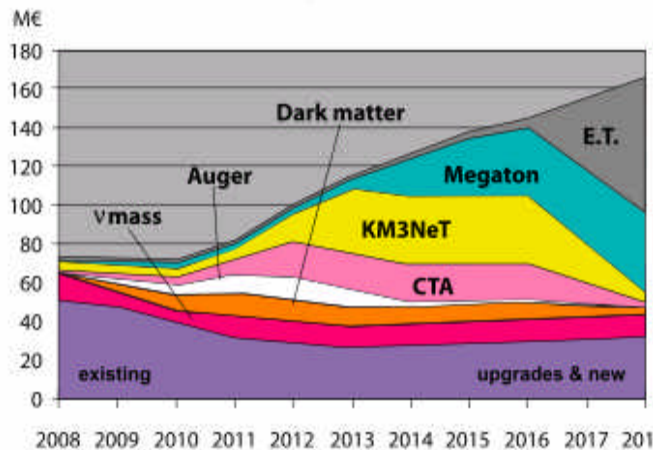
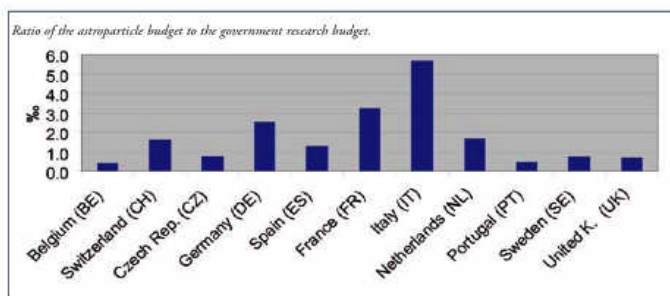


Figure 1 (left): A scenario for European particle astrophysics funding from the ASPERA review.

The ASPERA review also estimated the amount of funding currently going towards particle astrophysics activities in European countries (below):

Country	BE	CH	CZ	DE	ES	FR	IT	NL	PT	SE	UK
FTE	17	52	20	494	168	608	679	55	40	34	158
Budget(M€)	0.7	3.6	0.4	44.0	10.0	51.5	58.6	6.1	0.5	2.0	9.0
#Institutions	4	7	5	38	13	28	30	9	5	3	19

Figure 2 (left): Part per thousand of the astroparticle physics budget compared to the total government research budget by country in the European Union. The figure of 0.7 parts per thousand (0.07%) of the total UK research budget in the above graph broadly agrees with the STFC estimate that 2% of the STFC science budget not including subscriptions (which make up approximately two-thirds of the budget) goes to particle astrophysics projects.



These two figures from the ASPERA review make two important points:

1. There is a potentially large increase in European activity in particle astrophysics over the next decade.
2. The UK is currently supporting particle astrophysics at a relatively low level compared to other European countries (actually *the lowest* PA funding per capita)

These points are reflected in statistics for the total number of UK authors on particle astrophysics publications over the last 5 years and in numbers of UK researchers involved in major PA experiments. However, the UK is in a remarkably strong position to increase the UK impact in this area both in theory and experiment with leadership roles in a number of key projects despite relatively low levels of support.

The second point of reference for this document is the 2008 STFC programmatic review. The recommendations for particle astrophysics projects can be summarized in the following table which ranks the major *current facilities (as of 2008)*:

Project	Ranking
Advanced LIGO/Geo600	Alpha 5
CLOVER	Alpha 4
Zeplin III	Alpha 4
Inverse Square Law	Alpha 3
Auger	Alpha 3
HESS	Alpha 2
Veritas	Alpha 1

Table 1: Project ranking in particle astrophysics from STFC 2008 programmatic review.

This ranking does not include R&D for *future* projects such as LISA, CTA, ZEPLIN-LUX, EURECA, LAGUNA, Einstein telescope, etc.

1.3. Science questions

We can identify a number of important scientific questions today which particle astrophysics methods can help to answer. We group these into the following areas:

Cosmology and early universe:

- What is dark energy and how has it affected the expansion history of the universe?
- What is the origin and what are the properties of primordial fluctuations in the early universe? What is the imprint of these fluctuations on stochastic backgrounds (e.g. CMB, Gravity waves, neutrinos)?
- What happened in the first 3 picominutes? How did the universe take on the properties it has today? Are there topological defects? What happened during GUT symmetry breaking (Was there a GUT symmetry breaking)?
- Why is the universe flat? Inflation? If so, what caused inflation; at what energy scale did it happen? Does general relativity break down at large scales?

Fundamental particle physics:

- What is the nature of dark matter?
- Do protons have a finite lifetime?
- Does general relativity break down at small scales/high energies? What is the quantum nature of gravity?
- What is the nature of fundamental particle interactions at extremely high energies (higher than particle accelerators can reach)?
- What are the properties of neutrinos (e.g. masses, mixing angles, Majorana nature)?
- Are there any particles present in the universe which we have not yet detected either directly or indirectly (e.g. axions, magnetic monopoles, inflaton, etc.)?

High energy universe / Non-thermal universe:

- How and where are particles accelerated to ultra-relativistic energies in our galaxy?
- What is the origin of the highest energy $> EeV$ cosmic rays?
- What is the role of ultra-relativistic particles in active galaxies and in AGN/cluster feedback?
- What are the properties of black holes?
- What happens when black holes or neutron stars collide?
- What happens during a supernova?
- Are there stable states of matter at densities beyond neutron degeneracy?

