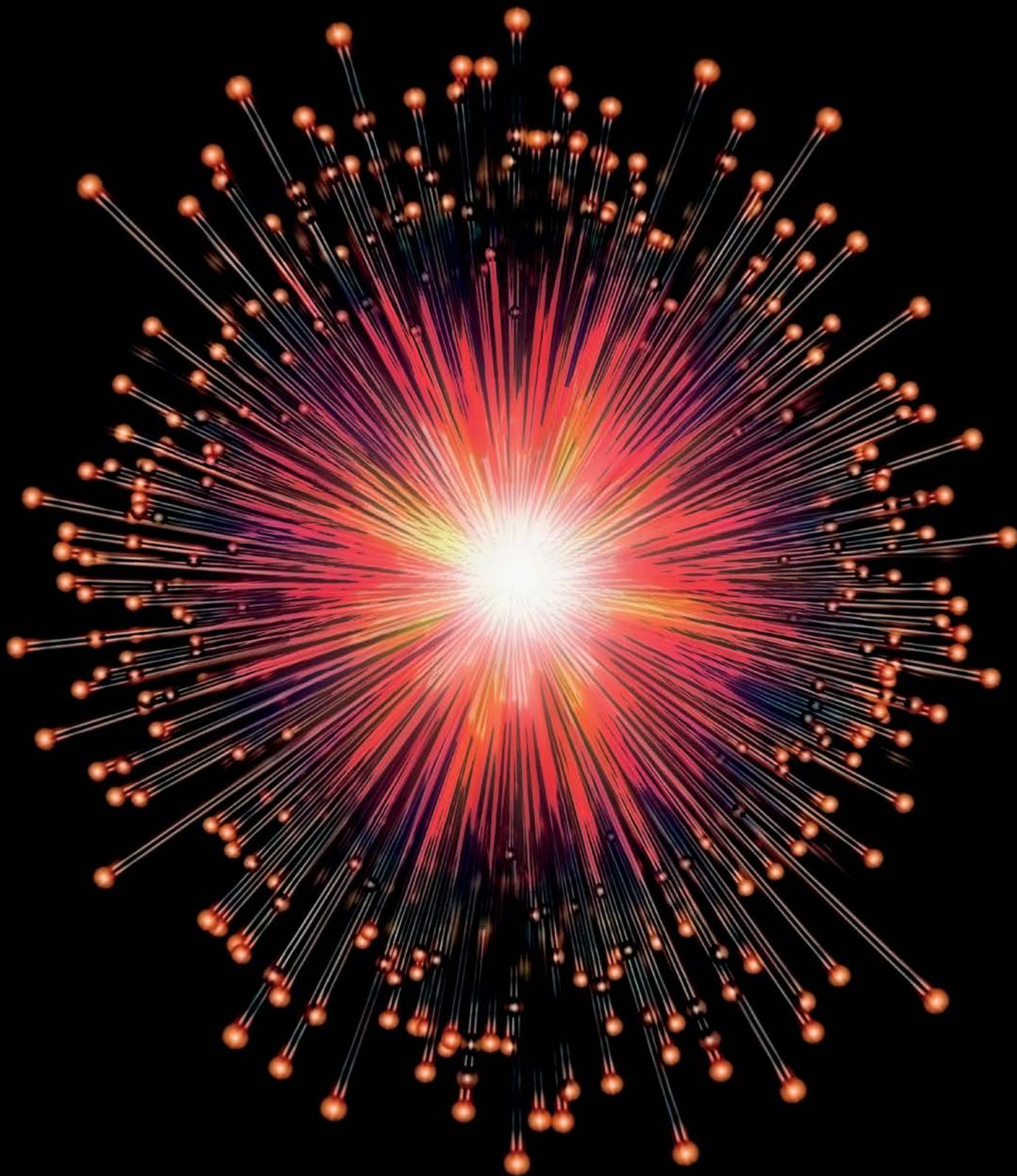


An Institute of Physics Report | June 2015

# A Review of UK Astroparticle Physics Research





**Cover image:** Computer artwork of neutrinos  
*Carol & Mike Werner, Visuals Unlimited/Science Photo Library*

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# EXECUTIVE SUMMARY

This review of the health of UK academic astroparticle physics was commissioned by the Science and Innovation Committee of the Institute of Physics (IOP). It is the latest in a series of such reviews of fields within physics aimed at informing IOP policy and influencing government investment for the next decade.

The overall terms of reference of the review were:

- To review, in an international context, the support for and progress of UK astroparticle physics in the past decade.
- To assess UK astroparticle physics in light of the scope of Research Councils UK (RCUK) and other funding sources, for example, the European Research Council (ERC).
- To recommend a broad strategy for UK astroparticle physics for the next 10 years, including key physics-based challenges, balance between activities, access to facilities, and interdisciplinary and international collaborations.

The membership of the panel set up to carry out the review is given in Appendix 1 (p37).

This review has examined contemporary astroparticle physics research being conducted by UK-based scientists, considering issues such as the scientific areas being researched, how these interface with the biggest questions in science, and the facilities and resources involved. A census of UK activity in astroparticle physics has been conducted, determining the size of the community, its present funding level, the balance between subfields and the division of effort between theory and experiment. In parallel, an international survey has explored the international perception of UK research in astroparticle physics, its strengths and its weaknesses. The review also considered the productivity of the area, in terms of volume and quality of peer-reviewed publications, the training of skilled people at MSc and PhD level, its contribution to the public understanding of – and engagement with – the physical sciences, and its contribution to industry and the economy.

This review concludes that the UK hosts a community of world-class astroparticle physicists, making major contributions to several of the most important projects in contemporary science. The scientific output of the community, as judged by the productivity and quality of refereed, peer-reviewed journal publications, is high. Furthermore, the international standing of the community is exceptional, with leading members holding many of the senior positions in major international projects. Several particularly strong examples of industrial engagement and knowledge transfer were identified in case studies, demonstrating the economic and societal value of astroparticle physics to the health and wellbeing of the UK.

However, the size of the community, and breadth of science that is receiving financial support, is *critically* low. This hampers the ability of the community to contribute to a wider range of pressing scientific questions, to develop new applications, and to train people in the necessary skills. This is caused by a number of issues detailed in the report.

This review **recommends** the following measures to address these issues:

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# 1

As the principal funder of research in this area, STFC should examine the structure of its peer review mechanisms to ensure that interdisciplinary fields such as astroparticle physics are adequately and equitably represented in the funding and prioritisation process.

- There is concern that Science Board and the Projects Peer Review Panel sometimes lack the necessary expertise and breadth to adequately assess astroparticle physics projects presented to them. While it is recognised that membership of these committees is not based on *pro rata* representation of subfields, it is recommended that more consideration might be given to those with astroparticle physics expertise. By its nature, such expertise is broad, and so can be of particular use to the panels. The implementation of the Science Board non-core College of Experts is seen as progress, but at present the number of suitable experts assessing astroparticle physics projects is still too low.
- For projects requesting support for exploitation being assessed within the grants lines (i.e. at the Particle Physics, Nuclear Physics or Astronomy Grants Panels) early, clear definition of the specific grants line within which any new project is to be considered is strongly encouraged. Membership of the relevant grants panel should adequately reflect the assignment. The panel must be advised that the project does lie within its remit, and deferring a proposal to another panel should be avoided.
- The establishment of an astroparticle physics grants line is not recommended at this time, as given the present funding levels it would likely inhibit significant further investment in the field.

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# 2

STFC should seize upon the opportunities offered by the exceptionally strong communities of UK scientists working on the Cherenkov Telescope Array (CTA) and on the LUX-ZEPLIN dark matter project. Investment in these projects, enabling significant scientific leadership, would usefully broaden the research base, is likely to lead to revolutionary new science, and strongly complements other research within the STFC portfolio. This should not be at the expense of funding for gravitational wave research.

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## 3

This review recognises the importance of astrophysical neutrino physics and notes that strong synergies exist with the particle physics programme. While internationally this is a major pursuit, with several remarkable ongoing and future projects, effort in the UK is at a very low level. The UK could develop a coherent and successful effort in this area.

This review recommends that the community of scientists involved in astroparticle neutrino physics develop a more strategic approach to the area, aiming to establish major leadership of one or more projects through contributions that are numerically significant both in terms of personnel and capital. The IOP Astroparticle Physics and High Energy Particle Physics groups should provide assistance as required, for example, by convening dedicated, targeted or joint meetings and workshops.

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## 4

The UK community of astroparticle physicists should do more to establish scientifically meaningful collaborations between its subfields, building on its technical breadth to coherently tackle common scientific objectives. The recent “Violent Universe” meeting held at IOP was a good example that could be repeated. Additionally, the IOP Astroparticle Physics Group should lead the establishment of joint half- and one-day meetings between itself and the IOP High Energy Particle Physics and Gravitational Physics groups, and with the Royal Astronomical Society (RAS).

These recommendations are intended to address the urgent need for support of this distinct community, introducing much needed resilience against short-term fluctuations. Internationally, astroparticle physics is vibrant. Building on the rich history that the UK has in this discipline, the existing expertise of its scientists, and the ample opportunities for future leadership, a similarly flourishing UK astroparticle physics programme is a realistic vision. To achieve this success requires clearer management of the field, both in a “top-down” sense in the way the relevant funding agencies consider the discipline, and “bottom-up” in terms of how the community organises and coordinates itself. Inevitably, additional research funds will be required. In addition to gravitational waves, the review identifies two world-class projects within which a substantial UK involvement would have immediate scientific impact, rapidly providing much of the urgently needed transformation. A strategy for further medium-term development of the field is suggested. The long-term objective is to establish UK astroparticle physics as a robust, energetic and confident field, ensuring its visibility in the forefront of the dramatic and unparalleled scientific discoveries that astroparticle physics is fully expected to deliver.

## INTRODUCTION

A relatively new discipline, astroparticle physics encompasses two distinct but complementary approaches to modern science. In one, the universe is used as a source of radiation with which to conduct frontier investigations, while in the second, the radiations emanating from space and detected here on Earth are used as unique probes of distant astrophysical environments. For example, the highest energy particles known to exist hit the atmosphere at energies several orders of magnitude greater than those produced in the Large Hadron Collider (LHC), and thus allow, in principle, experiments in particle physics in an otherwise inaccessible energy regime. The origin of these particles remains a mystery, but is certain to involve extreme astrophysical environments. In this case, and more generally, astroparticle physics lies at the intersection of particle physics and astronomy, probing both the smallest and largest scales, and informing particle physics beyond the Standard Model, and astrophysics at the limit of our present understanding.

Not all areas of research are so easily defined, with demarcation between particle physics, astronomy and astroparticle physics remaining a challenge. The question of what the label “astroparticle physics” includes is thus not particularly well-defined, especially in an international context. In particular, it should be noted that even the term “astroparticle physics” is essentially interchangeable with the term “particle astrophysics”<sup>1</sup>. However, despite these differences, it is frequently noted that many astroparticle physics projects share a degree of commonality in

facility, location, scale or technical approach.

Within the UK, the situation is a little clearer, largely due to recent funding decisions. Subjects within the banner of astroparticle physics include the study of cosmic rays, direct detection of dark matter, gravitational wave research, and very high-energy gamma rays. Where experiments or observatories are sensitive to astrophysical neutrinos, this too is included, and within the context of the IOP Astroparticle Physics Group, nuclear astrophysics is also embraced. All of these areas are seen as within the STFC portfolio. New projects are funded through specific planning lines and, because no dedicated astroparticle physics grants line exists, exploitation of existing projects is variously funded through the grants lines of particle physics, astronomy or nuclear physics, or for gravitational waves, through a dedicated grants line. Oversight of the area, and long-term strategy, are considered by a Particle Astrophysics Advisory Panel that reports to STFC Science Board. For clarity, it should also be stated that theoretical cosmology is not included within astroparticle physics, so that subjects such as baryogenesis, dark energy and inflationary models are considered elsewhere, even though there is significant scientific overlap between the areas.

In 2006, in response to a widely recognised need for distinct UK representation of the field, the IOP Astroparticle Physics Group was formed. Its membership presently stands at more than 600, with activities mainly focused on the support of themed meetings and PhD student development.

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<sup>1</sup> Some commentators do see a distinction, but these opinions are not consistent

## THE SCIENCE

The UK has a proud tradition of astroparticle physics, with pioneering roles in all the main areas. Described below are those areas of most relevance to the UK community.

### 2.1. Cosmic rays

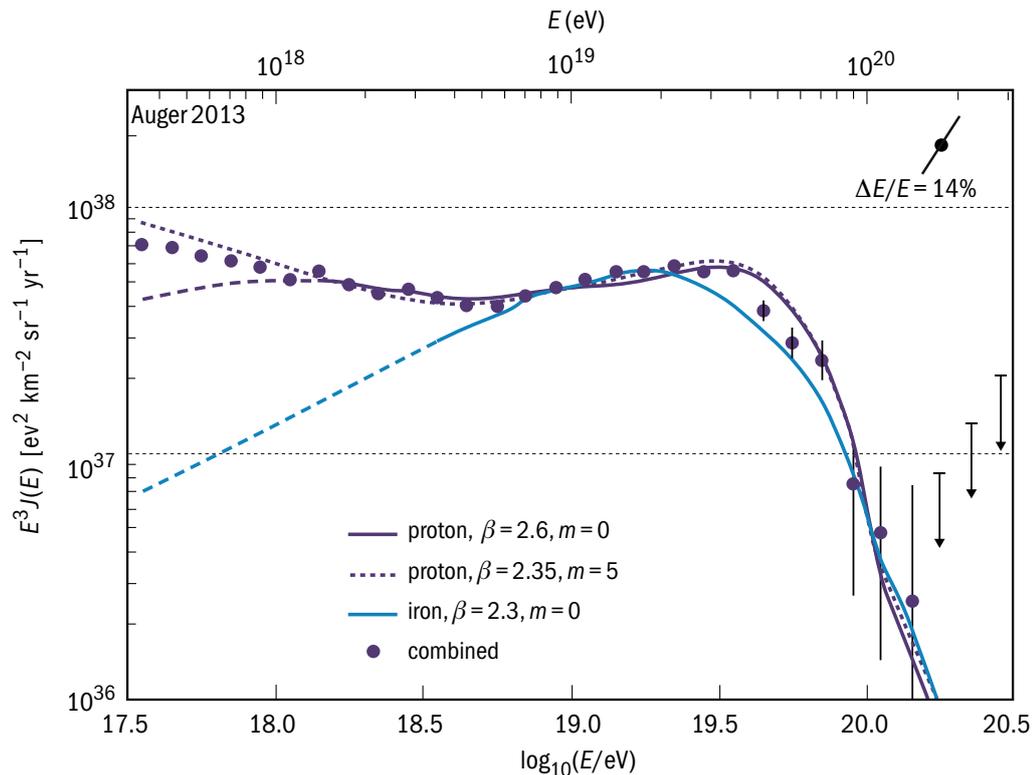
Cosmic rays are highly energetic particles that are naturally produced in deep space. They can be detected and studied as they slam into Earth's atmosphere. The energy of a single particle can reach tens of Joules – cramming the energy of Andy Murray's second serve into something smaller than a single nucleus. Such extremes are out of reach of man-made accelerators (such as the LHC) by factors of millions, so that the study of cosmic rays remains a crucial catalyst for progress in fundamental physics.

From its inception in 1912, the field has seeded rich spin-offs including modern particle physics, carbon dating, and an understanding of the role that electric currents play in Earth's weather. Although energetic gamma rays are a

component, the term “cosmic ray” is something of a misnomer: the majority are nuclei of the elements from hydrogen to uranium. Other significant and important components are electrons, positrons and neutrinos.

