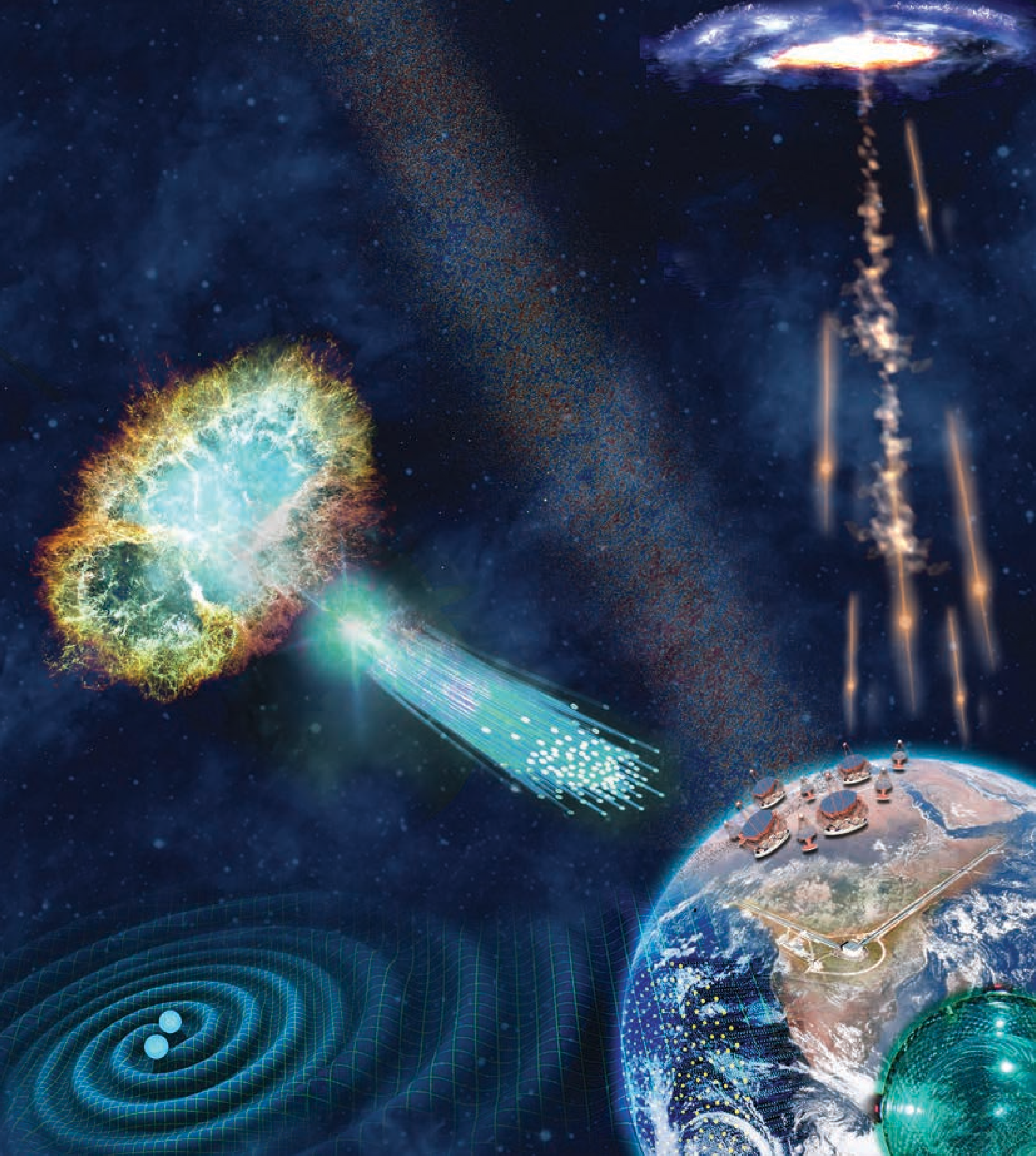
APPEC

European Astroparticle Physics Strategy 2017-2026



APPEC

Astroparticle Physics European Consortium

European Astroparticle Physics Strategy
2017-2026

APPEC

www.appec.org

Executive Summary

Astroparticle physics is the fascinating field of research at the intersection of astronomy, particle physics and cosmology. It simultaneously addresses challenging questions relating to the micro-cosmos (the world of elementary particles and their fundamental interactions) and the macro-cosmos (the world of celestial objects and their evolution) and, as a result, is well-placed to advance our understanding of the Universe beyond the *Standard Model of particle physics* and the *Big Bang Model of cosmology*.