These questions overlap with the key science questions within the areas of particle physics and astrophysics. The techniques used to answer these questions distinguish particle astrophysics from the other fields – i.e. using particle ‘telescopes’. These techniques can be divided into the following broad areas (with some projects that have current UK support indicated in brackets):

- Particle astrophysics theory
- Gamma ray astronomy (HESS, CTA)
- Direct dark matter detection (ZEPLIN-III, CRESST/EDELWEISS)
- Gravitational wave detection (LIGO, Advanced-LIGO)
- Neutrinos (SuperNEMO, SNO)
- Cosmic rays (AUGER South, ANITA, ACORNE)
- CMB polarisation studies (PLANCK, CLOVER*)

Area	Science questions
Gamma rays	<p><u>High energy universe</u></p> <ul style="list-style-type: none"> - What are the properties of black holes? - What happens when black holes or neutron stars collide? - What happens during a supernova? - How and where are particles accelerated to ultra-relativistic energies in galaxies? - What is the origin of the highest > EeV energy cosmic rays? - What is the role of ultrarelativistic particles in active galaxies? <p><u>Fundamental particle physics</u></p> <ul style="list-style-type: none"> - Does general relativity break down at small scales/high energies?
Direct dark matter detection	<p><u>Fundamental particles</u></p> <ul style="list-style-type: none"> - What is the nature of dark matter? - Are there any particles present in the universe which we have not yet detected either directly or indirectly?
Gravitational wave detectors	<p><u>Cosmology</u></p> <ul style="list-style-type: none"> - What is the nature of dark energy and how has it affected the expansion history of the universe? - What is the origin and what are the properties of primordial fluctuations in the early universe? - What is the imprint of these fluctuations on stochastic backgrounds? - Was there a GUT symmetry breaking or other phase transition(s) in the early universe? <p><u>High energy universe</u></p> <ul style="list-style-type: none"> - What are the properties of black holes? - What happens when black holes or neutron stars collide? - What happens during a supernova? <p><u>Fundamental particle physics</u></p> <ul style="list-style-type: none"> - Does general relativity break down at small scales/high energies?
Neutrinos (and large scale underground detectors)	<p><u>Cosmology</u></p> <ul style="list-style-type: none"> - What is the origin and what are the properties of primordial fluctuations in the early universe? - What is the imprint of these fluctuations on stochastic backgrounds? <p><u>High energy universe</u></p> <ul style="list-style-type: none"> - What happens when black holes or neutron stars collide? - What happens during a supernova? <p><u>Fundamental particle physics</u></p> <ul style="list-style-type: none"> - Do protons have a finite lifetime? - What is the nature of fundamental particle interactions at extremely high energies? - What are the properties of neutrinos? - Why do fundamental particles have the properties they have?
Cosmic Rays	<p><u>High energy universe</u></p> <ul style="list-style-type: none"> - What is the origin of high energy cosmic rays? What role do they play in astrophysics? - What is the origin of the highest > TeV energy cosmic rays? <p><u>Fundamental particle physics</u></p> <ul style="list-style-type: none"> - What is the nature of fundamental particle interactions at extremely high energies?
CMB-polarisation	<p><u>Cosmology</u></p> <ul style="list-style-type: none"> - What is the origin and what are the properties of primordial fluctuations in the early universe? - What is the imprint of these fluctuations on stochastic backgrounds? - Why is the universe flat? Inflation? If so, what is the energy scale of inflation?

Table 2: Science questions addressed by the different areas in particle astrophysics.

Three of these areas – gravitational waves, dark matter and CMB polarisation – represent fields which to date have only provided upper limits rather than detections of signals. Over the last several decades researchers have been developing the necessary technology, theoretical background and analysis techniques required to make the first detections in these areas. It seems likely that these milestones will be achieved in the near future with correspondingly large scientific impact. Of the other areas, gamma ray and ultra-high energy cosmic ray astronomy are clearly still in the early stages with only a small number of known sources and events. It is therefore reasonable to expect that the next generation of these observatories may continue to uncover unexpected new phenomena like gamma ray bursts.

2. Current programme:

In this section we describe the UK expertise in the different areas of particle astrophysics and how this fits into current and planned national and international projects.

2.1. Particle astrophysics theory

Theoretical activities in particle astrophysics in UK are generally of high international quality with a particular strength in theoretical cosmology, dark matter, gravitational waves modelling, as well as particle acceleration in jets and neutrino physics. UK activities in theoretical and computational cosmology (e.g. large scale structure formation simulations) are world-leading. *The community includes nearly 150 scientists (staff/researchers) and numerous PhD students in more than 20 institutions.* Most of these scientists do not focus uniquely on particle astrophysics but their research activities include other areas of research, for example astrophysics and theoretical particle physics. The international visibility of UK theoretical particle astrophysics is good with a strong participation in leading conferences and workshops. UK theoretical groups participate actively in international collaborations and networks, as the FP6 European Research and Training network UniverseNet lead by Oxford U., the FP7 European Design Study LAGUNA (Durham U.), UK-India collaborative initiatives and have an active role in the preparation of the proposal for the FP7 project of Integrated Infrastructure Initiative ILIAS-Next.

2.2. Gamma Ray Astronomy

There is a long history of major UK contributions to both space and ground-based gamma-ray astronomy and very strong current interest and expertise in this area. *Historically, most of the activity has been at Leeds and Durham but eleven institutes and a total of 20 researchers signed the Sol for the development of the next generation ground-based gamma ray observatory, CTA, sent to the STFC in 2008 and there is growing interest within a much wider community.*

Ground-based

The leading ground-based technique is based on the Cherenkov emission of gamma-ray initiated cascades. The first detection of Cherenkov light from particle showers in the Earth's atmosphere was made in the UK in 1953. The first detection of an astrophysical object (the Crab Nebula) at TeV energies was made using the **Whipple 10 m** telescope, an instrument with major UK involvement, in 1989. The breakthrough which led to this discovery was the invention in the 1980s of a new method for rejecting background events developed by Prof. Michael Hillas of Leeds University, a technique which is still in use today. More recently scientists in Leeds and Durham have played major roles in the hardware, data-analysis and scientific exploitation of current generation instruments **HESS** and **VERITAS** which (together with the European **MAGIC** instrument) have revolutionised the field in the last 5 years, bringing the TeV source count to 95 – with 8 distinct source classes. HESS is currently the tenth highest impact astronomical observatory [1], ranked above instruments such as *XMM-Newton* or *Gemini*, extremely successful given its ~£5M construction cost. Two of the seven science working group convenors of HESS are UK-based.