Today's most pressing scientific question relates to the origin and composition of the highest-energy cosmic rays, since these probe physics in extreme environments. **Figure 1** shows the measurements made with the Auger Observatory of the cosmic-ray spectrum in the region of  $10^{18}$ – $10^{20}$  eV. The standout result from this work is an upper bound on the energy of cosmic rays. This may indicate that the most extreme cosmic rays originate at distances of hundreds of millions of light years, but that those from the greatest distances are slowed on their way to Earth due to interactions with the cosmic microwave background (CMB). Alternatively, the rays may originate in our own cosmic neighbourhood, in which case the feature would be a reflection of a maximum energy generation capability.

**Figure 1:** Energy spectrum of the highest energy events detected by Auger, compared to models of possible primary cosmic ray composition. From A Schulz *et al* Proc. 33rd ICRC, Rio de Janeiro 2013



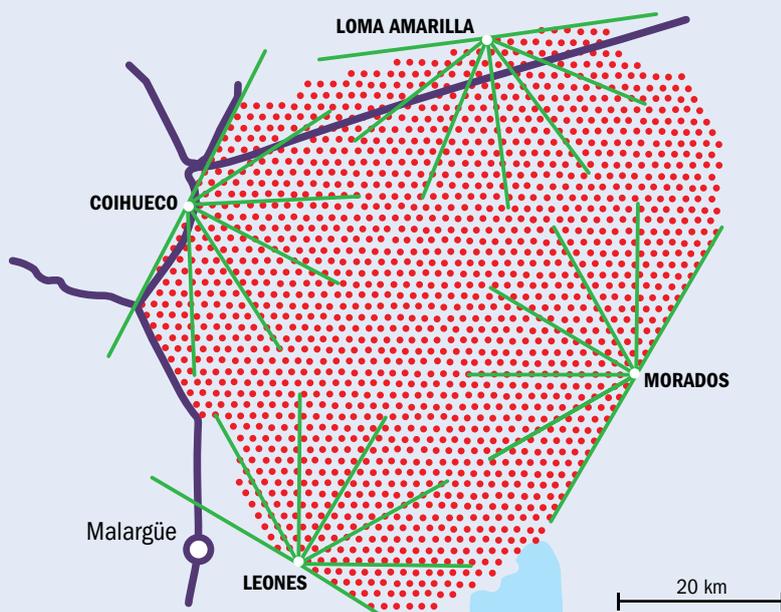
## 2.1.1. UK role

The UK's prominent role in the field was established early. C T R Wilson's cloud chamber – a device for making visible the tracks of electrically charged particles – was used in the discovery of the positron, the muon and the early strange particles. In 1927, Wilson was awarded the Nobel Prize in Physics for his invention, which was then further developed by P M S Blackett (Nobel Prize in Physics 1948). C F Powell (Nobel Prize in Physics 1950) developed a related technique using photographic emulsions, directly triggering the discovery of many other charged particles. The work of Blackett and Powell played a major role in establishing the strength of UK particle physics and our involvement with CERN.

When energetic cosmic rays strike the atmosphere, they produce huge numbers of secondary particles that spread over tens of square kilometres at ground level and lead to flashes of light known as Cherenkov radiation. The feasibility of detecting these with relatively simple equipment was first demonstrated at Harwell in the 1950s, using an array of detectors covering  $\sim 1 \text{ km}^2$ . This work has evolved in recent times to allow the study of high-energy photons or gamma-rays with energies around 10 GeV, leading to the involvement of many UK scientists in the HESS telescopes and to a major UK role in planning the world-leading CTA (see section 2.4).

The work on air showers at Harwell led in the 1960s to the creation of the British Large Air Shower Project at Haverah Park in Yorkshire where work continued until the late 1980s, yielding some of the best measurements of the energy spectrum and direction distribution of cosmic rays. The expertise developed there was translated directly to the ongoing success of an international project known as the Pierre Auger Observatory which covers  $3000 \text{ km}^2$  of western Argentina (see **figure 2**). UK scientists played a prominent role in the conception, the instrumentation and the development of the analysis methods of this project that is a joint project between 17 nations. The UK-developed data collection system collates information from 1600 sensors over an area the size of West Yorkshire. A commercial spin-off company licenses this technology to Network Rail, for example. Auger-like technology is used to make the single-track rail-lines in the Western Highlands safer and more reliable (see section 3.7).

UK physicists have also played a crucial role in the theoretical developments needed to relate the cosmic-ray observations to their likely sources. One strand of the work, diffusive shock acceleration, further manifests itself in shocks in the interplanetary medium and so has aided our understanding of space weather.



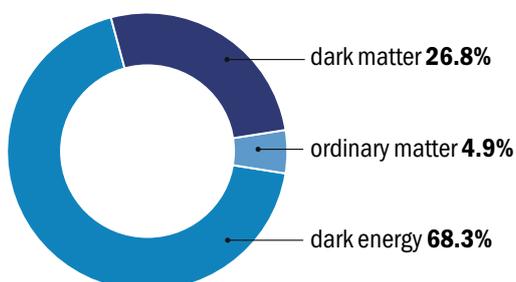
**Figure 2:** The geographical distribution of the Pierre Auger Observatory array components at the site in Argentina. The red dots indicate water tanks while the four air-fluorescence telescopes are indicated with green lines.

The map covers an area approximately equal to the area enclosed by the M25 motorway

### 2.2. Dark matter

Understanding the nature of dark matter is one of the most important challenges in modern physics. A vast array of astronomical observations – including the rotation of galaxies, the deflection of light around galaxy clusters and the patterns seen in the CMB – force us to the conclusion that just 5% of the universe is composed of ordinary matter. The remainder is thought to be a mixture of “dark energy” and “dark matter” (see **figure 3**). The latter seems to be a new type of particle that is ripe for experimental discovery, and as such, direct searches for dark matter are one of the main threads of astroparticle physics research.

**Figure 3:** The most recent measurement of the energy densities attributed to dark energy, dark matter and “ordinary” baryonic matter, as determined by the Planck satellite observations of the CMB [Ade *et al* *Astronomy & Astrophysics* (2014)]



Dark matter generates and feels the effects of gravity but is invisible, implying that the particles responsible do not respond to the electromagnetic interactions. That dark matter does not bind with atoms indicates it does not feel the strong force, and that we see its effects today means it must be stable (or at least nearly so). Neutrinos are the only known particle to have these characteristics, but they are too light to account for the missing matter. Consequently, dark matter cannot be made up of any Standard Model particles. While several viable candidates have been proposed, a particularly compelling example is known as the weakly interacting massive particle (WIMP) as a natural consequence of a deep but unconfirmed particle physics theory known as supersymmetry.

Dark matter is expected to be continuously streaming from space through Earth. The weak interaction will result in the occasional scattering of a dark-matter particle against an atom of a terrestrial material. The technological challenge of measuring these scattering events is formidable, requiring large detectors that are sensitive to extremely small and rare scattering events. Additionally, one must rule out all other sources of events. The detectors must be placed deep underground to escape cosmic muon-induced backgrounds, and complex strategies for active and passive shielding of environmental radiation must be developed. Yet the rewards for success are potentially immense, since dark matter constitutes our best pointer towards new physics beyond today's Standard Model.

#### 2.2.1. UK role

The UK is well-placed to build on its illustrious history in dark-matter technology. Since the 1970s it has commissioned many of the first projects using both cryogenic and xenon-based systems that continue to be at the core of today's detection strategies. It is particularly known for developing two-phase xenon devices (ZEPLIN) and direction-sensitive detectors (DRIFT).

The UK research programme was for many years exclusively based at the Boulby Underground Laboratory in the north-east of England (see **figure 4**). While the Boulby Mine is a fully operational commercial salt and potash mine, support from the owners together with a Joint Infrastructure Fund award has enabled the

construction of a world-class, fully equipped, 750 m<sup>2</sup> science laboratory, 1.1 km below ground. At this depth the cosmic-ray flux is reduced by a factor in excess of a million, in turn substantially reducing the flux of neutrons that otherwise might mimic dark-matter scattering events.

Today, the DRIFT collaboration continues to operate at the Boulby Underground Laboratory. The spin of Earth and its motion around the Sun lead to diurnal and annual changes in the arrival direction of dark matter. If seen, these would form a robust confirmation of the dark-matter nature of the signal. DRIFT is not funded as a project by STFC, but receives substantial support from US partners. It remains the leading



**Figure 4:** The Boulby Mine, a working salt and potash mine in the north-east of England, where much of the UK's dark matter research has been conducted

directional direct search instrument, but faces growing competition from collaborations such as NEWAGE, DM-TPC, MIMAC and D<sup>3</sup>. The UK has been a leader in this area – both in leading individual projects and in encouraging communication between teams through the establishment of the CYGNUS directional dark-matter workshops.

Boulby now also hosts part of the DM-Ice experiment, a NaI-based study to confirm or refute the findings of the DAMA/Libra project based at the Gran Sasso Underground Laboratory in Italy. For a number of years, this has detected a significant annual modulation signal, interpreted by some as evidence for the detection of the WIMP dark-matter wind. DM-Ice is currently testing individual NaI detectors underground at Boulby, prior to deployment at the South Pole. The project is presently funded by the US, but there is substantial influence and involvement from the University of Sheffield.

Another way in which Boulby is progressing astroparticle physics is through the development of world-class materials-screening capabilities. This will support current and future low background searches, such as those used in dark matter and neutrinoless double-beta decay experiments. Reduction of backgrounds

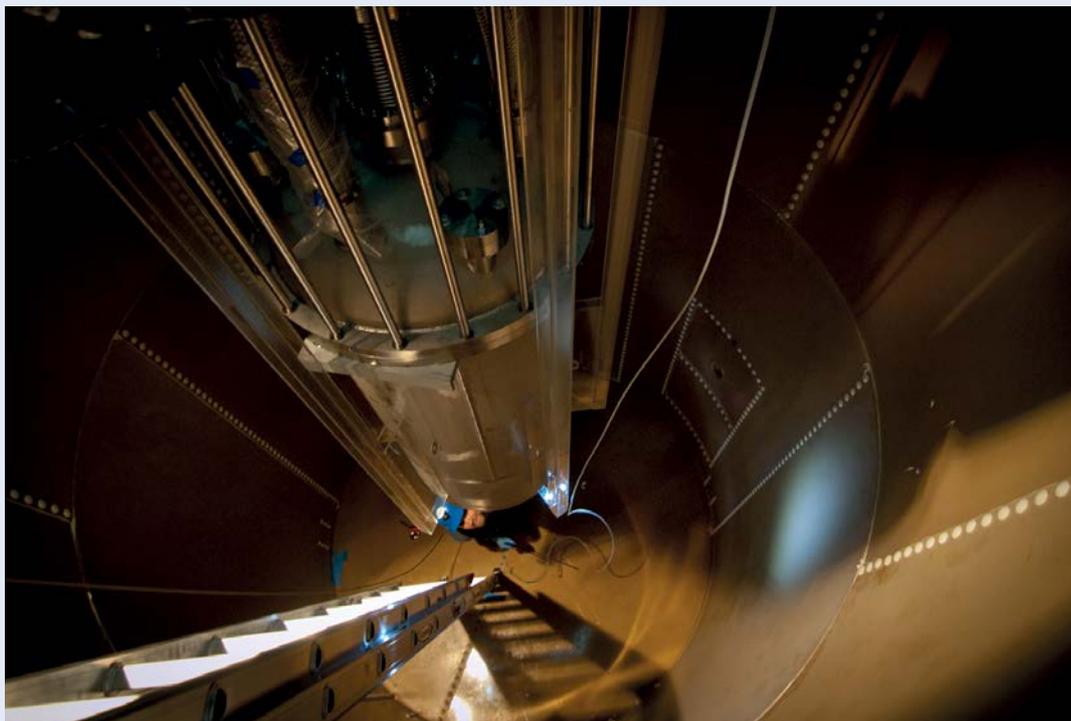
is essential for all current and future detectors of these types, and selection of low background emitting materials is an essential part of this. The facility currently has four ultra-low background high-purity germanium gamma-ray detectors, capable of screening materials for uranium and thorium at the ppb level. These are presently being used for screening of materials for the SuperNEMO and LZ projects, and will be available for other projects. Boulby is one of just a few sites in the world with the capability to do this.

Until 2012, the UK-led ZEPLIN collaboration operated a series of xenon-based instruments, also at Boulby. Liquid xenon is one of the most promising materials for a dark-matter detector. Its many excellent features include purity, density, the ability to produce both scintillation light and ionisation electrons following an energy deposition, and a remarkable ability to discriminate WIMP interactions from most other background types. The ZEPLIN programme contributed strongly to the development of this technology, setting some of the leading dark-matter interaction rate limits in the process.

In parallel with the ZEPLIN activities there was a significant effort to develop, construct and operate cryogenic bolometers using the detection of heat and scintillation (CRESST), or heat and

## 2: The science

<sup>2</sup>Phys. Rev. Lett. **112** (2014) 091303. <http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.112.091303>



**Figure 5:** The LUX direct dark matter detector (based in South Dakota), viewed from above during initial commissioning of the experiment. Image credit: P. Phelps, luxdarkmatter Flickr

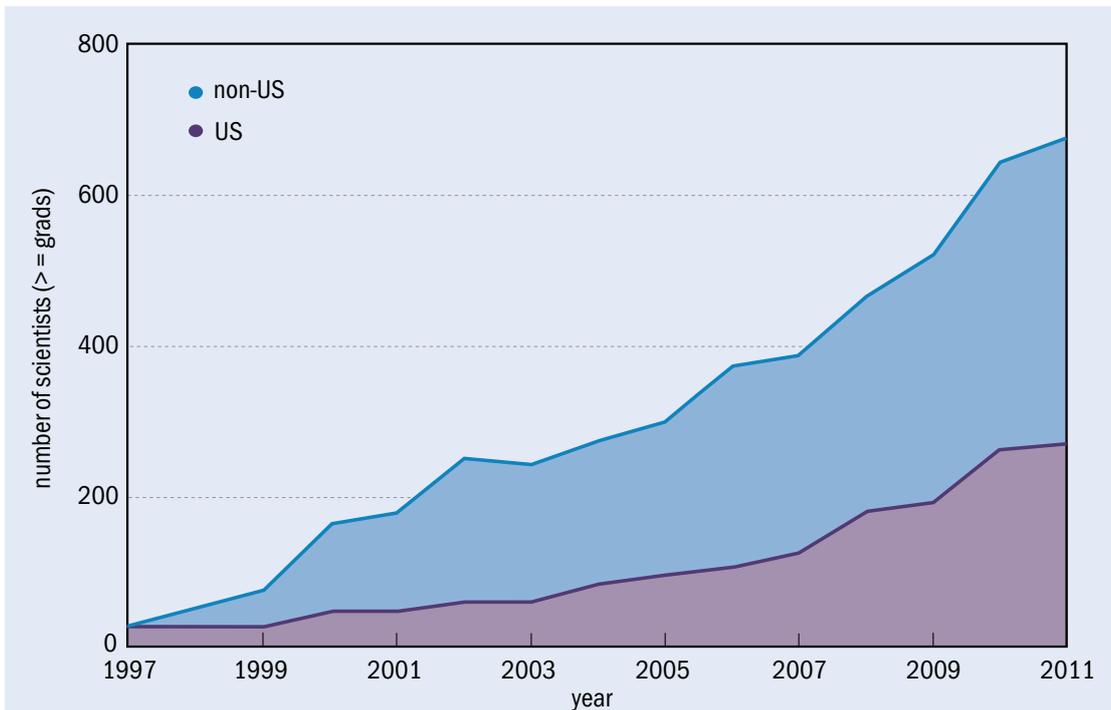
ionisation (EDELWEISS). UK groups played a key role in a conceptual design of the proposed cryogenic facility for WIMP searches, EURECA.