One of its paths is targeted at a better understanding of cataclysmic events such as: supernovas – the titanic explosions marking the final evolutionary stage of massive stars; mergers of super-massive black-hole or neutron-star binaries; and, most compelling of all, the violent birth and subsequent evolution of our infant Universe. This quest is pursued using the combined and often complementary power of all 'cosmic' messengers: *cosmic rays*, *electromagnetic waves* (i.e. 'light' but also photons at all energies), *neutrinos* and *gravitational waves*. Another path aims to elucidate long-standing mysteries such as the true nature of *Dark Matter* and *Dark Energy*, the intricacies of *neutrinos* and the occurrence (or non-occurrence) of *proton decay*.

The field of astroparticle physics has quickly established itself as an extremely successful endeavour. Since 2001 four Nobel Prizes (2002, 2006, 2011 and 2015) have been awarded to astroparticle physics and the recent – revolutionary – first direct detections of gravitational waves is literally opening an entirely new and exhilarating window onto our Universe. We look forward to an equally exciting and productive future.

Many of the next generation of astroparticle physics research infrastructures require substantial capital investment and, for Europe to remain competitive in this rapidly evolving global field of research both on the ground and in space, a clear, collective, resource-aware strategy is essential. As a relatively new field, European astroparticle physics does not benefit from a natural and strong inter-governmental

APPEC General Assembly 2016

organisation that has a remit to drive it, in the same way as CERN, ESO and ESA help to drive their areas of specialism. This is why, in 2001, European scientific agencies founded APPEC (the Astroparticle Physics European Consortium). Since 2012, APPEC became a consortium operated on the basis of a Memorandum of Understanding with the overarching aim of strengthening European astroparticle physics and the community engaged in this field.

Apart from promoting cooperation and coordination, a crucial APPEC activity is to formulate, update and realise the European astroparticle physics strategy. Building on earlier strategies released in 2008 and 2011, APPEC started a new roadmap process. The APPEC Scientific Advisory Committee (SAC) provided valuable contributions to the scientific part of the roadmap, followed by contributions from the agencies. In April 2016 the APPEC General Assembly, in close cooperation with the SAC, organised a very well-attended and animated two-day Town Meeting in Paris open to the entire astroparticle physics community. This provided the key ingredients that culminated in the 21 recommendations presented in this strategy document, endorsed by the astroparticle community – recommendations addressing, in addition to the scientific issues, crucial organisational aspects as well as important societal issues such as gender balance, education, public outreach and relations with industry. The APPEC General Assembly unanimously approved them at its meeting in Stockholm in November 2016. By acting coherently on these recommendations, Europe will be able to exploit fully the tantalising potential for new discoveries that is highlighted in the second part of this document.