The European next generation very high energy gamma-ray instrument is the **CTA** observatory, currently in its design phase and aimed for construction starting in 2013. CTA will bring an order of magnitude better sensitivity than HESS, substantially improved angular resolution and a much wider energy range. The UK is heavily involved in CTA. Two major work packages (array optimisation and performance studies and atmospheric monitoring and calibration) are led by UK scientists (Hinton and Nolan). Knapp (Leeds) is the current collaboration board chair. CTA is listed as an emerging project in the draft 2010 RCUK and ESFRI 2008 roadmaps and considered high priority by both ASPERA and ASTRONET. The major international competitor to CTA is the US-led **AGIS** project, also in the design phase and widely seen as less mature than the European effort.

Space based

The University of Southampton have played a major role in the **INTEGRAL** satellite, operating in the hard X-ray/soft gamma-ray regime, from the very beginning. INTEGRAL was launched in 2002 and will operate until at least 2010. Leicester has played a major role in the **SWIFT** satellite which has detected a large number of gamma ray bursts and enabled detailed follow-up observations which have shed light on new high energy phenomena. Whilst there was no UK participation in the GeV satellite **Fermi** (despite a bid to the STFC led by Liverpool), there is general feeling in the community that scientific exploitation of this instrument (for which all gamma-ray data are now publicly available) should be supported by the STFC at a modest level. Liverpool, Leicester and Southampton are all now involved in CTA, as are all UK scientists who participated in HESS and VERITAS.

2.3. Dark Matter

Direct DM detection is recognised internationally as a critically important area of Particle Astrophysics. *The UK has a very strong history and reputation in this area with approximately 30 academic researchers (out of 300-500 world-wide) including academics, post-docs and PhD students.* At present there are three major active programmes of research, with UK and international participation as indicated.

- **DRIFT/CYGNUS** (Sheffield, Edinburgh, plus several EU and US partners)
- **Edelweiss/Cresst** (Oxford, plus European partners)
- **ZEPLIN** (Imperial, RAL, Edinburgh, plus Russian and Portuguese partners)

To date, no credible direct detection of dark matter has yet been made. From a theoretical perspective, the most likely regions of parameter space are beginning to be reached by the best detectors that are of a few kg scale size. This parameter space broadly extends three orders of magnitude further in sensitivity; beyond this, alternative models of physics beyond the standard model are required. Thus there is a world-wide consensus that tonne-scale devices are required. The exception is the **DAMA** result, which already claims detection based on an annual modulation in a bulk signature. In the absence of an unexpected WIMP interaction, their detection is refuted by several other projects. The community remains highly skeptical.

The world's leading projects at present are **CDMS** (Soudan Mine), **ZEPLIN** (Boulby) and **XENON-10** (Gran Sasso), all with similar limits. Of these, the US **CDMS** project, based on sub-Kelvin cryogenic technology leads and is about to release new results with significant improvement. They are also installing more units for a scale up of the whole project by a factor of approximately 4. The two-phase liquid/gas xenon based detectors of **ZEPLIN** and **XENON-10** are close behind (the precise hierarchy dependent on analysis method). **ZEPLIN** are to commence a second science run imminently, which should deliver a further order of magnitude improvement, while the **XENON** collaboration are already running again with a larger instrument but which is experiencing problems in purifying the liquid and with the high voltage levels required.

The **CRESST** (Gran Sasso) and **EDELWEISS** (Modane) teams are among these, and are Europe's leading cryogenic based detector groups. They have well stated plans to unify under the banner of **EURECA**, and significantly for the UK, Hans Kraus (Oxford) is Spokesperson with significant involvement from the group in Sheffield. Reaching tonne-scale will clearly require further

development. Scaling up xenon-based technologies is financially probably more feasible than scaling up sub-Kelvin devices, but the signal discrimination level required is less well proven. The **ZEPLIN** team will be joining the US based LUX team to deploy a xenon-based instrument in the new SUSEL lab in the US. There will be a shared spokesperson role, with the European PI being T. Sumner, Imperial. **EURECA** is a well-established team and is strongly placed for European funding; there are plans to work with **CDMS**.

The UK therefore has spokesperson level engagement in the world's two leading projects in this very important field. From a scientific perspective it is as yet unclear which technology will ultimately be superior. Moreover, the WIMP interaction is expected to be such that two different target materials will yield not only confirmation of detection but also important additional information on the new physics being probed.

The UK is also making contributions to the **ArDM** and **DRIFT** projects. The Boulby-based **DRIFT** project uses a gas TPC to search for a directional signature. Being a gas, the target mass is relatively low to be competitive in detecting WIMPs with spin-independent interactions but it can be competitive for spin-dependent interactions and has a very attractive directional capability, with significant progress recently demonstrated. At present this activity has no UK funding but is ongoing at Sheffield and Edinburgh with support from the EU and US. Once dark matter has been identified, a directional device will become very important, allowing the local velocity distribution to be probed, yielding unique information on the history of the Milky Way. The contribution to ArDM is being made at Sheffield and consists of R&D for novel readout methods. The argon-based approach to dark matter detection is an exciting new possibility, with potential for significant expansion should the technology prove successful.

Indirect methods of detecting astrophysical signatures of dark matter decay and/or annihilation such as balloon-borne and space-borne cosmic ray or gamma ray detectors such as **PAMELA**, **ATIC** and **Fermi** also have the potential to constrain the properties of dark matter particles (as opposed to other astrophysical measurements which are only sensitive to the gravitational impact of dark matter). The UK contribution to this area is small but potentially high impact.

2.4. Gravity Wave Detectors

The UK has a core community in ground-based GW research with approximately 100 scientists (staff/researchers/students) in the Universities of Glasgow, Cardiff, Birmingham, Strathclyde, Southampton, Sheffield, Cambridge, and the Rutherford Appleton Laboratory. This community grew by about 50% in the last 2 years, with continued growth expected as the field matures. UK strengths exist in ultra-sensitive cryogenic mechanical system, sophisticated interferometry and new data analysis and computational techniques.