At the cessation of the ZEPLIN programme, several of the UK groups (Edinburgh, Imperial and UCL), supported by local institutional funding, joined the Large Underground Xenon (LUX) project (see **figure 5**). In late 2013, the team announced a world-leading sensitivity that, for lower mass WIMPs, improved on previous results by a factor of more than 20, significantly rejecting suggestions of signals in other devices. The findings that have been published<sup>2</sup> are exceptionally highly cited. A longer, more sensitive exposure of the instrument is planned for 2015, with discovery potential for much of the parameter space favoured by models of minimally symmetric supersymmetry.

Other UK activity in direct dark-matter searches is directed towards the DEAP and miniCLEAN experiments, single-phase liquid argon detectors located in the SNOLAB facility, Canada. The emphasis of the UK work is on distinguishing neutron scattering backgrounds from dark-matter interaction signals and on techniques to calibrate such devices. The current work on the DRIFT directional technology is complemented by an alternative R&D directional

project, DMTPC, where the use of CCD cameras enables the actual imaging of recoil tracks, potentially providing improved recoil information.

Despite rapid growth in the size of the international community (see **figure 6**), the scale, and thus cost, of future instruments means there will be some consolidation within the field. Indeed, in 2008, the ZEPLIN and LUX collaborations signed an MoU targeted at a longer-term joint programme, to be known as LUX-ZEPLIN. Consistent with the recommendations made in an STFC review of dark matter (Tovey *et al* 2012), the wider UK community has now also chosen LUX-ZEPLIN as the focus of its attention, while retaining expertise in other areas. In addition to the former ZEPLIN groups, academics from CRESST, EDELWEISS and elsewhere have joined the LUX-ZEPLIN effort, and it now represents the main focus for direct search activities in the UK. In the US, a major “down-select” process has been completed, and has also chosen LUX-ZEPLIN as the main project for investment for traditional WIMP-type dark matter searches. Scheduled for construction at the beginning of 2016, the device will reach an exquisite sensitivity, limited only by neutrinos from the Sun.



**Figure 6:** The growth in the number of scientists working in the area of direct dark matter detection (reproduced from figure 4 of the Snowmass CF1 Summary: WIMP Dark Matter Direct Detection, <http://arxiv.org/pdf/1310.8327.pdf>)

### 2.3. Gravitational waves

Gravitational waves (also called gravitational radiation) offer a completely new view of the universe. They are a prediction of Einstein's General Theory of Relativity that describes gravity as the curvature of space-time by matter and energy. While a body of indirect evidence supports their existence, such as the decay of the binary pulsar PSR 1913+16, which led to the award in 1993 of a Nobel Prize in Physics for Hulse and Taylor, projects are only now about to reach the sensitivity required to detect their direct effects. The ability to measure them routinely would give us an entirely new way of studying far-off, exotic objects – sources include the mergers of compact objects (such as neutron stars), cosmic strings and black holes.

As they travel through space, gravitational waves generate a regularly varying tidal strain, meaning that a ring of particles is alternately stretched and squeezed (see **figure 7**). Any asymmetric acceleration of mass will emit gravitational waves, but because gravity is a weak force, very large masses and relativistic motion are required

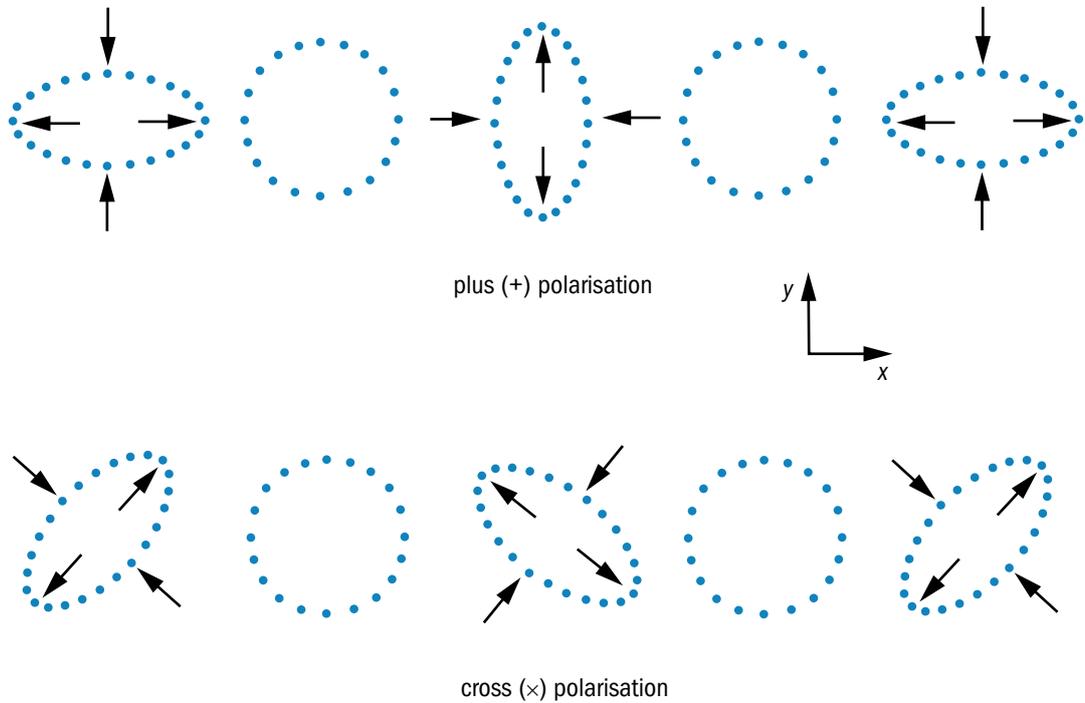
for significant tidal strain. To fulfil both these requirements the sources must be compact and dense, even in astrophysical terms. Accordingly, measuring gravitational waves will inform us about the extremes of the universe.

Just as the electromagnetic spectrum comprises visible light as well as infrared, ultraviolet, radio waves and so forth, the gravitational window on the universe can also be divided into different regimes, as shown in **figure 8**. Each of these requires a different detection technology.

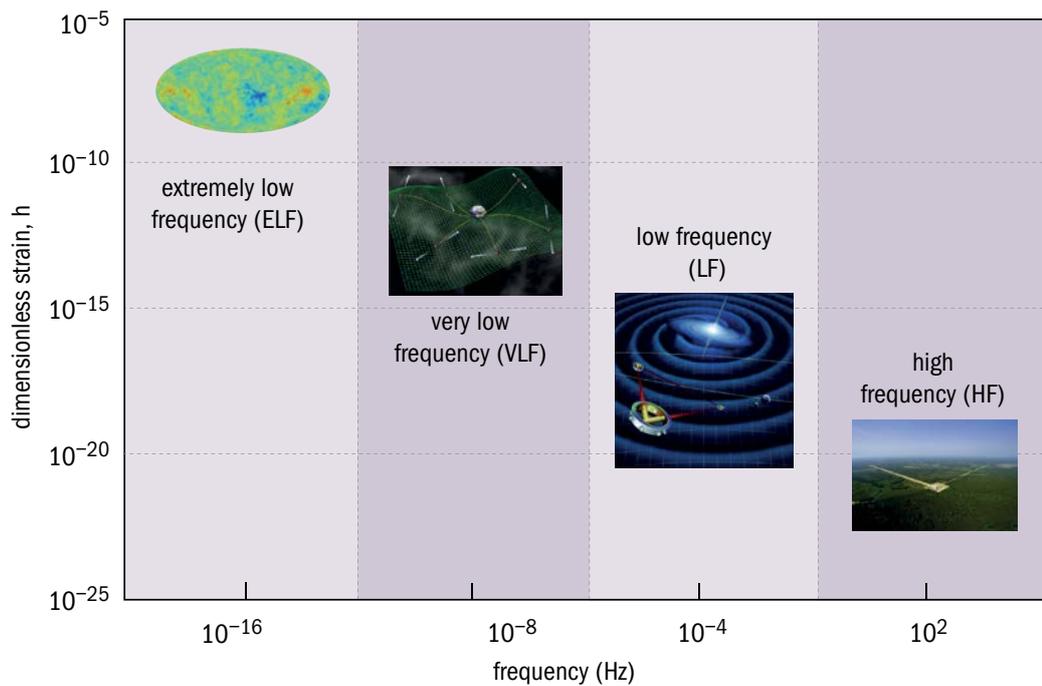
At extremely low frequencies (ELF) and very low frequencies (VLF), gravitational waves are detected through relatively indirect means. ELF signals could be imprinted into the CMB and would be observable via polarisation of the microwave photons. A much-publicised detection recently claimed by the BICEP2 collaboration appears to have been premature, but hopes of firm evidence through joint analysis with Planck remain. At VLF, gravitational waves may be observable by looking for nanosecond-irregularities in the otherwise regular timing of pulsars and correlating these to look for waves passing through our galaxy.

## 2: The science

**Figure 7:** The effect of a gravitational wave (travelling into the page) on a ring of free test masses. The “plus” [+] polarisation and “cross” [×] polarisation are orthogonal to one another



**Figure 8:** The gravitational wave spectrum from low to high frequency. The y-axis is the dimensionless strain parameter,  $h=2\Delta L/L$ , which describes the tidal strain between free falling test masses

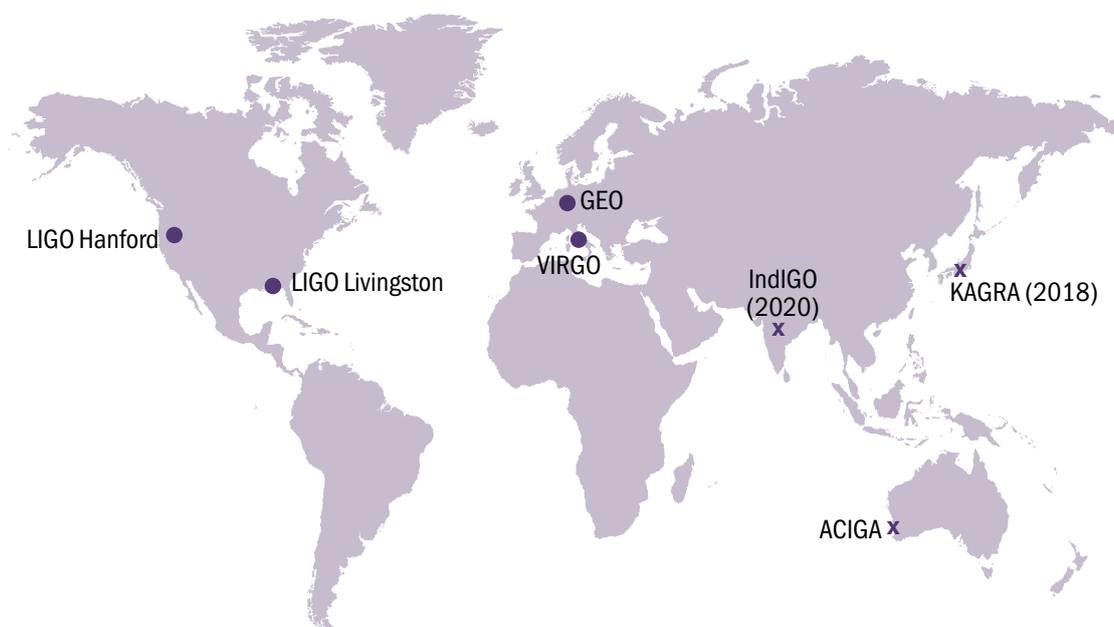


In the low frequency band (0.1 mHz – 1 Hz) sources include intermediate and supermassive black holes millions of times more massive than the Sun. Opening this band would therefore allow us to make a census of the cosmic black hole population and its history. The frequency range is accessible via space-based detectors; the Evolved Laser Interferometer Space Antenna (eLISA) has recently been selected by the European Space Agency (ESA) for launch in 2034, guaranteeing major technology development investment in the interim period. These missions use freely floating test masses separated by a few billion kilometres and detect deviations at picometre resolution, requiring drag-free satellites to eliminate all sources of confusion. A pathfinder mission will launch in 2015 to test some of the required technology. Airbus Defence and Space, based in Stevenage, is the primary contractor, with software support from SciSys UK. A number of UK universities are collaborating with the project, including Glasgow, Birmingham and

Imperial College London. There is significant UK leadership, for example, with Glasgow providing the LISA pathfinder optical bench.

In the high frequency (10 Hz – 10 kHz) regime, sources include the final inspirals of binary neutron stars before they coalesce, or stellar-mass black holes. Ground-based interferometers provide a strong prospect for detecting such sources in the near future (2016/17), supplementing our existing astronomical observations to develop a multi-faceted approach to understanding the extreme universe. The international ground-based network (see **figure 9**) comprises GEO600, a joint UK/German detector near Hannover, Germany, with 600 m folded arms; the US Advanced LIGO (Laser Interferometer Gravitational-Wave Observatory) detector with 4 km arms located at sites in Hanford, Washington and Livingston, Louisiana, and the Virgo detector in Cascina, Italy with 3 km arms. The KAGRA detector in Japan will have 3 km arms and is currently under construction in the Kamioka Mine.

**Figure 9:** The International network of gravitational wave detectors. IndIGO (the Indian Initiative in Gravitational-Wave Observations) is the proposed site for the third Advanced LIGO detector (network operation by 2020). KAGRA is a cryogenic detector currently under construction in the Kamioka Mine, Japan, with operation by 2018. ACIGA is a high-laser-power interferometric facility in Australia



## 2: The science

### 2.3.1. Detector technology

The field has gone through a variety of technological advances such that detectors are now approaching the sensitivity necessary to monitor test masses to  $10^{-18}$  m (1/1000<sup>th</sup> the diameter of a proton) over a baseline of 4 km. This results in a strain sensitivity of  $\approx 10^{-22}$  (at 10 Hz), which is the typical strength of signal from a binary pulsar in the Virgo supercluster of galaxies.

Initial attempts to construct a detector to observe gravitational waves were made by Joseph Weber in the 1960s. Weber used resonant bars, consisting of a suspended aluminium cylinder and an array of piezoelectric transducers, to monitor the displacement in the narrow frequency range around the bars' resonance. Building on this initial work, bar detectors including ALLEGRO (Louisiana, US), EXPLORER (CERN), NAUTILUS (Frascati, Italy) and NIOBE (Perth, Australia) have incorporated improved seismic isolation systems, multi-stage seismic isolation systems, superconducting transducers and low-temperature operation (<100 mK) to further improve their strain sensitivity. In parallel, pioneering work in the 1960s by Weiss and Forward led to a new detection paradigm based on interferometric sensing of suspended test masses. This had the benefit of providing broadband operation from tens of Hz to a few kHz. The interferometers that form the current

international network are based on a Michelson topology (GEO) with Fabry–Pérot cavities in the arms (LIGO, VIRGO, KAGRA) to enhance the light storage time. They are the most sensitive length-measuring devices in the world.