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APPEC General Assembly 2017

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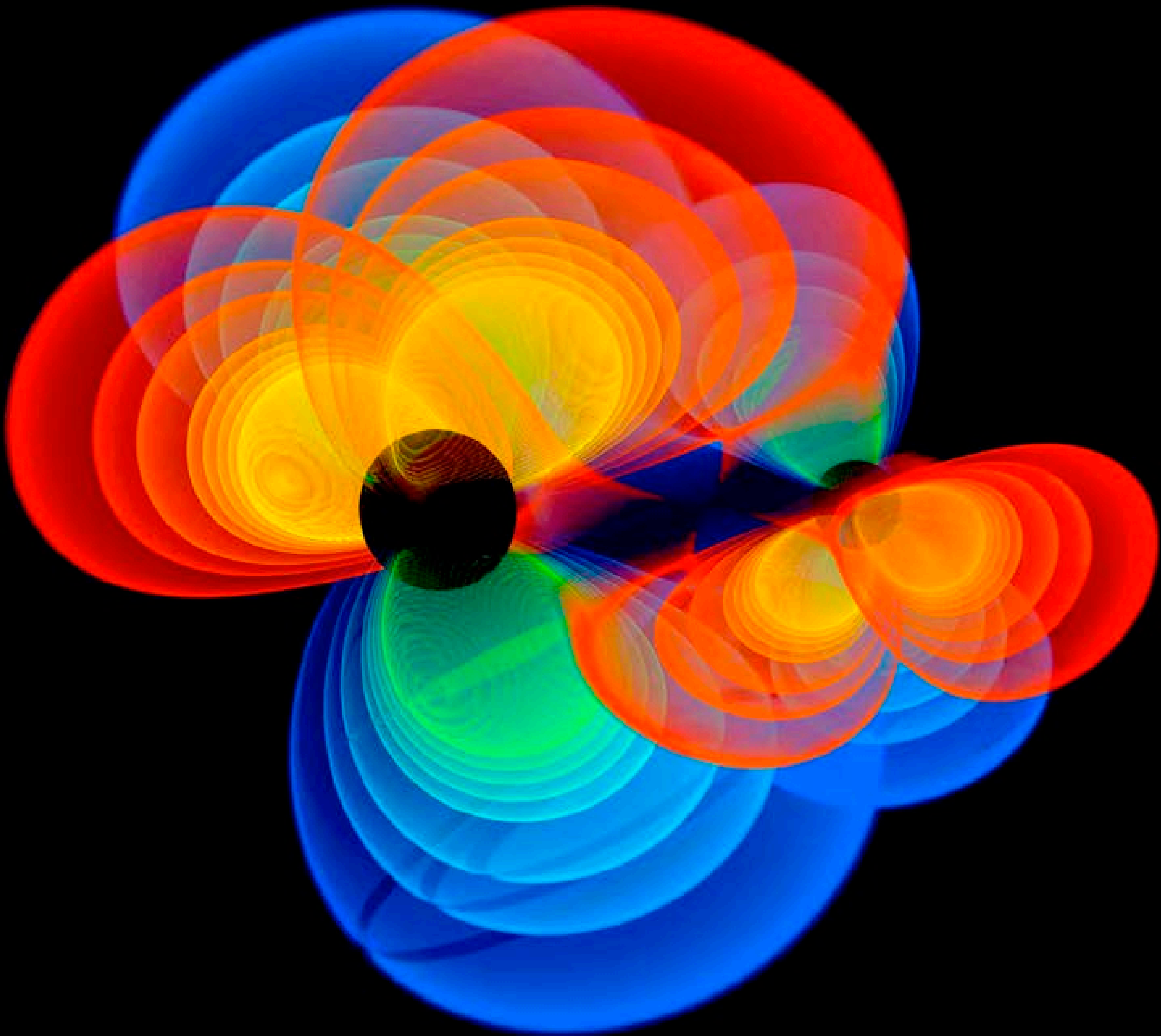
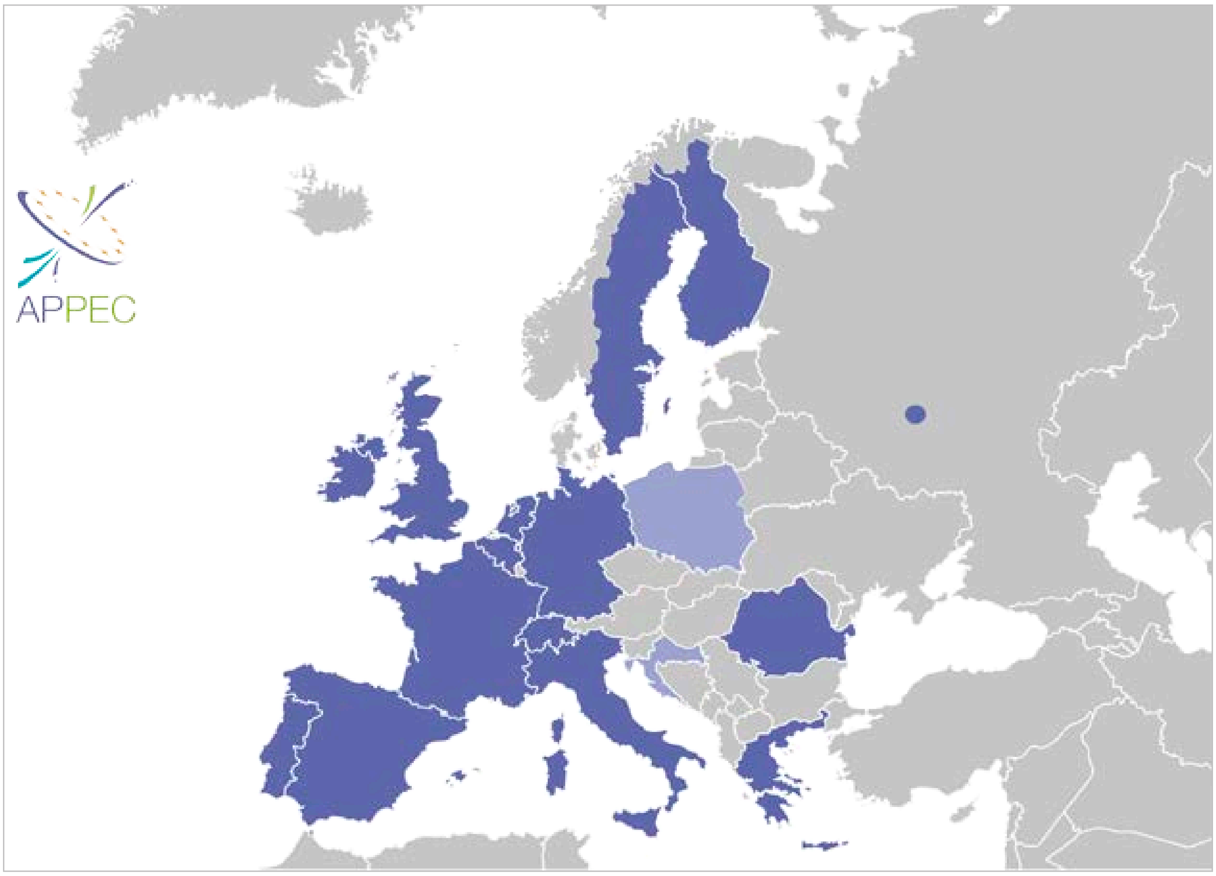