Recent years have seen a shift in the technologies used in gravitational wave searches as the first generation of large gravitational wave interferometers have begun operation at or near their design sensitivities. These ground-based km-scale interferometers and their advanced upgrades will be critical in establishing the field of gravitational wave astronomy through the detection of high luminosity gravitational wave sources such as the merger of binary neutron stars and black holes.

Over the last decades the UK has built an outstanding track record in technological and theoretical leadership in the international Gravitational Wave field through its pioneering work in instrumentation, phenomenology, and astrophysical source studies. The UK currently holds the elected Chair of the Gravitational Wave International Committee (**GWIC**: <http://gwic.ligo.org/>) – (the UK chair having been re-elected in 2009 for a second term). This policy body is formed from the laboratory and project leaders around the globe and facilitates collaboration and cooperation in the construction, operation and use of the major gravitational wave detection facilities world-wide.

UK innovation in instrumentation has led to the '**Advanced LIGO**' design being largely based on delicate monolithic silica suspension technology and advanced interferometry principles piloted for the UK-German **GEO** detector. These techniques are being transferred to the United States under

STFC funding, gaining STFC a full seat on the **LIGO** Oversight Committee. Furthermore, the UK-German **GEO** collaboration is the largest member of the **LIGO** Scientific Collaboration (with approximately 700 members worldwide) outside the **LIGO** Laboratory (Caltech and MIT) and this is further evidence of the track record, and international standing, of the UK in this field. The UK will continue to play a key role in further high frequency enhancements to **GEO** (**GEO-HF** based on novel technologies such as squeezed light), with UK leadership of an international prototype detector to test techniques for this carried out under the umbrella of LSC activities.

Current UK data-analysis strengths are also evident with two of the four data analysis groups of the **LIGO** Scientific Collaboration, the Continuous Wave detection group and the Coalescing Binary Search group, having UK co-chairs. Looking further to the future, UK strengths have secured key roles in new developments in the gravitational wave field, both experimentally and theoretically, with two of the four scientific work packages for the 3rd generation Einstein Telescope (**ET**) EC FP6 design study being led by UK participants (WP3: "Topology Identification" and WP4 "Astrophysics Issues"), in addition to major UK contributions to the study in other areas.

2.5. Neutrinos

Neutrino physics may be split into three broad areas: (a) Properties of neutrinos, including neutrino oscillations and neutrinoless double-beta decay (DBD); (b) solar and terrestrial neutrinos; (c) large neutrino detectors and neutrino telescopes. Since the discovery of neutrino oscillations, a wide international experimental programme in neutrino particle astrophysics is gaining momentum. *The UK is involved in neutrinoless double beta decay experiments (IC, MSSL, QMUL, UCL, U. of Leeds, U. of Manchester, U. of Oxford, U. of Sussex), R&D for future large scale multipurpose neutrino detectors (Brunel U., U. of Sheffield, U. of Warwick) and for neutrino telescopes such as IceCube, Km3Net and the Askaryan Radio Array (ARA) (UCL, U. of Aberdeen, U. of Leeds, U. of Liverpool, U. of Sheffield, U. of Oxford).*

Neutrino properties

The UK has world-leading involvement in a number of neutrino experiments, including the accelerator experiments **MINOS** and **T2K**, and the DBD experiments **SNO+** and **SUPERNEMO**. Although NDBD has in the past been included within the remit of PAAP, it is not generally regarded as belonging fully to the field of particle astrophysics; we note also that it is very well covered within the PPAP report, the conclusions of which this Panel strongly endorses. We therefore do not address it further.

Solar and terrestrial physics

The UK played a pivotal role in the crucially important SNO experiment. Interest in low-energy solar neutrinos continues: most importantly, they will allow us to test and resolve the apparent inconsistencies with helioseismology data. Other applications include the use of CNO neutrino measurements to help with understanding the ages of globular clusters, and the provision of a further handle on the neutrino mixing angle θ_{13} . Likewise, the study of geoneutrinos allows geophysicists a new window into the Earth's core. Although none of these measurements offers the high impact of DBD studies, they nonetheless represent a very low-risk, low-cost opportunity for valuable scientific return. The SNO+ experiment - the main scientific goal of which is DBD - has a much lower energy threshold than did SNO, and provides comprehensive coverage of all of these areas. It would in addition be a very sensitive supernova detector.

Neutrino detectors

On a slightly longer timescale, a multi-purpose megaton-scale detector will have the capability to detect neutrinos from astrophysical as well as terrestrial sources and to search for proton decay. It will allow studies of supernova neutrinos, detection of MeV to GeV neutrinos from the atmosphere and the Sun, searches for geoneutrinos and neutrinos from dark matter annihilations, depending on the detector technology of choice. In addition, such a detector could serve as the target for a long-baseline neutrino oscillation experiment searching for CP-violation and the hierarchy of neutrino masses. These studies will improve our knowledge of the neutrino properties, as well as our understanding of the evolution of astrophysical objects such as supernovae.

Current and future projects

IceCube is a 1 km³ neutrino telescope aimed at studying astrophysical neutrinos from energies above 100 GeV to 1 PeV, via the observation of the Cherenkov radiation from charged particles produced in neutrino interactions. At present the collaboration is finishing the deployment of the photomultiplier strings and is already taking data with the available string array. An extension of IceCube, Deep Core, is under construction adding a set of strings in the center. This configuration allows lowering of the energy threshold of the observed neutrinos by an order of magnitude. The UK is involved in IceCube with 2 scientists (U. of Oxford) mainly in theoretical activities. **Km3Net** is a future deep-sea research infrastructure in the Mediterranean Sea which will host a 1 km³ neutrino telescope. The Preparatory Phase of the infrastructure, funded by the EU FP7 framework, started in March 2008. Km3Net has been included in the European Roadmap for Research Infrastructure. The UK contributes to Km3Net with 11 scientists in 4 universities (U. of Aberdeen, U. of Leeds, U. of Liverpool, U. of Sheffield).