Joint observations between the LIGO/VIRGO/GEO sites took place from 2007 until 2010, placing important upper limits on gravitational waves from astrophysical sources. These first-generation interferometers have provided a wealth of astrophysical upper limits on potential sources of gravitational waves, including setting limits on the level of gravitational emission from the Crab and Vela pulsars, and constraining gamma-ray bursts (GRBs) in the direction of M31.

The international network is currently being upgraded to the advanced network (GEO-HF, Advanced LIGO, Advanced Virgo) which includes modifying many of the subsystems (lasers, seismic isolation and mirror suspensions). This will provide an order of magnitude increase in broadband sensitivity and an event rate increase by  $\times 1000$ . First direct observations are expected in 2016/17 and this will open up the gravitational window on the universe. Together with astroparticle detectors, including those detecting neutrinos and high-energy gamma rays, the field of multi-messenger astronomy will be born.

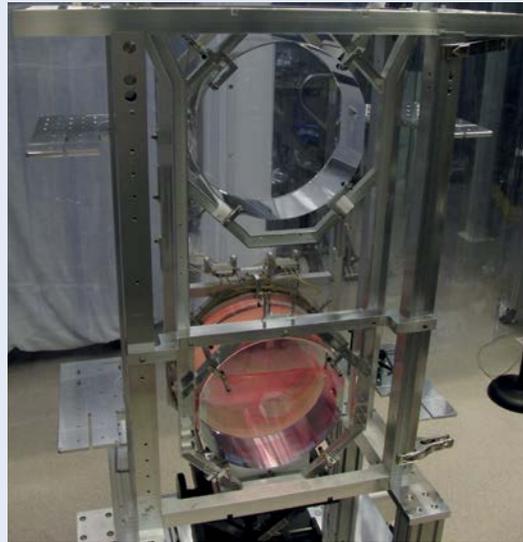
### 2.3.2. UK role

The UK groups involved in gravitational wave science (universities of Glasgow, Cardiff, Strathclyde, West of Scotland, Birmingham, Sheffield, Cambridge and the Rutherford Appleton Laboratory) have carried out research across the full spectrum of experimental gravitational wave instrumentation and interferometry. The Glasgow and Cardiff groups are co-founders of the GEO600 collaboration, with significant investment from the UK research councils underpinning state-of-the-art experimental laboratories. Experimental expertise in the areas of low thermal noise optics/suspensions and advanced optical topologies for interferometers has shaped and continues to define the worldwide field of gravitational wave detection. In particular, the UK led the design, R&D, construction and installation of the ultra-low-noise suspensions currently in operation in GEO600 and Advanced

LIGO (see **figure 10**). These suspensions are essential to push the lowest operating frequency of the detectors to 10 Hz. The UK also plays an internationally leading role in R&D focused on low-thermal noise optical coatings for gravitational wave detectors at room and cryogenic temperature, and in new interferometer topologies and optical techniques (e.g. optical springs), and it has pioneered the use of Bayesian inference for gravitational wave data analysis. In the field of analysis, there are two current and two outgoing LIGO scientific collaboration data analysis working group co-chairs in the UK (Glasgow and Cardiff). The Cardiff group is one of the world's largest and most active in compact binary coalescence source searches and is also active in searches for unmodelled bursts. The Glasgow group focuses on unmodelled burst searches and searches for continuous wave sources. The Birmingham group

is also very active in compact binary coalescence analysis work. The Sheffield group focuses on real-time and rapid response searches and electromagnetic follow-up in the optical and the radio wavebands. In the optical waveband, GOTO is a new UK-based project led by Warwick to create a dedicated optical follow-up instrument for gravitational wave searches. There are also extensive source-modelling activities at Cardiff, Southampton and Cambridge.

**Figure 10:** The Advanced LIGO monolithic lower-stage pendulum suspension was developed, installed and commissioned by researchers within the UK. Image credit: University of Glasgow

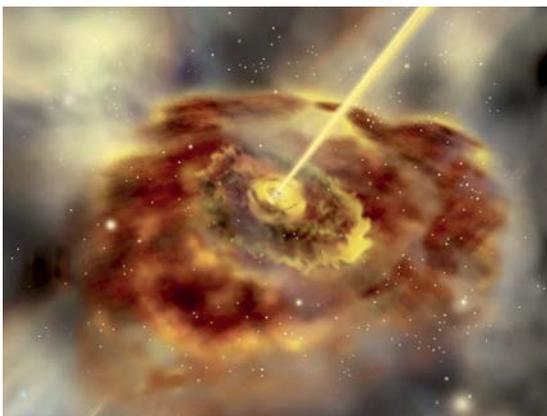


#### 2.4. Very-high-energy gamma rays

Very-high-energy (VHE) gamma rays constitute the highest-energy electromagnetic radiation used for astronomical investigation. Studying their propagation can shed light on ideas from galaxy formation to particle physics and quantum gravity. Their generation is deeply entwined with the acceleration of particles to near-light speed in shock waves and astrophysical jets, processes that are poorly understood.

In fact, the impact that high-energy particles can have on their environments, by providing a source of pressure and helping to generate and sustain

**Figure 11:** An artist's impression of an active galactic nucleus, in which a supermassive black hole at the centre of a galaxy drives powerful emission over much of the electromagnetic spectrum, including very-high-energy gamma rays. Image credit: ESO



magnetic fields, is crucial to our understanding of giant molecular clouds, star clusters, galaxies and galaxy clusters. Gamma-ray observations of objects such as supernova remnants, active galactic nuclei (AGN) and GRBs are required to understand these systems.

Meanwhile, the interaction between gamma rays and cosmic radiation fields provides an absorption signature that can be used to infer the density of the extragalactic background light, and hence constrain models of galaxy evolution and structure formation. Current observations of AGN are starting to challenge the expected lower limits to this effect, which may mean that the models should include interaction with magnetic fields inducing oscillations. This would provide evidence for the existence of new, light, spin-zero bosons or other axion-like particles. Additionally, gamma rays are a unique probe of theories of quantum gravity that predict an energy-dependent speed of light: observations of AGN and GRBs would show a dispersion in the arrival time of photons, with current measurements leading to an upper bound on this effect.

Finally, VHE gamma rays also have a role to play in the search for dark matter. WIMP annihilation is expected to produce gamma-ray emission, and a number of systems have been suggested as good candidates for such emission, including the galactic centre, dwarf spheroidal galaxies, and nearby galaxy clusters. A dark-matter signal from a gamma-ray telescope would provide key information on the distribution of the dark matter and the nature of the dark-matter particle.

### 2.4.1. UK role

Gamma rays are difficult to detect, since they do not propagate to ground level, cannot be reflected or refracted, and are rare. At lower energies, from a few 100 MeV to a few tens of GeV, it is usual to employ a satellite-based telescope, such as the current Fermi instrument. However, the collection area of the Fermi Large Area Telescope is only  $\sim 1\text{m}^2$ , which means that the detection rate above 100 GeV is very low. At very high energies, typically from a few tens of GeV to a few hundred TeV, a different technique must be employed.

The key to the detection of VHE gamma rays is the realisation that such gamma rays entering Earth's atmosphere will create air showers and Cherenkov radiation, in a similar manner to hadronic cosmic rays (see section 2.1). The remaining difficulty is the presence of an overwhelming background of Cherenkov radiation produced by hadronic cosmic rays.

The very first VHE gamma-ray telescope was constructed at Harwell in the UK in the 1950s. Several generations of telescopes were then created in the 1970s and 1980s, by scientists in the UK and elsewhere, which demonstrated the basic feasibility of the technique.

UK scientist Michael Hillas demonstrated that it is possible to use simple imaging techniques to extract the gamma-ray events from the cosmic-ray-induced events. This led directly to the creation of much more sensitive telescopes, including the current MAGIC, VERITAS and HESS (see **figure 12**) telescopes, the latter two with a substantial UK involvement (e.g. 13 people in HESS). These have succeeded in opening this new window on the universe, demonstrating imaging capability at these energies and high sensitivity to transient events, and extending the catalogue to some 150 objects.

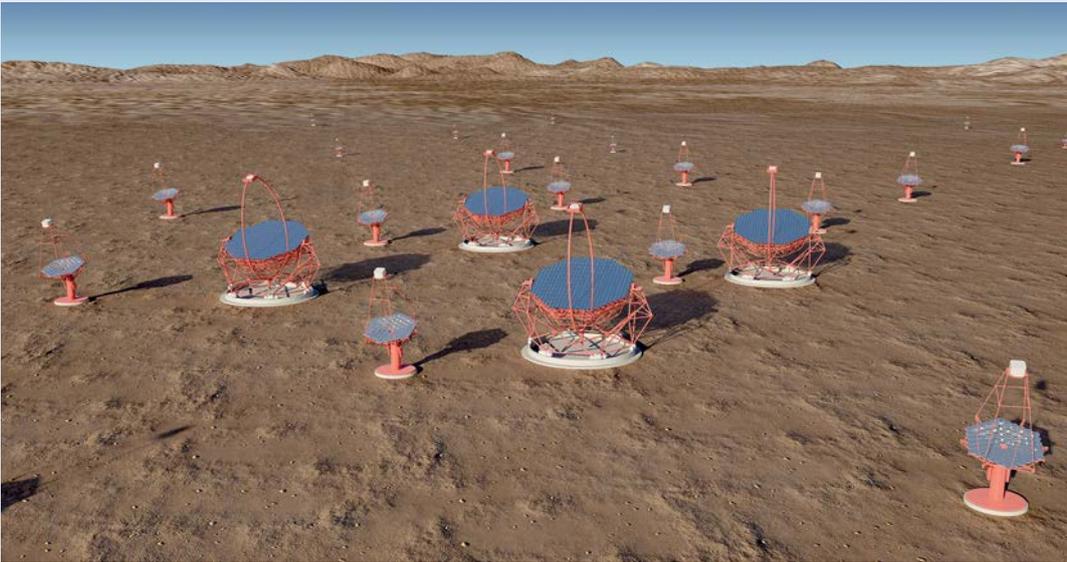
The next-generation instrument, CTA (see **figure 13**), will provide greatly enhanced capability over current instruments, having better angular and energy resolution, greater energy reach, and higher sensitivity across the board. The recent success of VHE gamma-ray astronomy has attracted more than 1000 scientists from 29 countries, including the UK, to CTA, and for the first time we will have an open observatory for the exploration of this important waveband. CTA will consist of two arrays of telescopes,

one in the northern hemisphere and one in the southern hemisphere. The exact layouts of the arrays are presently the subject of simulation studies, but the southern array will be the larger of the two, consisting of around four large-sized telescopes of 23 m diameter, designed to detect the lowest energy gamma rays from a few tens of GeV to a few hundred; around 20 medium-sized telescopes of 12 m diameter, designed to cover the range from 100 GeV to a few TeV, and more than 70 small-sized telescopes (SSTs) of about 4 m diameter, which will detect gamma rays from a few to several hundred TeV.

Groups in the UK at the universities of Durham, Leicester, Liverpool, Liverpool John Moores and Oxford are working on the design and construction of the SSTs. These telescopes present an interesting technical challenge. Ideally, the SSTs should have a wide field of view, around  $10^\circ$  across, but this is difficult to achieve with conventional single-mirror instruments. The UK team has therefore pioneered an innovative dual-mirror design, which is able to use the latest in detector technology to create a small (35 cm in diameter) camera that nonetheless supplies the required field of view. The prototype telescope, built with colleagues in France, Japan, Germany, Australia, the Netherlands and the US, will be undergoing field trials in 2015. These groups, together with others from Edinburgh, Hertfordshire, King's College London, Nottingham, Sheffield and Southampton, are also framing the scientific priorities for this exciting new observatory.



**Figure 12:** The Milky Way as imaged by HESS, superimposed on the night sky above one of the HESS telescopes. Image credit: F Acero and H Gast



**Figure 13:** An artist's impression of the fully deployed southern hemisphere CTA, consisting of four large-sized telescopes, about 20 medium-sized telescopes and upwards of 70 small-sized telescopes. Image credit: G Perez (IAC, SMM), CTA

### 2.5. Astrophysical neutrinos

Extreme astrophysical environments are expected to be prodigious sources of neutrinos. In 1987, about two hours before a visible explosion was seen, a total of 24 neutrinos were detected from supernova 1978A during a period of less than 13 seconds, confirming the Type-II supernova core-collapse mechanism. The light was delayed due to the time required for the underlying explosion to propagate to the surface of the blue supergiant star. No correlation between neutrino energy and neutrino arrival time was seen. This allowed an upper limit on the mass of the neutrinos to be set ( $10\text{--}20\text{ eV}/c^2$ ), since if they had significant mass, more energetic neutrinos would have arrived earlier than the less energetic ones. More recently, the IceCube neutrino observatory located in the Antarctic ice has found the first solid evidence for astrophysical neutrinos from cosmic accelerators, a discovery that has been described as “the dawn of a new age of astronomy”.

As with gamma rays, neutrinos are particularly attractive astrophysical messengers. Without charge, they should be unaffected by magnetic fields, and thus their arrival direction allows imaging of their source. This is of particular relevance for studies of ultra-high-energy cosmic rays (see section 2.1). Here, the arrival directions may be able to discriminate between alternative models of sources that can generate particles

of energies up to  $10^{20}\text{ eV}$  – for example, AGN or GRBs. Neutrinos have much smaller interaction probabilities compared to gamma rays and can traverse large thicknesses of matter on their way to Earth, informing us about the properties of particle accelerators in the deep universe.

Other sources of neutrinos include the debris of high-energy particles hitting Earth's atmosphere, where the production of hadrons and muons and their subsequent decay generates neutrinos. Lower-energy neutrinos are produced in the nuclear reactions taking place in the core of the Sun. Both these types of neutrinos have been detected, for example, in the Kamiokande/Super-Kamiokande and Sudbury Neutrino Observatory (SNO) detectors, the latter with a strong involvement of UK groups. The deficit in the flux of observed solar neutrinos, compared to that expected, led to the discovery of neutrino oscillations. With three types of neutrinos, there are two mass differences – observations of solar neutrinos constrain one of these mass differences, while observations of atmospheric neutrinos constrain the other.

Several UK groups have made a prominent contribution to the initial stages of the ANTARES and KM3Net projects, both in hardware and software. These activities, however, have gradually come to an end following cessation of STFC and other funding for these projects.

From the perspective of fundamental particle physics, neutrino physics is seen as a promising route to exploring physics beyond the Standard Model. The access that neutrinos provide to flavour physics has resulted in a significant programme within the scope of the UK particle physics community, with major recent activity involved in the long baseline neutrino project MINOS and now T2K. A major role in the next-generation long-baseline neutrino facility is hoped for, with work having started on Hyper-Kamiokande and the Long-Baseline Neutrino Experiment (LBNE) at Fermilab. The potential absence of neutrinos in double-beta decay, enabled if the neutrino is its own antiparticle, is another significant theme of research, with substantial contributions to projects such as SuperNEMO. The UK has a major role in the successor to the SNO project, SNO+, and contributed the idea of replacing the heavy water with a Te-loaded liquid scintillator, providing one of the best opportunities for observation of neutrinoless double-beta decay. Although these projects are conducted within the particle physics programme, the detectors and the measurements do retain some astrophysical relevance.

A low level of UK activity is maintained in some explicitly astrophysical neutrino projects. The Antarctic Impulsive Transient Antenna (ANITA) experiment, is a balloon-borne radio-interferometer that flies high above Antarctica searching for signals from ultra-high-energy neutrinos interacting in the ice below. This international collaboration of scientists from three countries is attempting to turn the entire continent into a gigantic telescope to probe the furthest reaches of the universe using neutrinos.