Introduction

Astroparticle physics is the rapidly evolving field of research that lies at the point where astronomy, particle physics and cosmology meet. Experimentally, it combines the advanced instrumentation harnessed by particle physicists with the highest standard of imaging of the cosmos undertaken by astronomers. Theoretically, it connects the Big Bang Model of cosmologists to the Standard Model of particle physicists; the former gives a detailed description of the evolution of the macro-cosmos while the latter describes the micro-cosmos with stunning precision. Scientifically, it aims to gain insights into long-standing enigmas at the heart of our understanding of the Universe – for example:

- **The Extreme Universe:** *What can we learn about the cataclysmic events in our Universe by combining all of the messengers – high-energy gamma rays, neutrinos, cosmic rays and gravitational waves – that we have at our disposal?*
- **The Dark Universe:** *What is the nature of Dark Matter and Dark Energy?*
- **Mysterious neutrinos:** What are their intricate properties and what can they tell us?
- **The Early Universe:** *What else can we learn about the Big Bang – for instance, from the cosmic microwave background (CMB)?*



APPEC member states in 2017

Introduction

Against the backdrop of the increasing complexity, extensive running time and high capital investment of the experiments operated and planned by the European astroparticle physics community, the field organised itself in 2001 with the establishment of APPEC as its coordinating body. The illustration shows APPEC's member countries in 2017.

APPEC published a science vision, coined the 'European Strategy for Astroparticle Physics', in 2008 and its first prioritised roadmap in 2011.

Since then, the field has made revolutionary progress, with a highlight being the recent discovery of gravitational waves tracing back to one of the most energetic events in our Universe ever witnessed by humanity: the merging of two black holes. The coming decade promises to be equally successful and significant, with an impressive arsenal of cutting-edge experiments expected to start operations that will probe deeply into the scientific questions outlined above.

Competitive European participation in this dynamic and exhilarating field of research requires careful prioritisation – notably regarding larger infrastructures – and in most cases consultation and collaboration with our global partners and colleagues working in astronomy, particle physics and cosmology. The construction costs and, most importantly, the running costs of projects must be carefully scrutinised.

APPEC's new European Astroparticle Strategy 2017-2026 takes into account the collective funding level expected to be available at national agencies and through the EU; as such, it not only sets out a science vision but also aims to be a resource-aware roadmap. The attribution of resources across the various activities is indicated in the following graphic which summarises APPEC's funding priorities in the context of global scientific ambitions. Its realisation will allow European researchers to capitalise successfully on past efforts and investments, and promises to shed bright light on the composition and mindboggling dynamics of our Universe.

Formulated as 21 individual recommendations, the goals that APPEC aspires to achieve in the decade ahead are presented below. They are grouped into three categories:

- scientific issues;
- organisational issues; and
- societal issues.

Coherent action on all 21 recommendations will be vital to the success of the strategy set out in this roadmap document. It can only be achieved with close cooperation between the scientific community that APPEC represents – Europe's astroparticle physicists – and our various national governments and funding agencies, the European Commission, our partners outside Europe, those working in the intimately connected fields of particle physics, astronomy and cosmology research, and the strong pillars that these three fields of research rely on (CERN, ESO and ESA).