Research and development

A strong R&D activity is currently taking place worldwide focussed on the development of the technology required for a megaton scale detector, e.g. water-Cherenkov, Liquid Argon TPC and scintillator tracking calorimeters. The UK is currently involved in R&D on liquid argon TPC and on scintillators. A European coordination of the efforts is provided by the **LAGUNA** (Large Apparatus studying Grand Unification and Neutrino Astrophysics) design study under the FP7 programme, which is investigating the feasibility of a 0.1-1 Megaton detector with a site study including Boulby. UK institutions contribute significantly to LAGUNA in all the WP of the design study and lead the Safety, environmental and socio-economic issues WP (Sheffield).

2.6. Cosmic Rays

World class research in the field of cosmic ray astrophysics has taken place in the UK since the early days of this field. *At present there is a small but high quality core of 10-15 researchers at Leeds, UCL and Sheffield in this area.* The current world leading instrument is the (now complete) 3000 km² southern component of **the Pierre Auger Observatory**, the idea of Prof. Alan Watson FRS (Leeds) and noble-laureate Prof. Jim Cronin (Chicago). Watson was spokesperson of the collaboration for many years and is still a leading figure in the field.

The current air-shower / cosmic-ray activity in the UK is largely confined to Auger activities and involves the Universities of Leeds and Oxford. There is a general feeling that a UK contribution to the construction of **Auger-North** (a factor 7 larger array in the US) is difficult to justify given the size of the community (4 academic staff are part of the UK Auger activity) and the competition with other major projects in the area of High Energy Astrophysics. Scientific exploitation of **Auger-South**, however, capitalising on UK investment in hardware and intellectual input to the project – is widely supported. Knapp (Leeds) is the leader of simulations activity in Auger which is critical for disentangling the particle physics and astrophysics aspects of the Auger measurements. There is no UK involvement in the **JEM-EUSO** satellite project. The feeling in the community is that we (the UK) should wait for new results and/or the emergence of new technologies (such as radio detection) before planning future activities in this field.

The work on ultra-high-energy neutrino detection in the UK (**ARA** - formerly **IceRay**, **ACORNE**, – UCL, Oxford and Sheffield) is closely related - as interacting UHECRs provide the most robust predicted signal.

2.7. CMB polarisation

The UK is a world leader in cosmic microwave background (CMB) research in the areas of instrumentation, theory and data analysis. *The UK CMB community consists of approximately 100 researchers mainly working on PLANCK operation and data analysis and ground-based CMB experiments.* The UK played major roles in pioneering experiments such as Boomerang, CAT, the

Ryle telescope, VSA and AMI which have made detailed measurements of the temperature anisotropies and have had a major impact in cosmology, contributing to the 'lambda-CDM' model.

In 2001, the DASI experiment reported observation of E-mode polarisation, opening up CMB polarisation as a new area of observational research. The result has been confirmed and refined by a number of experiments including BOOMERANG, WMAP, BICEP and QuAD. Detection of a second polarisation mode, B-mode, is now a high priority. The interest stems from the possibility of using the entire universe as a gravity wave detector. Gravity waves present in the universe at the time of decoupling of radiation from matter will have left an imprint in the CMB. This imprint would be in the form of B-mode polarisation, a distinctive pattern of polarisation vectors on the sky with magnetic field-like negative parity. Gravity waves generate this pattern as well as an even-parity pattern known as an E-mode due to the quadrupole (tensor) nature of gravitational radiation. In contrast, density and velocity perturbations in the early universe can only generate the E-mode polarisation pattern and hence detection of B-modes is a good signature of gravitational waves. Temperature or intensity anisotropies in the CMB are dominated by these density and velocity perturbations.

The candidate sources of gravity waves in the early universe are events such as breaking of fundamental symmetries (e.g. electroweak, GUT), processes that spawn distortions in space-time known as 'topological defects', or violent cosmological events such as inflation and reheating. Detecting any of these cosmological gravity waves would have a very high scientific impact and is one of the 'holy grails' of gravitational wave experiments (see Nature, 20 August, 2009).

The CMB polarisation signal is expected to be strongest on the largest angular scales. Therefore the gravity waves probed correspond to wave periods on the order of the Hubble time. These frequencies are much lower and the distance scales much larger than those probed by gravity wave interferometers such as LIGO and LISA (km scales). CMB polarisation experiments are the only known way to detect these phenomena. An additional advantage is that there are, by definition, no events in the post-recombination universe that can generate gravity waves on the scales probed by the CMB, so any detected signal has to be of primordial origin. The amplitude of these primordial gravity waves is directly related to the energy scale at which they were produced.

The UK has a strong role in CMB polarisation observations, with leadership roles in QuAD and **CLOVER**, and a strong role in **PLANCK**. QuAD delivered the most sensitive measurement of E-mode polarisation to date, but is now decommissioned. Despite a strong science case and alpha-4 rating in the 2008 prioritisation, cost over-runs have led to funding for CLOVER being terminated. The project will soon be dormant, but there continues the possibility that it could begin again if significant international partnership can be found. The UK continues to have a significant role in the satellite based PLANCK project. This was recently successfully launched, is operating well, and science data is now being collected. Smaller roles in several other projects (e.g. ACT-Pol, BICEP, BICEP-2, C-BASS, EBEX, MAXIMA, POLARBEAR, QUIET, QUIJOTE, SPIDER, SPT) have been achieved through specialist technical expertise; these now offer a scientific opportunity for further work.