A flight of 22 days' duration was recently completed. In a similar vein, the Askaryan Radio Array (ARA) is a project to instrument the Antarctic ice with radio substations, listening for the tell-tale signals of high-energy neutrinos from GZK processes impacting the ice. Short-term Leverhulme Trust support has been secured for the UK contribution to this project, which is developing a trigger system for the experiment. In another new initiative, scientists at the University of Manchester and at QMUL have joined the Precision IceCube Next Generation Upgrade (PINGU). This aims to develop a closely packed array of sensors within the heart of the IceCube array, enabling a reduction of systematic uncertainty and thus improved calibration. Overall, the primary goal is to measure the neutrino mass hierarchy. Both these areas

illustrate how astrophysical neutrinos may be used as the source for front-rank physics experiments. The work is not currently funded by STFC.

### 2.6. Nuclear astrophysics

Although not usually thought of as an area of astroparticle physics, nuclear astrophysics is included within the remit of the IOP Astroparticle Physics Group, promoting interaction between these closely related communities. The subject aims to provide understanding of the origin of the chemical elements and the energy-generation mechanisms in stars. Typically, low- and medium-energy particle accelerators are used to determine relevant nuclear properties. Combined with hydrodynamic simulations, detailed stellar models may be developed. This allows the comparison of computed observables of features such as light curves, X- and gamma-ray emission spectra, and ejecta abundances with real observations. Short-lived (i.e. explosive) phenomena, such as novae, X-ray bursts and supernovae are the result of nuclear reaction processes that themselves occur on similar timescales, and thus involve similarly short-lived (i.e. radioactive) nuclei. The quest to understand these objects has contributed to the recent development of radioactive beams, for example, at CERN's ISOLDE facility, the TRIUMF facility in Canada, and FAIR, the major European initiative in Germany. The nuclear reactions involving stable nuclei lead to much more slowly evolving astrophysical objects, most importantly the stars that populate the main sequence such as our own Sun. These reactions are very slow, and thus very hard to measure. In the same way that this means rare-event searches in astroparticle physics need to be located deep underground, now too are some low-energy accelerators. The most prominent example is LUNA, which is operating very successfully at the Gran Sasso laboratory in Italy.

A new facility, DIANA, is planned for the Homestake Mine in the US. Within the UK, the dominant contributions in this area come from scientists at the universities of Edinburgh, York, Surrey and Birmingham, with technical support provided by the Nuclear Physics Group at Daresbury Laboratory. The overlap in techniques and subject matter make the inclusion of nuclear astrophysics within the remit of the IOP Astroparticle Physics Group valuable. Further details on UK research in this area can be found in the 2012 IOP report, *A Review of UK Nuclear Physics Research*<sup>3</sup>.

### 2.7. Interfaces with other communities

Astroparticle physics is an intrinsically international discipline. UK scientists are actively involved in, and there is strong STFC support for, the Astroparticle Physics European Consortium (APPEC). Correspondingly, the UK research priorities tie in well with the European Strategy for Astroparticle Physics<sup>4</sup>. Additionally, the work has specific impact in, and takes input from, several other fields of physics.

From the experimental perspective, the discipline employs techniques that intermesh with astronomy, nuclear physics and particle physics, including the use of telescopes, beamlines and time-projection chambers, together with all the associated ancillary equipment. To strengthen links, annual meetings of the IOP Astroparticle Physics Group are held together with the IOP High Energy Particle Physics Group. Additionally, dedicated astroparticle physics sessions are held each year at the National Astronomy Meeting, organised and sponsored by the IOP Astroparticle Physics Group.

From a facility perspective, the UK's Boulby Underground Laboratory is closely associated with the other EU and world laboratories through formal and informal joint initiatives, networks and communications. The Boulby Underground

Laboratory is recognised as one of the world's important sites for leading ultra-low-background astroparticle physics studies (and other deep underground science) and strong communication between the world's laboratories persists.

Underpinning astroparticle physics research is a robust theoretical framework, spanning particle physics phenomenology to cosmology. In particular, the field motivates, and takes inspiration from, extensions to the Standard Model of particle physics. In combination with astrophysical theoretical work these, for example, set detailed technical requirements for dark-matter detection programmes and motivate study of particles arriving at Earth (see sections 2.1–2.5).

Computing is a vital tool for experimental and theoretical progress. High-performance computing facilities, especially the UK's DiRAC system, are vital for the particle physics and cosmology communities. A number of consortia compete for time on these facilities to run internationally leading research programmes that impact strongly on global astroparticle research. For example, the Virgo and Horizon consortia lead the field in setting expectations for the distribution of dark matter, while the UKMHD collaboration studies the complex magnetic fields that control the propagation of cosmic rays.

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<sup>4</sup> *European Roadmap for Astroparticle Physics, an ASPERA/APPEC Roadmap, 2008, [www.appec.org/strategy/roadmap.html](http://www.appec.org/strategy/roadmap.html)*

## THE HEALTH OF UK ASTROPARTICLE PHYSICS

<sup>5</sup> *Funding methodologies in European astroparticle physics research*, 2nd edition, an ASPERA report, November 2011, [www.aspera-eu.org/images/stories/frontpage/census2011.pdf](http://www.aspera-eu.org/images/stories/frontpage/census2011.pdf)

In this section we consider the health of UK astroparticle physics. A key contribution to our assessment comes from an international survey that was commissioned by IOP and a census of present UK astroparticle physics research, the analysis of which is presented in Appendix 2, p38. A further resource used is the *Funding methodologies in European astroparticle physics research* report of ASPERA<sup>5</sup>, a network of national government agencies responsible for coordinating and funding national research efforts in astroparticle physics. ASPERA has now finished, but is succeeded by APPEC, of which the UK, through STFC, is a member.

### 3.1. International relevance and reputation

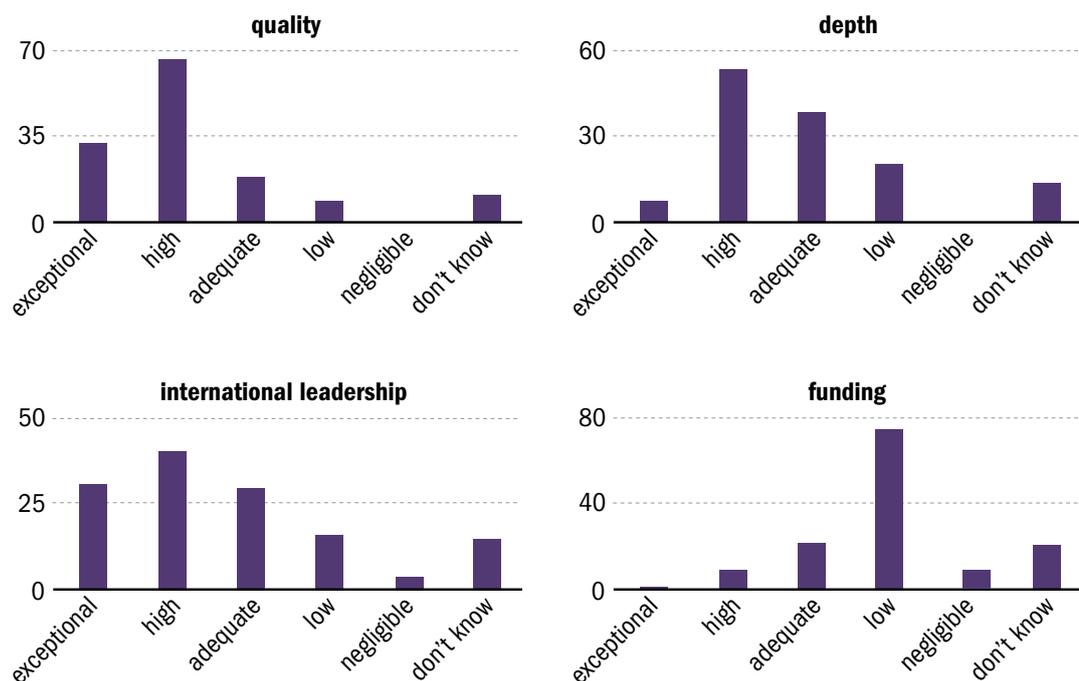
The international survey conducted to gain input for this report received a total of 164 responses from 25 countries. About half the respondents thought they were “highly” aware of UK astroparticle physics research with most of the remainder having a “medium” level of awareness. The areas of expertise of the respondents covered all areas of astroparticle physics and included members of all

the relevant major international projects.

It is clear from the survey that the UK astroparticle physics community is highly regarded. This is evidenced by the responses to a set of questions on quality, depth and international leadership of UK astroparticle physics research, presented in **figure 14**. The vast majority of those responding thought the UK astroparticle physics community was of either high or exceptional quality, and the depth of the research was either high or adequate. Over half thought that the UK community exhibited either high or exceptional levels of international leadership. However, the response to the funding level for UK astroparticle physics research was particularly striking, with the vast majority of respondents describing this as low.

Compared to 10 years ago, the general opinion of the UK community is that its research excellence has improved and that it is at least as innovative as it has been. For many years the UK has been leading in international working groups, conducting pioneering research responsible for many breakthrough discoveries. Individual researchers and working groups are highly regarded and the

**Figure 14:** Responses from the international survey exploring the quality, depth, international leadership and funding of UK astroparticle physics



number of new developments from UK groups and the leadership positions of UK scientists is much higher than would be expected based solely on the size of the community.

The survey asked what the most exciting developments in astroparticle physics had been in the past 10 years, and then asked what the level of the contribution of UK scientists had been to these successes. From the responses it is clear that the rapid and substantial progress made in neutrino physics and gravitational waves has deeply impressed the community, while significant awareness in high-energy gamma rays, dark matter and cosmic-ray physics is also recognised. As a clear indication of the strong standing of the UK community, the most common response was that UK scientists were seen to be at the forefront in an innovative way in all the leading developments.

Similarly, the international survey then queried what people thought would be the most exciting development in astroparticle physics in the next 10–15 years, and what the expected level of the UK role would be in these areas. Dark matter and gravitational waves are seen as the most exciting future topics and, again, the expectation is that the UK will have a leading role in these areas.

**3.2. Size and scope of the UK community** A census of UK academic institutions was performed (see Appendix 2) and revealed that at present there is a total of 29 full-time equivalent (FTE) permanent academics working on astroparticle physics in the UK, scattered over 17 institutions. Eleven of these FTEs are concentrated in two universities – Glasgow and Sheffield. A further six FTEs of temporary academic staff (e.g. fixed

term lecturers) and 5.1 FTE of emeritus staff were reported. Research fellow and postdoctoral support is significantly stronger, with nine and 39 positions presently active, respectively. A total of 59 PhD studentships were reported, with over half supported through the research councils. There are 10 FTEs of technical support (e.g. engineering) and a total of six FTEs of other support staff (e.g. computing and secretarial/admin). The comparator communities in the UK are those within STFC science programme areas: nuclear physics, particle physics and astronomy. The most recent UK-wide census from which data are available is from 2008, and is presented below in **table 1**. The number of UK academics working in astroparticle physics reported here is broadly in agreement with the 29 FTE reported in this review’s census. Clearly, the astroparticle physics community is the smallest, especially when one considers that since 2008 it is understood that there has been a steady growth in the number of academics across the UK.

We welcome the current model adopted in the Ernest Rutherford Fellowship scheme where there is good representation across all science themes in STFC funded research. The panel highlight that the mechanism used to award fellowships; panel specific shortlisting followed by interviews, works well to provide breadth across the areas of astronomy, astroparticle physics and particle physics. It is likely one of the successes of this mechanism is sufficient representation of all fields at the interview stage, which further highlights the importance of this review’s first recommendation (see p35).

<sup>6</sup> Survey of Academic Appointments in Physics 2004–2008, an IOP report, January 2010, [www.iop.org/publications/iop/2010/page\\_38419.html](http://www.iop.org/publications/iop/2010/page_38419.html)

<sup>7</sup> Survey of Academic Appointments in Physics 1999–2004, an IOP report, February 2005, [www.iop.org/publications/iop/archive/page\\_52057.html](http://www.iop.org/publications/iop/archive/page_52057.html)

<sup>8</sup> 15.2 Statistics Paper 3: New Academic Appointments, an IOP Briefing Note, November 1999

**Table 1:** Numbers of UK physicists in STFC science programme areas. Data are shown for academics (professors, readers, senior lecturers and lecturers) and fellows (research fellows, experimental officers and senior experimental officers). Sources<sup>6–8</sup>

	Total	Academics	Fellows
Astroparticle physics (2013)	44	35	9
Nuclear physics (2008)	65	50	15
Particle physics (2008)	278	221	57
Astronomy (2008)	407	307	100

# 3: The health of UK astroparticle physics

<sup>9</sup> *Funding methodologies in European astroparticle physics research*, 2nd edition, an ASPERA report, November 2011, [www.aspera-eu.org/images/stories/frontpage/census2011.pdf](http://www.aspera-eu.org/images/stories/frontpage/census2011.pdf)

<sup>10</sup> *Bibliometric evaluation and international benchmarking of the UK's astroparticle physics research*, an IOP report, April 2014, available on request

<sup>11</sup> *Bibliometric evaluation and international benchmarking of the UK's physics research*, an IOP report, January 2012, [www.iop.org/publications/iop/2012/file\\_53967.pdf](http://www.iop.org/publications/iop/2012/file_53967.pdf)

An international perspective to the numbers of people working in astroparticle physics is explored in the *Funding Methodologies in European Astroparticle Physics Research* report of ASPERA<sup>9</sup>, with results from that report reproduced below in **table 2**. The reported value for the UK (245 people) is surprisingly large, but it is noted specifically for this entry that: “*the reported numbers include very likely contributions from neighbouring fields (astronomy, astrophysics, elementary particle physics and nuclear physics)*”, at least in part explaining the dramatic difference with the UK census numbers. Indeed, particle cosmology was at that time included within the STFC definition of astroparticle physics. Therefore, it seems likely that the UK astroparticle physics community is *very significantly* smaller than comparator European countries, with France, Italy, Germany and Spain having much larger fractions of scientists working in this area. In Germany, for example, the ratio of those working in particle physics to those working in astroparticle physics, is 2.2:1.

**Table 2:** The size of astroparticle physics communities by country, reproduced from an ASPERA report<sup>9</sup>

\*The reported numbers include very likely contributions from neighbouring fields (astronomy, astrophysics, elementary particle physics and nuclear physics)

Country	Astroparticle physics personnel
Belgium	24
Switzerland	72
Czech Republic	29
Germany	584
Spain	338
France	712
Greece	61
Croatia	18
Hungary	21
Italy	650
The Netherlands	43
Poland	58
Portugal	38
Romania	7
Sweden	37
United Kingdom	245*

Some evidence for the impact of a smaller community is seen in the international survey, where it was asked how the depth of the UK astroparticle physics compared with equivalent research in other countries. Some 40% thought this was high, but 44% thought the depth was moderate or low. This is better than one might have expected given the relative size of the UK community.

An alternative metric of the distribution between fields of UK physicists may be taken from the membership levels of IOP groups. This must of course be treated with caution, and perhaps reflects more the areas of interest rather than the areas of activity. Interestingly, the numbers of members of the relevant IOP groups presently stand at 897 (nuclear physics), 865 (high energy particle physics), 583 (gravitational physics) and 648 (astroparticle physics) – a much more even distribution.