Astroparticle physics is a dynamic, rapidly developing field. Its scope and focus therefore vary slightly from one country to another. Despite this, the APPEC General Assembly adopted these recommendations by consensus at its tenth meeting, held in Stockholm in November 2016. Primarily, the scientific issues outlined below address 'big science' projects whose realisation hinges on a concerted multinational and often multidisciplinary strategy. Without exception, these projects build on a vibrant ecosystem of smaller-scale experiments, innovative R&D and model-building rooted in national institutes, laboratories and universities throughout Europe. Crucial to the future successes of European astroparticle physics, the continuation of this ecosystem is APPEC's overarching priority.

Scientific issues

Large-scale multi-messenger infrastructures

To improve understanding of our Universe, APPEC identified as a very high priority those research infrastructures that exploit all confirmed high-energy 'messengers' (cosmic particles that can provide vital insights into the Universe and how it functions). These messengers include gamma rays, neutrinos, cosmic rays and gravitational waves. European coordination is essential to ensuring timely implementation of such infrastructures and enabling Europe to retain its scientific leadership in this field.

1. High-energy gamma rays

Through the use of ground-based gamma-ray telescopes (e.g. HESS and MAGIC) and key participation in satellite missions such as Fermi, Europe has played a leading and pioneering role in establishing high-energy gamma rays as an ideal messenger to enable exploration of the extreme Universe – as demonstrated by the astonishing number of gamma-ray sources discovered in recent years. The next-generation European-led, ESFRI-listed global project will be the Cherenkov Telescope Array (CTA), which has excellent discovery potential ranging from astrophysics to fundamental physics. The CTA is expected to start full operation as an observatory in 2023.

APPEC fully supports the CTA collaboration in order to secure the funding for its timely, cost-effective realisation and the subsequent long-term operation of this observatory covering both northern and southern hemispheres.

2. High-energy neutrinos

IceCube's first observation of PeV-scale cosmic neutrinos in 2013 has opened an entirely new window onto our Universe: neutrino astronomy. As well as presenting the opportunity to resolve neutrinos' mass hierarchy by studying atmospheric neutrinos, this led ESFRI to include KM3NeT 2.0 in its 2016 roadmap, with operation anticipated to commence in 2020. Within the Global Neutrino Network (GNN), the IceCube, KM3NeT and Baikal-GVD collaborations already join forces to provide a network of large-volume detectors viewing both northern and southern hemispheres and to exploit efficiently the full discovery potential inherent in neutrino astronomy.

For the northern hemisphere (including Baikal GVD), APPEC strongly endorses the KM3NeT collaboration's ambitions to realise, by 2020: (i) a large-volume telescope with optimal angular resolution for high-energy neutrino astronomy; and (ii) a dedicated detector optimised for low-energy neutrinos, primarily aiming to resolve the neutrino mass hierarchy. For the southern hemisphere, APPEC looks forward to a positive decision in the US regarding IceCube-Gen2.

3. High-energy cosmic rays

The Pierre Auger Observatory is the world's largest, most sensitive ground-based air-shower detector. Understanding the evident flux suppression observed at the highest energies requires good mass resolution of primary cosmic rays: are they predominantly light nuclei (protons) or heavy nuclei (like iron)? This is the missing key to deciding whether the observed cut-off is due to particles being limited in energy because of interactions with the CMB, or to cosmic accelerators 'running out of steam' to accelerate particles. The Auger collaboration will install additional particle detectors (AugerPrime) to measure simultaneously the electron and muon content of air showers, in order to help determine the mass of primary cosmic rays. This upgrade will also deepen understanding of hadronic showers and interactions at centre-of-mass energies above those accessible at the LHC.

APPEC strongly supports the Auger collaboration's installation of AugerPrime by 2019. At the same time, APPEC urges the community to continue R&D on alternative technologies that are cost-effective and provide a 100% (day and night) duty cycle so that, ultimately, the full sky can be observed using very large observatories.

4. Gravitational waves

The first direct observations of gravitational waves by the LIGO-Virgo consortium have revealed a scientific treasure trove. Multi-solar-mass black holes coalescing within seconds into a super-massive black hole and simultaneously radiating the equivalent of a few solar masses of energy as gravitational waves are now an established fact; they also provide unprecedented tests of General Relativity. Another new, revolutionary window onto our Universe has therefore now opened: gravitational-wave astronomy. In this field, the laboratories that host gravitational-wave antennas play a crucial role by developing new technologies to increase detection efficiencies further. The incredibly high precision in monitoring free-falling objects in space recently achieved by ESA's LISA Pathfinder mission is an important step towards complementary (low-frequency) space-based gravitational-wave astronomy.