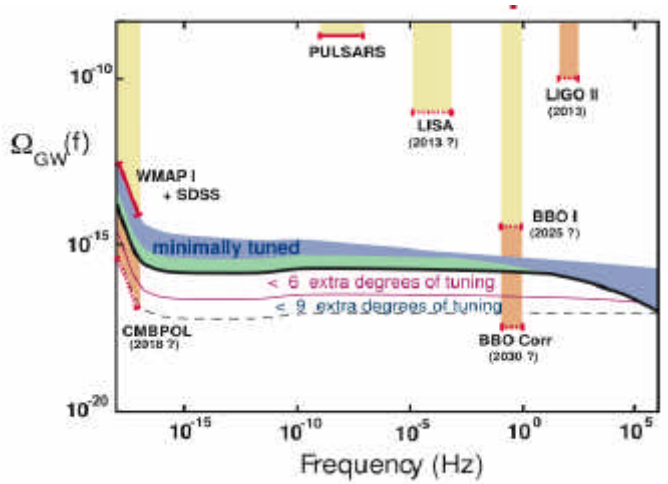


Figure 3 (left): Prediction of level of primordial gravity waves from a slow roll inflationary model (reference). The best upper limit from a combination of the WMAP CMB measurements combined with measurements of large scale structure from the Sloan Digital Sky Survey are shown at the left of the graph. The change in slope of the primordial gravity wave spectrum at a frequency of approximately 10^{-16} Hz is due to the difference in damping of primordial gravity waves that enter the horizon in the matter dominated era vs. the radiation dominated era.

2.8. Small projects

Inverse Square Law

Over the past decade there has been significant interest in searching for deviations from the inverse square law (ISL) of gravity at distance scales less than 100 μ m. It is perhaps surprising that our current knowledge of gravity at short ranges could allow for a force 10^5 times the strength of gravity at a test mass separation of 10 μ m. In addition, deviations of the ISL of gravity also provide a strong probe for testing theories with Supersymmetric Large Extra Dimensions (C.P. Burgess arXiv:hep-th/0411140), which could provide a possible solution to the Cosmological Constant problem, testing modified gravity and the search for new particles such as dilatons, chameleons and axions. The UK currently has a high visibility in this field in the form of a relatively small project being carried out at the University of Birmingham. Even with modest funding the group has already developed an impressive track record which includes the best limit on axion couplings between mass and spin (G.D. Hammond, Phys. Rev. Lett., 98, 081101 (2007)) and promising preliminary measurements of the ISL of gravity in the range 3 μ m-30 μ m at 4.2K.

3. Future opportunities:

Generally it is acknowledged that the UK can only afford to participate in areas where we have the capability and possibility to make ground-breaking discoveries. These areas are those in which we have previous expertise, current strength and future capability. Furthermore, the forward programme should be defined in terms of the scientific concepts being explored, as well as in terms of technical approach. This is because most projects tackle multiple scientific problems, which often cross the boundaries between the Advisory Panels. In this section, we describe the main future facilities as prioritised by the UK particle astrophysics community in the different areas.

3.1. UK Facilities needed

Boulby underground laboratory:

Currently **Boulby** hosts the UK's internationally respected **ZEPLIN-III** and **DRIFT-II** Dark Matter search experiments as well as the Danish/UK (EPSRC) funded climatology experiment SKY-ZERO. Thanks to the ongoing support of the mine operators Cleveland Potash Ltd the UK has up to now had its own world-class deep underground science laboratory which is maintained at a very low-cost compared to other world sites not hosted by industry (**~0.3 M \pounds /year**). *Boulby has been the focus of UK low-background science and R&D for over 20 years now and the continuation of activity at the site is important to maintain the UK's standing in the field.* There is currently a plan for Boulby to host the nuclear astrophysics project **ELENA**. There are also plans to establish low-background radiological test facilities at Boulby to support the current and emerging low-background experiments e.g. **DRIFT**, **ZEPLIN**, and SKY-ZERO successors, **SuperNEMO** and **LUX-ZEPLIN** and **EURECA**. The need for such facilities is evidenced by the use of similar facilities in competing laboratories. The busy Modane facility in France for example has 13 germanium detectors and is oversubscribed, supporting low-background physics as well as environmental, industrial and defence projects. Looking further to the future, some of the major European underground detector projects (e.g. **LAGUNA**) are also considering Boulby as a host facility, especially in light of the deeper, more stable areas now being mined.

Particle astrophysics theory:

It is recognised that the theoretical particle astrophysics community needs a sustained and stable level of funding, and might be at present underfunded. Areas which need further support are: research staff and PhD student funding, travel funds and high performance computing facilities. The strengthening of collaborative links between UK theoretical particle astrophysics groups and a stronger interaction with experimental groups should be encouraged.

Gamma Ray Facilities:

The **Cerenkov Telescope Array (CTA)** is the highest priority gamma ray facility. It is seen to have a very broad science case, will be a world leading instrument for a decade or so, and has a strong

level of UK leadership. It is also expected that this will have (low risk) guaranteed science returns as well as (higher risk) discovery potential. Continued involvement in **HESS** is strongly supported, and there is a small but important continuing UK role in **VERITAS**.

Dark Matter Detection:

Direct detection of dark matter is seen as an area of very high importance and one in which the UK already has a very strong international role (e.g. **CRESST/EDELWEISS** and **ZEPLIN-III**). It is high-risk (there may not be a detection) but the discovery would be of the highest level of significance. The UK has Project Spokespersons for two of the main future international projects - **EURECA** and **LUX-ZEPLIN**. The two projects use different technologies, which are complementary and at this time there is community support for continuing in both at a significant level. There is also support for the somewhat newer technology of liquid Argon, and also for directional detectors (i.e. **ArDM**, **CYGNUS/DRIFT**) but this is generally considered a lower priority until after discovery. Continued R&D in these areas would keep possibilities open for the future.

Gravity Waves:

There is strong community support for the Gravitational Wave field with **LIGO**, **Advanced LIGO** and **LISA** being the most highly cited. Similar to dark matter this can be seen as high risk until a definite detection. However, the confidence in expected signal levels from known sources is high and detectors are reaching the sensitivity level required to open up the gravitational window on the universe, inevitably discovering new unexpected phenomena. In the coming decade the field will be transformed from a "first detection" status to an important astrophysical technique which can answer high priority questions in fundamental physics, particle astrophysics and astronomy. To allow the UK to maintain its current position at the forefront of the field, both experimentally and theoretically, it is important that the appropriate laboratory scale experimental and theoretical research toward advanced and 3rd generation detectors is fully supported.