### 3.3. Research output

In support of this review, IOP commissioned Thomson Reuters to perform a bibliometric analysis of UK astroparticle physics research<sup>10</sup>. The findings present the UK community, given its size, as an outstandingly strong contributor to the field. UK authors appeared on 17.5% of all astroparticle physics papers published in 2012, up from 14.2% in 2003. The UK's output has grown at a faster rate, 69.5%, than the world total, 37% and its citation impact is also growing. The Thomson Reuters study found that while UK astroparticle physics research is performing strongly, there are other countries that perform just as well and are in the process of rapid expansion. It is worth noting that a previous study<sup>11</sup> by the same company for IOP looking at UK physics overall found that the UK share of publications was reducing due to strong growth in the Asia region – astroparticle physics is bucking this trend.

### 3.4. Facility usage

In modern astroparticle physics, experimental research is conducted predominantly on medium-to large-scale dedicated international facilities. For example, present direct-search dark-matter projects are typically at the scale of a few million pounds, with future proposals including facilities at the £10–40 million scale. In high-energy gamma rays, CTA has an anticipated budget of approximately €200 million. The Advanced LIGO is expected to cost upwards of US\$200 million, while the space-born LISA will be significantly more expensive.

**Figure 15:** The ultra-low-background material screening facilities at the Boulby Underground Laboratories



The UK has, at Boulby, one of the world's important deep underground science facilities, capable of hosting ultra-low-background astroparticle physics projects and/or running support projects for astroparticle physics studies hosted elsewhere. Its 1.1 km depth provides shielding equivalent to 2800 m of water, attenuating the cosmic-ray muon flux by around a factor of a million, compared to the flux at the surface. The rock within which the laboratory is located is itself relatively low in radioactivity, resulting in ambient background gamma ray and radon levels amongst the very lowest of all the underground laboratories. All current science projects at Boulby are located in the Palmer Laboratory – a 1000 m<sup>2</sup> footprint facility supported by communications, air filtration, lifting and transportation facilities. The facility also houses a growing ultra-low-background germanium detector facility for material screening (down to sub-ppb levels), see **figure 15**. With the current underground laboratory now more than 10 years old and suffering some degradation due to local rock movement, STFC has recently granted funds to build a new underground laboratory at Boulby. This new laboratory has a similar footprint, but is taller (up to 7 m high) and wider (7 m wide) than the current Palmer Laboratory. It is presently under construction and will be completed by late 2015.

### 3.5. Funding

Within the UK, funding for astroparticle physics research falls within the remit of STFC. The senior body of STFC is its Council. The principal scientific advisory body reporting to Council is Science Board, whose “purpose is to provide STFC with a strategic scientific overview and assessment of, and science advice on, all of the programmes STFC supports. It is supported by advisory panels (including a Particle Astrophysics Advisory Panel), peer review committees and other advisory committees.”<sup>12</sup>

STFC regularly conducts Programmatic Reviews aiming to ensure it is providing a programme of science balanced between areas and within a realistic financial planning envelope. A prioritisation for projects and science areas is performed and is then used in deciding whether planning provision should be made within the programme for a given area or project, and as part of the process of deciding the size of any such provision. The most recent review, reported in 2013<sup>13</sup> makes several comments regarding astroparticle physics research. In particular we highlight Recommendation 15: “We recommend that maintaining involvement in gravitational wave, dark matter, and high energy gamma ray experiments be a priority for the sake of the diversity of the UK programme.”

<sup>12</sup> [www.stfc.ac.uk/696.aspx](http://www.stfc.ac.uk/696.aspx)

<sup>13</sup> [www.stfc.ac.uk/files/programmatic-review-report-2013](http://www.stfc.ac.uk/files/programmatic-review-report-2013)

### 3: The health of UK astroparticle physics

<sup>14</sup> Funding methodologies in European astroparticle physics research, 2nd edition, an ASPERA report, November 2011, [www.aspera-eu.org/images/stories/frontpage/census2011.pdf](http://www.aspera-eu.org/images/stories/frontpage/census2011.pdf)

Annex G of the Programmatic Review is the report of the sub-group that actually conducted the review for Science Board. This discusses the methodology, the findings and, importantly, their anticipated impacts. Several funding scenarios were considered, and under the flat-cash scenario that subsequently transpired, the sub-group noted: *“It would not be possible to retain a leading UK involvement in both CTA and direct dark matter searches. Both these areas are high priority and the UK has recently invested in them, and future planning would depend upon the length of time over which a flat cash budget was imposed.”*

For actual funding decisions, for all new projects, the Projects Peer Review Panel provides advice and recommendations. Funding for projects in their exploitation phases, and additional advice in funding matters, is provided by grants panels. While there are grants panels for nuclear physics, particle physics and astronomy, there is at present no grants panel for astroparticle physics. Projects are instead considered within the Particle Physics Grants Panel, or the Astronomy Grants Panel, as

perceived to be appropriate. Gravitational waves research is funded via a consolidated grants line.

Anecdotal evidence from the community suggests the above arrangements are not entirely satisfactory. For some projects, especially those most clearly straddling the particle physics/ astronomy boundary, there has been a lack of clarity as to which grants panel should consider their proposals. There is further concern that the grants panel chosen then did not have the full capability and/or willingness to adequately evaluate the research. At a higher level, instances have been raised of inconsistencies at Science Board, with contradictory feedback from successive meetings, and with feedback from the advisory and grants panels. Overall, there is a feeling within the community that the relatively small size of the community and the projects it works on, and the low membership of astroparticle physicists on the key scientific review committees, has resulted in astroparticle physics research being overly squeezed, with a disproportionate loss of breadth.

**Table 3:** The level of funding of astroparticle physics communities by country, reproduced from an ASPERA report<sup>14</sup>

Country	Population (M)	Astroparticle physics budget (M€)	Budget/population (€/person)
Belgium	10.8	0.85	0.08
Switzerland	7.8	5.93	0.76
Czech Republic	10.5	0.51	0.05
Germany	81.8	49.56	0.61
Spain	46	16.7	0.36
France	64.7	59.40	0.92
Greece	11.3	2.65	0.235
Croatia	4.4	0.48	0.11
Hungary	10	0.336	0.03
Italy	60.3	57.7	0.96
The Netherlands	16.6	5.35	0.32
Poland	38.2	Not communicated	
Portugal	10.6	0.448	0.04
Romania	21.5	0.56	0.03
Sweden	9.3	3.0	0.32
United Kingdom	62	11.52	0.19

Responses from the UK Census indicated that the total funding awarded from RCUK sources between academic years 2006/7 and 2012/13 (inclusive) was £23.767 million, i.e. £4 million a year, while the total funding awarded from industry and other sources over the same period was £9.464 million, i.e. £1.6 million a year. The ASPERA report<sup>14</sup> provides a snapshot of European funding levels in the year 2009, and its findings are reproduced in **table 3**. The figure reported for the UK is broadly consistent, but again shows the level of support for astroparticle physics to be significantly lower than that in comparator nations such as France, Germany, Italy or Spain. This confirms the perception of low funding of astroparticle physics found in the international survey.

### 3.6. Education, training and inspiration

From the unimaginable heat of the Big Bang, to black holes and supernovae, the most violent events in the universe are the most exciting. Streaming across space, the messengers from these cataclysmic events may yet hold the keys to unlocking the deepest secrets of nature. In the next few years, driven by experimental advances, a revolution in our understanding of the cosmos can be confidently predicted. Gravitational waves will be detected, opening an entirely new window on the universe. The next generation of dark matter search devices are reaching the sensitivity at which a signal may be seen. Very-high-energy gamma ray astronomy will be transformed by the building of CTA. Research in these topics is the very definition of curiosity-driven science, naturally lending itself to the inspiration of a new generation of scientists.

The principal mechanism of education and training in astroparticle physics is the PhD (or DPhil) doctoral degree. In the UK, a PhD will typically take between three and four years to complete, and requires the student to perform and document novel research of publishable quality. Typically, associated with the PhD would be several peer-reviewed scientific papers, with the student first (or corresponding) author.

The census conducted for this review reported a total of 59 studentships across the community, corresponding to around 15–20 PhDs in astroparticle physics research being awarded each year. Precise destination statistics for these researchers are not available, but are known to include postdoctoral research associate positions and research scientist positions in defence, the energy sector (including the nuclear industry),

nuclear medicine, engineering and scientific consultancy. These employment opportunities reflect the skills developed in the PhD, including specialist and detailed knowledge of technical instrumentation, a wide variety of radiation detection methods, numerical analysis, modeling and simulation. Many astroparticle physics projects now involve the use of large and complex data sets, leading to experience in data science and big data. The environment within which astroparticle physics research is typically conducted, i.e. sizeable international collaborations that require coordination, management and focus, develop important softer skills that may be equally valued, such as communication, time-management, problem-solving and the willingness and maturity to accept responsibility.

The excitement of the topic is easily communicated and recognised, such that the field has an extremely healthy public outreach component. Astroparticle physics features strongly on mainstream media, including, for example, contributions to recent television programmes such as the BBC 4 *Light and Dark* series, and BBC 2's *Horizon* and *The Sky at Night*. On radio, recent examples include BBC Radio 4's *Today* programme and *In Our Time*, BBC Radio Scotland's *Newsdrive*, the BBC World Service and National Radio New Zealand.

The UK astroparticle physics community is also providing input to outreach activities targeted at the key 12- to 16-year-old audience. For example, CERN@school is a research and engagement programme that brings CERN technology into the classroom, enhancing physics teaching and providing huge motivation for school students by enabling them to partake in authentic scientific research. Built around Timepix, a hybrid silicon pixel detector developed by the Medipix Collaboration, CERN@school gives students access to a ground-based detector (via the IOP's Physics Teacher Network) and LUCID (the Langton Ultimate Cosmic ray Intensity Detector<sup>15</sup>) deployed aboard the Surrey Satellite Technology Limited (SSTL) satellite, TechDemoSat-1. The five detectors should be capable of providing measurements of cosmic rays encountered in its Sun-synchronous, ~640 km altitude orbit as it surveys the Low Earth Orbit (LEO) space radiation environment. The first data from LUCID was received in December 2014, providing initial electron and proton measurements from regions including the polar electron belts and the South Atlantic Anomaly.

<sup>15</sup> <http://cernschool.web.cern.ch/content/lucid>

## 3: The health of UK astroparticle physics

Beyond the aforementioned examples, additional activities include:

- Public talks at local astronomical societies.
- Exhibitions, both within the UK and on an international stage.
- Web-based resources, including games and teaching resources.
- School talks, summer internships and work experience.
- Undergraduate projects involving students in research.

These activities are essential for inspiring and attracting young people to study STEM subjects and promoting STFC-related physics among undergraduates. This in turn is essential to underpin the future scientific workforce.

Recently, it has been agreed that STFC will be taking responsibility for APPEC outreach activities. This will likely include the website, newsletter, media communications and publications. We welcome this development.

### 3.7. Wider contributions to science, industry and the economy

Astroparticle physics is an area of core research that probes matter, gravity and energetic particles/photons from the most extreme and violent events in the universe. The field is underpinned by a

vibrant and diverse theoretical and data-analysis community, and maintains an internationally competitive programme of hardware development focused on precision low-noise instrumentation, optical techniques and high-performance detector technology.

The field aims to answer fundamental questions on the nature of the universe, including:

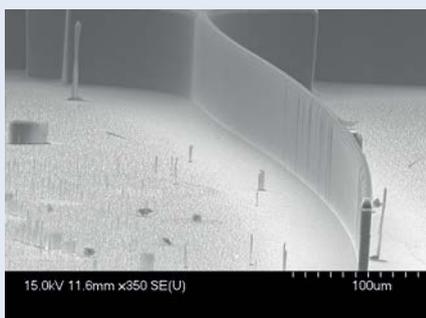
- How did the universe begin and how is it evolving?
- What are the fundamental constituents and fabric of the universe and how do they interact?
- How can we explore and understand the extremes of the universe?

However, the impact of the field on wider society and the economy goes well beyond these core science questions. Forefront research in physics pushes the boundaries of what is possible, with resulting economic and societal benefit. Cutting-edge technology developed for astroparticle physics can be used in applied themes that have strong links to industry and the societal challenges such as energy, environment, healthcare and security. This in turn has a direct economic impact and is essential for a healthy knowledge economy. Examples of some activities that are being transferred from the astroparticle physics sector are highlighted in the following case studies.

### Case study 1: Oil and gas sensing

The development of the ultra-low-noise suspensions used on gravitational wave interferometers has provided the technology necessary to push the operating bandwidth of oil and gas detectors down to 10 Hz, while providing unsurpassed thermal noise performance via the use of fused silica.

One application of this work is the development of novel low-frequency MEMS-based devices, for example, as shown in **figure 16**, suitable for potential borehole gravity surveying. Current gravimeters are bulky instruments and can cost in excess of £100,000. This imposes significant constraints on the number of devices that are deployable, and limits them to surface operation. By utilising expertise



**Figure 16:** A MEMS accelerometer prototype device. Image credit: Richard Middlemiss, Institute for Gravitational Research

in the development of thermal noise modeling techniques and the use of silicon at cryogenic temperatures, researchers from the gravitational wave community are developing new MEMS-

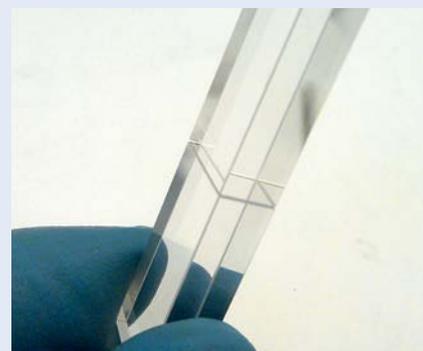
based gravimeter technology capable of performing at a similar level to the more traditional gravimeter. There is significant interest in this from industrial leaders of gravity instrumentation and surveying, and it has the potential to lead to a transformative new technology, with applications in the societal areas of:

- Defence: dense object detection, or the monitoring of subterranean tunnels.
- Energy: maximum extraction of resources and targeted drilling applications.
- Environment: monitoring underground repositories including CO<sub>2</sub> capture and nuclear waste.

### Case study 2: High-performance bonding

The need for ultra-stable mechanical structures for both the ground-based and space-based gravitational wave community has led to the further development of hydroxide catalysis bonding. First developed for the GP-B mission, and then transferred to Glasgow, this technique enables high thermal and mechanical jointing of materials with a native oxide, or those that can have an oxide grown on them. Such a technique has found potential applications in wide-ranging fields including:

- Bonding piezo actuators for potential use in deformable telescope mirrors.
- Bonding of sapphire samples to enable an ultra-high-stability joint with an almost identical refractive index, leading to applications for high-power lasers.
- Working with defence companies on the development of silicon carbide bonding for potential applications in high-performance shielding.



**Figure 17:** Bonded samples of sapphire. Image credit: Marielle van Veggel, Institute for Gravitational Research

### Case study 3: Screening of radioactivity

The need for future instrumentation for dark matter searches to be constructed from components of exceptionally low radioactivity has resulted in fruitful collaborations between UK astroparticle physicists and several UK-based companies.

Canberra UK Ltd is one of the UK's leading suppliers of low-background, high-purity germanium (HPGe) detectors for gamma-ray spectroscopy, delivering instrumentation for nuclear safety, security and environmental monitoring applications. Driven by the need for improved sensitivity, UK astroparticle physicists have used the

low-radioactivity environment of the Boulby Underground Laboratory to evaluate a new product line of broad-energy germanium (BEGe) detectors. The partnership is looking to enhance Canberra's own proprietary and industry-leading HPGe/BEGe software, providing better mitigation of gamma-ray backscattering and higher accuracy estimates of detector efficiency.

Both BEGe and HPGe detectors require customised lead and copper shields, themselves constructed from low-radioactivity material. Customised shielding with reproducible configuration is key to minimising

systematic uncertainty. Collaboration with Lead Shield Engineering Ltd is leading to the optimisation of shield thicknesses, novel layered structures, interlocks to prevent line-of-sight through the shield, nitrogen-flushed inner cavities, and retractable roofs for sample input and retrieval. This knowledge exchange is enhancing the research capacity, knowledge and skills of the organisation. The castle designs have already migrated to shields that the company will be constructing for the Atomic Weapons Establishment (AWE).

### 3: The health of UK astroparticle physics

#### Case study 4: Railway safety

One of the challenges faced in creating the Pierre Auger Observatory was how to collect data from more than 1600 water-Cherenkov detectors deployed on a 1500 m grid over an area the size of Lancashire in a remote part of Argentina's Mendoza Province. It was necessary to identify occurrences of cosmic-ray signals within a few microseconds of each other at three or more adjacent detectors with a 3 W power budget at each station. The communication between the data centre and the individual detectors and the readout of the detectors required purpose-built instrumentation. A cutting-edge system was developed by a group of electronic engineers and physicists from the University of Leeds using ideas adapted from mobile-phone technology. The instrumentation was designed and built in Leeds and deployed in Argentina between 2000 and 2004. It has operated successfully since then. The budget for this aspect of

the project, funded by the former PPARC, was around £1 million, considerably less than a quotation from Australian Telecom of \$12 million for a system that would have been less flexible and difficult to adapt economically. The 2001 report<sup>16</sup> from an international review panel stated: "The difficult issue of communication between the 1600 surface detector stations and the Auger campus has been solved with brilliance using a custom radio design."

Building upon the success of the communication system for cosmic-ray research, one of the leaders of the effort, Paul Clark, left the University of Leeds in 2004 to set up his own company, Comms Design Ltd. This firm has been very successful. Its first contract with Network Rail used the concepts developed for the Pierre Auger Observatory to make the single-track rail lines in the Scottish Highlands safer and more reliable. The outdated Radio Electronic Token Block system then in

use was upgraded and since November 2010 the new RETB radio system has been deployed more than 700 km of track in rural areas following extensive tests and after gaining the necessary approval certificates.

The total potential benefit is hard to quantify, but the cost of the new RETB system is approximately 10% of that of conventional signalling. The new design is "infrastructure-light" in terms of trackside equipment and cabling, and also sidesteps the growing problem of cable theft that plagues modern railways. This may make an RETB-like system attractive for all railway lines – not only the remote, single-line tracks. The new hardware will also likely be used in other areas of the UK, and might well become the standard for the next 30 years. The three most senior people working in Comms Design were involved for many years in the development of the radio system for the Pierre Auger Observatory.

<sup>16</sup> *International Review of the Auger Project*, [http://tdserver1.fnal.gov/auger/reviews/fbr/fbr\\_summary-report.pdf](http://tdserver1.fnal.gov/auger/reviews/fbr/fbr_summary-report.pdf)

**Figure 18:** Government Minister of State for Energy, Michael Fallon MP, listens to UK astroparticle physicists explaining the muon tomography for the CCS project, during a visit to the Boulby Underground Laboratory



### Case study 5: Muon tomography

Carbon capture and storage (CCS) is seen as an important component of a long-term solution to the rise in carbon dioxide (CO<sub>2</sub>) emissions into the atmosphere. A major source of CO<sub>2</sub> is the burning of fossil fuels. The concept here is to capture the CO<sub>2</sub> during power generation, compress it into a fluid, and transport it to be stored, typically 0.8–3.5 km beneath the sea bed in depleted oil or gas fields, or in saline aquifers. It is estimated that this process could reduce emissions from fossil fuel power stations by up to 90%. However, a challenge with CCS is having the ability to measure how full the underground storage sites are, and to understand where the CO<sub>2</sub> will migrate once stored underground.

The current method of monitoring storage sites – 4D seismic surveying – is episodic and expensive. One potential alternative is muon

tomography, whereby muons generated by cosmic rays impacting the atmosphere are used to image the storage site. Atmospheric muons have high enough energy to penetrate deep into the Earth's surface. A large array of muon detectors, as used frequently in astroparticle physics projects, may be used to measure the intensity of the muons, with higher fluxes indicating a reduced density in the material above the detector. This is the same principle used in medical X-rays, except with the stored CO<sub>2</sub> replacing the bones, atmospheric muons replacing the X-rays, and muon detectors replacing the photographic plate. A collaboration of scientists from the universities of Sheffield, Durham and Bath is working with colleagues at the Boulby Underground Laboratory and Caltech on this project. As a proof of principle,

caverns at the Boulby Mine have been instrumented with plastic scintillator muon detectors, and are testing whether the change in the depth of water due to tides can be measured in this way. Separately, a detector designed for borehole installation in carbon-capture sites is also being developed and tested at the Boulby Underground Laboratory. The UK's Minister of State for Energy, Michael Fallon, visited the project in June 2014 to see the progress of the project (see **figure 18**), which is co-funded by a grant from the Department of Energy and Climate Change (DECC), Premier Oil and Gas and STFC. The next stage of the project will be to instrument boreholes in North Sea oilfields and other potential sites proposed for CO<sub>2</sub> storage. The researchers are aiming to develop a working prototype by 2015.

### 3.8. Summary

In this section, the overall health and relevance of astroparticle physics research in the UK has been reviewed. Input has been taken from a new international survey of scientists, a national census of activity, a bibliometric study of peer-reviewed research publications, and from other sources.

We find that the contribution by UK scientists to the field is extremely highly regarded by international colleagues, that UK groups are delivering world-leading scientific results in some of the most high-profile and exciting topics, and that UK physicists occupy a disproportionately large number of leadership positions internationally. This has been achieved despite the community being of relatively small size, and receiving a low level of funding, especially as compared to other disciplines within the UK. We find that this is in contrast to the larger European

countries where astroparticle physics form a larger fraction of the physics/astronomy research base. The bibliometric study found that, given its size, the UK community of astroparticle physicists is an outstandingly strong contributor to the field. UK universities educate around 15–20 people to the level of a doctorate each year in astroparticle physics, providing highly skilled scientists for a wide variety of career destinations. Although the science pursued in this field is purely driven by curiosity, a number of case studies very clearly demonstrate the wider impact that astroparticle physics is having on the UK economy and society. These include sensing applications for the oil and gas industry, novel bonding of materials for industry and defence, partnerships for knowledge transfer in the screening of radioactivity, improvements to railway safety, and technology development to improve opportunities and monitoring of CO<sub>2</sub> storage sites in the North Sea.

## CONCLUSIONS AND RECOMMENDATIONS

This report has presented a snapshot of the research being carried out by UK astroparticle physicists currently. Overall, we find a small but vibrant community, focusing efforts in important topical areas. Many of these have the capacity to revolutionise not only our understanding of astroparticle physics, but of the very nature of the universe itself. The volume and quality of the UK community's scientific research output is excellent, competing well with other countries and at least as well as similar fields of physics within the UK.

Case studies have illustrated the unexpected but exciting ways that astroparticle physics is contributing to the economic and societal wellbeing of the UK. These amply demonstrate the values of the skills developed in “blue skies” research when transferred beyond academia.

The output of this review is a series of recommendations, designed to establish a more sustainable framework for UK research in astroparticle physics.

Our first recommendation addresses the recognition and evaluation of research in this field. The principal source of funding for astroparticle physics research in the UK is STFC. As such, it is vital for the health of the field that there is clarity and fairness in its funding mechanisms for the field. At present there is no dedicated grants line for astroparticle physics research. The small size of the astroparticle physics programme, coupled with the fluctuations that arise through the various phases of a project (design, construction and exploitation), mean that a dedicated astroparticle physics grants line would, at present, be over-constraining and counter-productive. There would be additional risks, for example, that other fields not easily defined as particle physics or astronomy might also become included in such a grouping. Consequently, we do not recommend establishment of a ring-fenced budget for astroparticle physics.

As discussed in section 3.5, new projects are usually brought to the attention of STFC through one of the advisory panels (Particle Physics, Nuclear Physics, Astronomy, Solar System, and Particle Astrophysics). A Statement of Interest may be submitted and if seen as suitable, a full proposal may be invited. This is considered at the Projects Peer Review Panel and at Science Board. Community input to this review suggests there

is concern that Science Board and the Projects Peer Review Panel sometimes lack the necessary expertise and breadth to assess adequately astroparticle physics projects presented to them. While it is recognised that membership of these committees is not based on *pro rata* representation of subfields, it is recommended that more consideration might be given to those with astroparticle physics expertise. By its nature, such expertise is broad, and so can be of particular use to the panels. The implementation of the Science Board non-core College of Experts is seen as progress, but at present the number of suitable experts assessing astroparticle physics projects is still too low. In principle, projects reviewed at Science Board and Projects Peer Review Panel remain neutral as to their designation as particle physics, nuclear physics or astronomy, but in reality it seems such an expectation is formed. There is a concern that this is detrimental to astroparticle physics projects, as it falsely tensions them in competition with a particular area.

Funding for a project in the exploitation phase is likely to be through a grants panel. There is no astroparticle physics grants line (see this review's third recommendation, p35), and thus projects in this area must be placed within one of the particle physics, astronomy or nuclear physics grants panels (note, gravitational waves research has its own grants panel arrangement). Community input to this review suggests that there remains an opportunity for earlier and clearer designation as to which path a given project or activity is to be allocated. Furthermore, when such allocations are made, additional effort should be made to ensure that the membership of the relevant review panel is fully appropriate, and that the review panel fully understand that the proposal is within its remit, and should not be rejected for its partial match to the main business of the particular panel.

The major weakness of the current UK astroparticle physics research programme is its lack of diversity, with only research in gravitational waves having received significant long-term support. The international survey conducted for this review identified areas expected to have a particularly strong scientific impact in the near future. The foremost of these – firm, direct evidence for gravitational waves – is expected in a matter of

## 4: Conclusions and recommendations

just a couple of years, as Advanced LIGO reaches sufficient sensitivity. Past investment places the UK in a leading position for the dawn of a genuinely new type of astronomy, and continued investment in this area must be a high priority.

Opportunities for *additional* breadth in the programme are the focus of our second recommendation. The international survey identified the direct detection of dark matter and CTA as particularly promising areas.

For dark matter, the  $\lambda$ CDM “concordance” model of cosmology continues to provide the most complete understanding of the universe, at scales ranging from the size of galaxies to the entire universe itself. At the same time, theoretical frameworks that aim to resolve known weaknesses in the Standard Model of particle physics frequently imply the existence of particles with the properties required for dark matter. Confirmation of the dark matter paradigm is thus of the highest importance. Direct detection of dark matter particles is sought in highly sensitive detectors operated in the radioactively quiet environments provided by deep underground laboratories. At the forefront of the next generation of such devices is LUX-ZEPLIN, which will develop the present world-leading technology to the level at which other anticipated astrophysical backgrounds (neutrinos) begin to dominate. Its sensitivity will be sufficient for a discovery throughout a very large fraction of the presently favoured theoretical parameter space, and is largely complementary to accelerator-based searches with the LHC. UK scientists, largely from the former ZEPLIN programme that was hosted at the Boulby Mine, but also including many others with relevant expertise in the UK, have established exceptionally strong leadership roles in the project, and a bid for construction funds is presently under consideration by STFC.

Internationally, a particularly strong theme of astroparticle physics is in very-high-energy gamma rays, and the international survey identified this as an area of great contemporary excitement. The UK pioneered this area, and has made seminal contributions to successive generations of instruments. Around the world, consolidation of the field has occurred, leading to CTA. This will have approximately order-of-magnitude improvements in all primary technical respects: energy reach, energy resolution, field of view and spatial resolution. Existing telescopes have demonstrated that an exciting and unexpected high-energy universe exists, but CTA promises to revolutionise

the field again. It will provide exquisite precision to tie down the underlying physics in known sources, allowing genuine multi-messenger comparisons with traditional astronomical observations.

Furthermore, it will have the sensitivity for new discoveries – both those already imagined, for example, evidence for Lorentz invariance violation and the existence of axion-like particles, and, more exciting still, those as yet unimagined. Here, UK scientists have again established particularly strong leadership roles in the project, in particular, leading the small-sized telescopes that provide sensitivity to the highest-energy events. This review recommends STFC should seize on these opportunities for significant roles in the world-class, world-leading science of LUX-ZEPLIN and CTA, noting that they will provide a significant increase in programme breadth and community stability.

Our third recommendation relates to research in astrophysical neutrino physics. The international survey recognised this as the astroparticle physics field that had delivered the most exciting results in the recent past, with observations of solar and atmospheric neutrinos driving the understanding of neutrino oscillations. IceCube has provided evidence for neutrinos with energies above 100 TeV from outside the solar system, and searches for point sources of neutrinos continue. Similarly, the ANITA and ARA search for high- and ultra-high-energy neutrinos impacting the Antarctic ice, and projects such as PINGU, will allow questions such as the mass hierarchy to be addressed. These projects are highly complementary to neutrinoless double-beta decay searches as conducted by projects such as SNO+ and SuperNEMO, and the long-baseline neutrino measurements of MINOS, T2K and those proposed with LBNE(F) and Hyper-K. The latter two, with a large involvement by UK scientists, will also be sensitive to astrophysical neutrinos from supernovae, the Sun and possibly other sources. Should there be a core collapse supernova anywhere within our galaxy, a strong signal would be expected in a number of large water, scintillator and, in the future, liquid argon detectors, providing detailed information on the collapse mechanism, perhaps evidence of black-hole formation, and even a target-of-opportunity trigger to enable traditional electromagnetic observatories to capture, in unprecedented detail, the onset of an explosion.

A number of small-scale efforts dedicated to astrophysical neutrinos have been established in

## 4: Conclusions and recommendations

the UK. These present highly exciting opportunities, especially for a younger generation of scientists who could rapidly advance to leading roles. However, we find that at present the number of scientists working in any one of these projects is subcritical. Consequently, this review recommends that the community of scientists involved in astroparticle neutrino physics develop a more strategic approach to the area, aiming to establish major leadership of one or more projects through numerically significant contributions in both personnel and capital. The IOP groups should provide assistance as required, for example, by convening meetings and workshops.

Our fourth and final recommendation is action by the wider astroparticle physics community, although we see a strong leadership role here for IOP. The field of astroparticle physics is, by its very nature, highly interdisciplinary, covering topics at all scales of the universe and over a huge range of energies, including the most energetic particles ever seen. Yet at its heart, there exists great commonality in the underlying physics and astrophysics being probed. Opportunities exist for increased communication between the subfields, and between the astroparticle physics and related communities. Our recommendation is that more should be done to exploit this. As an example, IOP recently supported and hosted “The Violent Universe”, a topical meeting on the subject of astroparticle physics, which brought together leaders in the fields of gravitational waves, dark matter, very-high-energy gamma rays, cosmic rays and members of the corresponding theoretical communities, to explore opportunities for closer

integration. Hosting this prestigious meeting in the UK gave the opportunity to highlight UK science, and UK scientists. At a smaller scale, the IOP Astroparticle Physics Group, which presently provides support for a range of half-day and one-day meetings in individual areas, should coordinate with the IOP’s Gravitational Waves, High Energy Particle Physics, and Nuclear Physics groups, and with RAS, to establish coordinated joint meetings on relevant topics.