High energy Cosmic Rays:

There is strong support for full exploitation of **AUGER-South**, but little support for participation in the future Northern site. *We strongly encourage continuing support for new ideas for studying high energy cosmic rays such as acoustic detection (e.g. **ACORNE**) and radio Cherenkov radiation (e.g. **ANITA**, **ARA**).*

Neutrinos:

UK participation in a European 1 km³ neutrino telescope, **KM3NeT**, is supported at a low level as it does not promise a large advance in sensitivity over **IceCube**. Participation in R&D for a future **large volume multipurpose neutrino detector** is of high priority and should be maintained within the LAGUNA design study or future similar programmes. The topic of neutrinoless double beta decay is one that overlaps with the remit of the PPAP. This is seen as an important research area and one where it is important for the UK to retain a leading role. Of the future NDBD experiments, SNO+ also has significant capabilities particularly for solar and terrestrial neutrino detection.

CMB-polarisation:

There is strong support for operation and exploitation of **PLANCK**. The science case for ground-based B-mode polarisation experiments such as **CLOVER** remains strong. *Engagement with international partners is strongly recommended on a short time scale in order for the UK to take advantage of scientific and technical work done on CLOVER and other B-mode experiments.* It is not clear if there will be a next-generation CMB satellite after PLANCK although there is a significant level of ongoing design studies and technology development with UK leadership.

Small projects:

There is general support for a small projects budget line for continued funding of experiments like the ISL tests. There is some confusion whether the PPRP managed PRD line already covers this. A key point is that new ideas should be encouraged and this funding line should respond quickly to requests.

3.2. Prioritisation

Broadly speaking, we can divide the different facilities into two categories:

1. Primarily single goal – e. g. CMB polarisation, dark matter
 - a. Risk level – i.e. how likely is discovery?
 - b. Impact level – i.e. how significant would a discovery be?
 - c. Breadth - Science other than main goal?
2. General observatory – e. g. CTA, LIGO, LISA, KM3NET
 - a. Risk level – i.e. what are chances for different science cases?
 - b. Impact level – i.e. how important is the science?
 - c. Breadth – i.e. what types of questions can be addressed?

In general, areas where there has not yet been a detection of a signal such as gravitational waves and dark matter are higher risk than areas where detections have already been made such as cosmic rays and neutrinos. However, this increase in risk is often correlated to an increase in impact as the first discovery of a new signal is usually high impact by itself as well as potentially leading to other new discoveries.

Priorities:

We recommend supporting a portfolio of facilities in particle astrophysics that balances scientific breadth, impact, UK strength and cost and includes strong support for theory and exploitation of facilities. The table below gives our prioritisation of the different areas in each of these categories.

Area	Breadth	Risk level	Impact level	UK strength	Cost
Gamma rays	Medium	Low	Medium/High	Medium	Low
Cosmic Rays	Low/Medium	Low	Medium	Medium/High	Low
CMB-Pol	Low	High	High	High	Medium
Dark Matter	Low	High	High	High	Medium
Gravity Waves	Medium/High	Medium	High	High	High
Neutrino detectors	Medium	Medium	Medium	Medium/High	Medium

Table 4: Prioritisation of particle astrophysics areas. Breadth is a measure of the number of science questions addressed by projects in this area. Risk level is a measure of the likelihood of achieving the science goals and impact level is a measure of the significance of the science if the goals are achieved. UK strength is rated high if proposed facilities are world-leading and UK-led or where the UK has a critical role. The area of neutrino detectors does not include neutrinoless double beta decay which has low breadth, high risk and high impact.

We find that strong UK participation in upcoming large facilities in the following areas is essential (listed in no particular order):

- Gamma Rays
- Dark Matter
- Gravitational wave detectors
- Neutrinos

We find that it is also essential to maintain a lower level of UK participation (e.g. science exploitation and R&D for future instruments) in the following areas:

- CMB-polarisation
- Cosmic rays

This prioritisation is represented in the following projected funding profile figure:

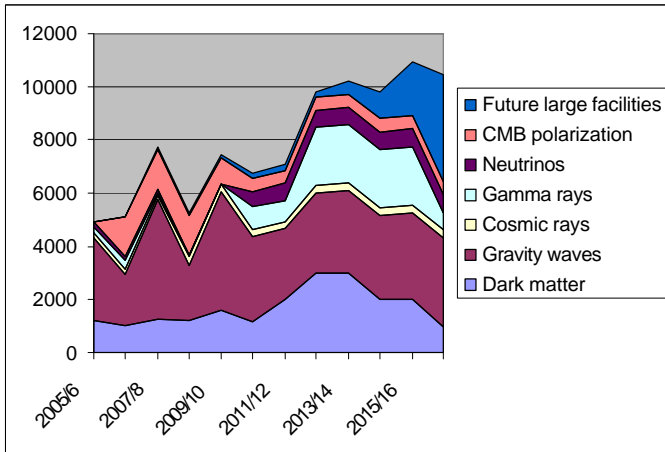


Figure 4 (left): Possible UK funding profile by area in particle astrophysics. Note this does not include funding for R&D for space-related work such as LISApf and LISA. This projection corresponds to an increase in funding for the areas of dark matter, neutrinos and gamma ray astronomy, level funding for cosmic ray research and a decrease in the funding for CMB polarisation.

We recognise that the opportunities for growth, and perhaps even stability, in the overall level of particle astrophysics funding are constrained in the current budget. The prioritisation we present in Table 4 above gives a guide to the relative *scientific* merits of the different areas (i.e. breadth, risk, impact and UK strength). A full evaluation of projects within each area requires more detailed information (i.e. project proposals and costings). We recommend that a unified approach to large facilities within different areas be adopted in a similar way to the rolling grant scheme with periodic announcement of opportunities for project proposals (i.e. one per year) so that a side by side comparison of proposals within a given area can be made.