### **Addendum**

It is noted that since this report was drafted, and following extensive peer review, STFC has committed to support a strong UK participation in the construction phase of the LUX-ZEPLIN direct dark matter search project.

Additionally, following approval from the Department for Business, Innovation and Skills, STFC became the UK shareholder in CTA, formerly signing the shareholder agreement in DESY Hamburg in April 2015. The CTA GmbH is constituted as an interim legal entity for the pre-production phase and a further (founding) agreement and investment decision is required before the project can proceed to the full construction phase.

These two developments are warmly welcomed, going a long way to fulfil this review’s second recommendation. Forefront roles in direct dark matter searches and very-high-energy gamma ray astronomy provide additional breadth for the astroparticle physics community, and ensure that the UK maintains influence over, and will benefit from, the future development of these areas.

## SUMMARY OF RECOMMENDATIONS

### 1

As the principal funder of research in this area, STFC should examine the structure of its peer review mechanisms to ensure that interdisciplinary fields such as astroparticle physics are adequately and equitably represented in the funding and prioritisation process.

- There is concern that Science Board and the Projects Peer Review Panel sometimes lack the necessary expertise and breadth to adequately assess astroparticle physics projects presented to them. While it is recognised that membership of these committees is not based on *pro rata* representation of subfields, it is recommended that more consideration might be given to those with astroparticle physics expertise. By its nature, such expertise is broad, and so can be of particular use to the panels. The implementation of the Science Board non-core College of Experts is seen as progress, but at present the number of suitable experts assessing astroparticle physics projects is still too low.
- For projects requesting support for exploitation being assessed within the grants lines (i.e. at the Particle Physics, Nuclear Physics or Astronomy Grants Panels) early, clear definition of the specific grants line within which any new project is to be considered is strongly encouraged. Membership of the relevant grants panel should adequately reflect the assignment. The panel must be advised that the project does lie within its remit, and deferring a proposal to another panel should be avoided.
- The establishment of an astroparticle physics grants line is not recommended at this time, as given the present funding levels it would likely inhibit significant further investment in the field.

### 2

STFC should seize on the opportunities offered by the exceptionally strong communities of UK scientists working on CTA and on the LUX-ZEPLIN dark matter project. Investment in these projects, enabling significant scientific leadership, would usefully broaden the research base, is likely to lead to revolutionary new science, and strongly complements other research within the STFC portfolio. This should not be at the expense of funding for gravitational wave research.

## 5: Summary of recommendations

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# 3

This report recognises the importance of astrophysical neutrino physics and notes that strong synergies exist with the particle physics programme. While internationally this is a major pursuit, with several remarkable ongoing and future projects, effort in the UK is at a very low level. The UK could develop a coherent and successful effort in this area.

This review recommends that the community of scientists involved in astroparticle neutrino physics develop a more strategic approach to the area, aiming to establish major leadership of one or more projects through numerically significant contributions in both personnel and capital. The IOP Astroparticle Physics and High Energy Particle Physics groups should provide assistance as required, for example, by convening dedicated, targeted or joint meetings and workshops.

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# 4

The UK community of astroparticle physicists should do more to establish scientifically meaningful collaborations between its subfields, building on its technical breadth to coherently tackle common scientific objectives. The recent meeting on “The Violent Universe” held at IOP was a good example that could be repeated. Additionally, the IOP Astroparticle Physics Group should lead the establishment of joint half- and one-day meetings between itself and the IOP High Energy Particle Physics and Gravitational Physics groups, and with RAS.

## APPENDIX 1: MEMBERSHIP OF THE PANEL

### Panel members

Prof. Alexander Murphy	Chair, University of Edinburgh
Prof. Alan Watson FRS	University of Leeds
Dr Giles Hammond	University of Glasgow
Prof. Paula Chadwick	Durham University
Dr Andrew Pontzen	University College London

IOP provided the secretariat for the panel:  
Philip Diamond and Tajinder Panesor.

## APPENDIX 2: SUMMARY OF RESPONSES TO THE UK CENSUS

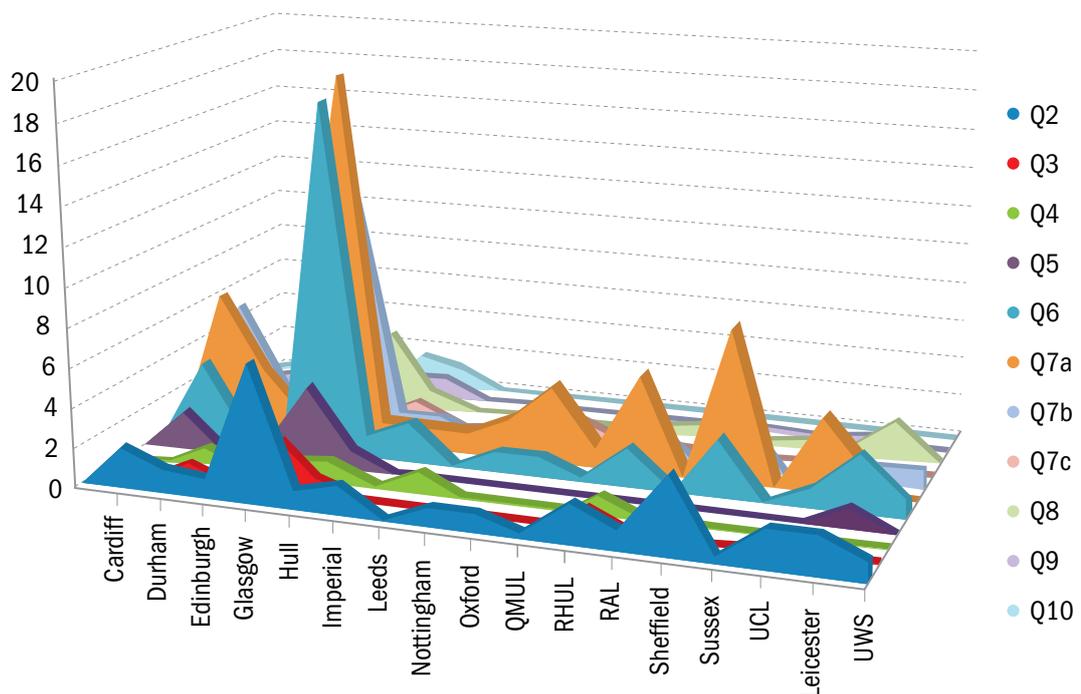
Early in 2014, e-mail requests were sent to all the major academic institutions in the UK, and circulated on standard academic e-mail address lists of the nuclear, particle and astronomy communities. Additional personalised e-mails were sent to known leaders of research groups with activity in astroparticle physics. The e-mail requested that recipients fill in an online Survey Monkey® form. The questions, and a summary of the responses are presented below.

Eighteen institutions answered the call for input, with one submitting two sets of responses, separately covering different research areas. In the tables below those two submissions have been combined. The responding institutions include all the major astroparticle physics groups in the UK.

### Question 1: Institution

*Cardiff, Durham, Edinburgh, Glasgow, Hull, Imperial, Leeds, Nottingham, Oxford, QMUL, RHUL, RAL, Sheffield, Sussex, UCL, Leicester, UWS.*

Questions 2–10 requested information on the numbers of academic staff, researchers and students



### Question 2: Number of full-time equivalent permanent\* academic staff

\*Permanent is defined as personnel with open-ended contracts

*Summary of responses:* There are a total of 29 FTE permanent academics; 15 institutions have less than 2 permanent FTEs; one institution has 4; one institution has 7.

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**Question 3: Number of full-time equivalent temporary\* academic staff**

\*Temporary is defined as personnel with fixed-term contracts (e.g. if at this snapshot in time there exists at your institution a 3-year temporary lectureship appointed in a relevant area then this is to be considered as contributing 1 FTE)

*Summary of responses:* A total of 6 FTE was reported in this category. Half of this is located in one institution, while the remainder is spread over four institutions.

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**Question 4: Number of full-time equivalent emeritus staff**

*Summary of responses:* Five institutions reported 1 FTE member of emeritus staff; one institution reported a 0.1 FTE contribution.

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**Question 5: Number of full time equivalent competitively awarded fellowships\***

\*Include for example Royal Society Research Fellowships and STFC Rutherford Fellows.

*Summary of responses:* A total of 9 FTEs were reported for this category. These are located in five institutions, with four in a single institution.

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**Question 6: Number of other full-time equivalent postdoctoral associates\***

\*Include, for example, PDRAs funded by consolidated grants and project support.

*Summary of responses:* A surprisingly large total of 39 FTEs of PDRAs was reported, though again, one institution is responsible for nearly half of this total. Five institutions reported 0.5 or less FTEs.

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**Question 7: Current number of PhD students – total number of PhD students; how many of these are fully RCUK-funded; how many are partially RCUK-funded**

*Summary of responses:* The total number of PhD studentships reported was 59; 33 are fully RCUK-funded; 2 are partially RCUK-funded.

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**Question 8: Number of full-time equivalent engineering and technical effort**

*Summary of responses:* 9.97.

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**Question 9: Number of full-time equivalent computing officers**

*Summary of responses:* 3.2.

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**Question 10: Number of full-time equivalent of any other staff**

*Summary of responses:* 3.

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**Question 11: What is the nature of this (these) position(s)**

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**Question 12: Research topics studied by the group**

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**Question 13: Total funding awarded\* from RCUK sources between academic years 2006/7 and 2012/13 (inclusive)**

\*Total funding pound sterling (£). Details of grants are not required.

*Totals for the respondents:* £23.767 m.

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**Question 14: Total funding awarded\* from industry and other sources between academic year 2006/7 and 2012/13 (inclusive)**

\*Total funding in pound sterling (£). Details of grants are not required.

*Totals for the respondents:* £9.464 m.

## APPENDIX 3: GLOSSARY

<b>AGN</b>	Active galactic nucleus, a compact region at the centre of a galaxy that has a much higher than normal luminosity
<b>APPEC</b>	Astroparticle Physics European Consortium is a consortium of national government agencies and institutes responsible for coordinating and funding national research efforts in astroparticle physics
<b>Astroparticle Physics</b>	Alternative name for particle astrophysics
<b>Auger Observatory</b>	The Pierre Auger Observatory is an international cosmic-ray observatory in Argentina designed to detect ultra-high-energy cosmic rays
<b>Boulby Mine</b>	The second deepest mine in Europe, a commercial salt and potash mine on the north-east coast of England, run by Cleveland Potash Ltd, Home of the DRIFT and ZEPLIN dark matter searches
<b>CERN</b>	The European Organization for Nuclear Research
<b>CMB</b>	Cosmic microwave background
<b>CTA</b>	The Cherenkov Telescope Array, a proposed very-high-energy gamma-ray observatory
<b>Cosmic ray</b>	Particles originating from space observed in the atmosphere and on Earth
<b>CRESST</b>	A cryogenic dark matter experiment detecting heat and scintillation, located at the Gran Sasso Laboratory, Italy
<b>Dark matter</b>	Hypothesised non-baryonic component of the universe, thought to account for some 27% of the total energy density, and about 85% of the matter content of our galaxy
<b>DEAP-3600</b>	A direct search dark matter experiment based at the SNOLAB in Canada
<b>DIRAC</b>	Distributed Research utilising Advanced Computing
<b>DRIFT</b>	The Directional Recoil Identification From Tracks direct dark matter search project, based at the Boulby Mine, UK
<b>EDELWEISS</b>	A cryogenic dark matter experiment detecting heat and ionisation, located at the Modane Underground Laboratory, France
<b>ERC</b>	European Research Council
<b>ESO</b>	European Southern Observatory
<b>EU</b>	European Union
<b>EURECA</b>	A proposal for a future dark matter experiment in Europe using cryogenic bolometers
<b>ESA</b>	European Space Agency
<b>FTE</b>	Full-time equivalent
<b>Gamma ray</b>	High-energy electromagnetic radiation (photons) produced by nuclear decay and in other processes
<b>GZK</b>	Greisen–Zatsepin–Kuzmin processes, by which ultra-high-energy cosmic rays interact with CMB radiation
<b>GEO600</b>	A ground-based interferometric gravitational wave detector located near Hannover, Germany

<b>GeV</b>	Giga-electron volt, a unit of energy
<b>Gravitational wave</b>	A consequence of general relativity, ripples in the fabric of space-time predicted to occur as a result of events such as binary black hole mergers, or from the Big Bang
<b>GRBs</b>	Gamma-ray bursts: highly energetic bursts of gamma rays. Located at cosmological distances, they are the most powerful explosions known in the universe
<b>GW</b>	Gravitational wave
<b>HESS</b>	The High Energy Stereoscopic System, an array of imaging atmospheric Cherenkov telescopes to investigate cosmic gamma rays in the energy range from 10s of GeV to 10s of TeV
<b>Homestake Mine</b>	A deep underground gold mine located in Lead, South Dakota, USA, that closed commercial operations in 2002. It was home to the work of Ray Davis that led to the solar neutrino problem. It is now home of the Deep Underground Science and Engineering Laboratory, where the LUX project is located
<b>HPGe</b>	High purity germanium detector, an instrument mainly used for detecting low energy gamma rays
<b>IOP</b>	Institute of Physics
<b>LHC</b>	The Large Hadron Collider, at CERN
<b>LIGO</b>	Laser Interferometer Gravitational-Wave Observatory operated at two sites in Livingston, Louisiana, and Hanford, near Richland, Washington, USA
<b>LUX</b>	The Large Underground Xenon experiment, based at the Homestake mine in South Dakota. At the time of writing, this is the most sensitive instrument
<b>LUX-ZEPLIN</b>	A proposed direct search dark matter detector, based on two-phase liquid xenon, planned to be located at the Homestake mine in South Dakota, USA
<b>KAGRA</b>	The Kamioka Gravitational Wave Detector that will have two interferometers in tunnels at the Kamioka Mine, Japan
<b>keV</b>	Kilo-electron volt, a unit of energy
<b>MeV</b>	Mega-electron volt, a unit of energy
<b>MiniCLEAN</b>	A technology demonstrator for future direct search dark matter instruments, based at SNOLAB, Canada
<b>Nuclear astrophysics</b>	The branch of physics that explores the origin of the chemical elements and the energy generation mechanisms in stars
<b>Particle astrophysics</b>	Alternative name for astroparticle physics
<b>PhD</b>	Doctor of Philosophy, a postgraduate degree awarded by universities. Senior to an MSc (Master of Science). Also abbreviated as DPhil
<b>PINGU</b>	The Precision IceCube Next Generation Upgrade
<b>PPARC</b>	The Particle Physics and Astronomy Research Council. In 2007 it was merged with the Council for the Central Laboratory of the Research Councils to form STFC
<b>RAS</b>	Royal Astronomical Society
<b>STFC</b>	Science and Technology Facilities Council, one of the seven UK publicly funded research councils, covering the areas of particle physics, nuclear physics, astronomy, space science and astroparticle physics

## 8: Appendix 3

<b>SUSY</b>	Supersymmetry, a leading theory of physics beyond the Standard Model
<b>UKMHD</b>	UK magnetohydrodynamics consortium
<b>Very-high-energy gamma rays</b>	Gamma radiation with photon energies of 10 s of GeV to 100 s of TeV. Given the source requirements, they are tracers of the most violent environments
<b>VHE</b>	Very-high-energy
<b>Virgo</b>	A gravitational wave detector in Italy, which started operating in 2007
<b>WIMP</b>	Weakly interacting massive particle, a candidate for dark matter
<b>ZEPLIN</b>	A programme of three direct dark matter search instruments located at the Boulby Mine, UK; completed operations in 2012

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