Theme	Current Projects	In-Build	Future projects
<u>High Energy Universe</u> What is the origin of Cosmic Rays? What is the origin of Gamma Ray Bursts? Understanding Supernovae Understanding Black Holes and BH coalescence Understanding neutron stars and quark stars	Auger South GEO 600/LIGO H.E.S.S VERITAS ANITA	Ad-LIGO ICECUBE GEO HF	CTA Einstein Telescope ARA (IceRay) Large scale Neutrino detector LISA KM3Net
<u>Early Universe and Cosmology</u> What is Dark Matter? What is Dark Energy? Did Inflation occur & what drove it? What is the origin and nature of primordial perturbations?	DRIFT H.E.S.S VERITAS ZEPLIN III PLANCK CRESST II EDELWEISS II	H.E.S.S. II CLOVER	BBO CMB Satellite LUX-ZEPLIN EURECA Einstein Telescope DRIFT/CYGNUS
<u>Fundamental Physics</u> Is Lorentz Invariance valid at all energies? What is the quantum nature of gravity? What are the properties of neutrinos? Do protons have finite lifetime?	Auger South GEO 600/LIGO H.E.S.S. n-EDM NEMO III SNO VERITAS	Ad-LIGO eEDM Inverse Square Law GEO HF	LISA SNO+ Super-NEMO Einstein Telescope Large scale Neutrino detector DRIFT/CYGNUS

Table 5: The above table lists the main facilities with large UK involvement currently in use, undergoing construction and planned for the future. For a more complete list of projects by area see section 2. Projects in green are small projects with total funding < £1 M. Projects in the last column in red are ones which we have identified as the highest priorities from the community feedback. Where there are two projects in the same area (e.g. SNO+/SuperNEMO and LUX-ZEPLIN/EURECA) we have factored only one project from each area into the funding projection figure. The other projects in the last column are expected to be further in the future than 2015/2016 and require ongoing R&D support.

4. Technology and outreach:

4.1. Relevant technologies

Gamma rays:

A key technology required for future gamma ray observatories is a large area photon counting detector for optical/UV Cerenkov radiation. The technology used in current gamma ray observatories is the photomultiplier tube (PMT). These are limited in quantum efficiency (30%) and cumbersome to use. Development of a solid state replacement of PMT's would have a large impact on capability and have applications in many other areas outside of particle astrophysics.

Dark Matter:

The main technologies under development for dark matter detectors are liquid noble gas detectors (Xe and Ar), gas TPC technology, cryogenic calorimeters using transition edge superconducting thermometers (TES) and/or kinetic inductance detectors (KIDs).

Neutrinos:

Some of the technologies which need to be developed for neutrinos are:

- noble gas detectors and in particular liquid argon TPC and other types of neutrino detectors such as scintillator tracking calorimeters
- low background detectors for neutrinoless double beta decay
- PMTs
- large format calorimeters for single beta decay experiments.

Gravitational waves:

There are a number of important technologies under development for gravitational wave detectors and ways in which this research may benefit industry.

- Studies of mirror coating thermal noise have shown that it poses a limit for light sources for atomic spectroscopy and frequency standards. Relationships with vendors are leading to improved coatings for IR mirrors.
- Collaboration with a US company (under a Non Disclosure Agreement) regarding improvements, based on GW suspension technology, in borehole seismometers for the oil industry.
- Knowledge Transfer relating to the oxide-bonding technique developed in Gravitational Wave research continues to seed developments in the optics industry. A project to develop glass integral field units for astronomical spectroscopy is now being taken forward for use in prototype mirror actuators for the ELT.
- A concept for a compact interferometric sensor (EUCLID) developed as part of Advanced LIGO is now being commercialised for high volume production.

CMB polarisation:

Future CMB experiments require development of a number of technologies including:

- arrays of superconducting bolometers (TES or KID)
- millimetre-wave antennas/horns, filters, ortho-mode transducers

- polarisation modulators – waveplates or phase switches/phase shifters

4.2. Outreach and public engagement

Communicating the excitement of science to the general public is a vital but difficult task. To do so effectively requires both a topic of great interest and communicators of sufficient skill. Particle Astrophysics is exceptionally well placed to achieve this, providing effective opportunities for scientific outreach at all levels and for all members of the the public.

At the forefront of modern research, coupling the scale of the entire cosmos to the fundamental building blocks of nature, particle astrophysics easily captures the imagination. The topics being addressed range from highly abstract concepts that seem almost like science fiction, to the reality of acquiring data in often remote and hostile environments. Moreover, this is an area in which the Big Questions and grand scale of research can be communicated in a surprisingly straightforward way, with no reliance on overly sophisticated methodology or mathematics, increasing its accessibility greatly.

The community consultation exercise revealed a community highly engaged in public understanding of science activities, with many examples given. The AUGER project has an impressive Argentina-based outreach centre, which provides activity days for local children, extensive web pages, releases of data for educational use, and even a feature in Google Earth. Literally hundreds of visitors, of all ages, have visited the dark matter research work at Boulby mine, many going underground to visit the apparatus itself. Nottingham and Lancaster Universities have worked together to provide science masterclasses for local schools. At Sheffield, the CREATE project has introduced cosmic ray research to many more while, working with the Royal Society, gravity wave researchers are running specially designed websites that are garnering significant attention. The community is contributing of order a hundred public talks per year, including Cafe Scientifique's, talks at science festivals, the Big Debate series at Imperial, and talks at local astronomy clubs and societies. In addition, particle astrophysics is highly popular with the media, with a great number of radio interviews, newspaper and magazine items, as well as several examples of more prestigious items such as the BBC Horizon and Sky at Night programmes. In addition, there is a big new exhibit in the London science museum (cosmos and culture) that includes the first DRIFT I dark matter detector from Boulby.

Despite all this activity, the consultation suggested that there are opportunities for more activity still. Suggestions included more engagement between STFC and the BBC to produce better public dissemination of the ongoing UK-led particle astrophysics research, the possible creation of Particle Astrophysics Visitor Centres at STFC national laboratories, and action to generate better penetration in to the national and local science museums with University and/or lab groups being able to bid for significant resources to help update tired and ancient displays.