With its global partners and in consultation with the Gravitational Wave International Committee (GWIC), APPEC will define timelines for upgrades of existing as well as next-generation ground-based interferometers. APPEC strongly supports further actions strengthening the collaboration between gravitational-wave laboratories. It also strongly supports Europe's next-generation ground-based interferometer, the Einstein Telescope (ET) project, in developing the required technology and acquiring ESFRI status. In the field of space-based interferometry, APPEC strongly supports the European LISA proposal.

Medium-scale Dark Matter and neutrino experiments

APPEC considers as its core assets the diverse, often ultra-precise and invariably ingenious suite of medium-scale laboratory experiments targeted at the discovery of extremely rare processes. These include experiments to detect the scattering of Dark Matter particles and neutrinoless double-beta decay, and direct measurement of neutrino mass using single-beta decay. Collectively, these searches must be pursued to the level of discovery, unless prevented by an irreducible background or an unrealistically high demand for capital investment.

5. Dark Matter

Elucidating the nature of Dark Matter is a key priority at the leading tip of astroparticle physics. Among the plethora of subatomic particles proposed to explain the Dark Matter content of our Universe, one category stands out: the Weakly Interacting Massive Particle (WIMP). WIMPs arise naturally, for instance, in supersymmetric extensions of the Standard Model of particle physics. Many experiments located in deep-underground laboratories are searching for WIMP interactions. For masses in excess of a few GeV, the best sensitivity to WIMPs is reached with detectors that use ultra-pure liquid noble-gas targets; such detectors include XENON1T (using 3.5 tons of xenon) and DEAP (using 3.6 tons of argon), which both started operating in 2016. Their sensitivity can be further enhanced by increasing the target mass. A suite of smaller-scale experiments is exploring, in particular, low-mass WIMPs and other Dark Matter hypotheses such as those based on dark photons and axions.

APPEC encourages the continuation of a diverse and vibrant programme (including experiments as well as detector R&D) searching for WIMPs and non-WIMP Dark Matter. With its global partners, APPEC aims to converge around 2019 on a strategy aimed at realising worldwide at least one 'ultimate' Dark Matter detector based on xenon (in the order of 50 tons) and one based on argon (in the order of 300 tons), as advocated respectively by DARWIN and Argo.

6. Neutrino mass and nature

Despite all previous efforts, some of the neutrino's very fundamental characteristics remain unknown. Notably, these include neutrino mass and whether the neutrino is its own anti-particle or not (in other words, whether it is a Majorana-type particle or a Dirac-type particle). Both of these issues can be explored by studying the beta decay of selected isotopes. Single-beta decay allows direct kinematical inference of neutrino mass; first results from the world-leading KATRIN experiment in Germany are eagerly awaited. The double-beta decay of, for instance, germanium, tellurium or xenon, meanwhile, is used to probe physics beyond the Standard Model in a unique way by searching for decays without neutrinos. This process is only allowed if neutrinos are Majorana-type particles and its observation would not only reveal the neutrino's nature and pinpoint its mass but also demonstrate violation of lepton number. Among the various experiments worldwide searching for neutrinoless double-beta decay, European experiments such as GERDA (focusing on germanium), CUORE (tellurium) and NEXT (xenon) are some of the most competitive.

APPEC strongly supports the present range of direct neutrino-mass measurements and searches for neutrinoless double-beta decay. Guided by the results of experiments currently in operation and in consultation with its global partners, APPEC intends to converge on a roadmap for the next generation of experiments into neutrino mass and nature by 2020.

Synergies with astronomy, particle physics and cosmology

To shed light on neutrino mixing and the neutrino mass hierarchy, APPEC is a long-term proponent of experiments using natural neutrinos from the Sun and from Earth's atmosphere as well as neutrinos from nuclear reactors and accelerators. Recognising the increasingly interdisciplinary reach of astroparticle physics, APPEC has broadened the scope of its roadmap to include explicitly two topics referred to in its 2008 science vison: the CMB and Dark Energy. These are flourishing fields of research, as demonstrated by Nobel Prizes awarded in 2006 and 2011. They not only complement core astroparticle physics topics but also yield stringent constraints on neutrino masses and on the role of neutrinos in the early Universe. So far in these recommendations, the focus has been on projects primarily funded by European astroparticle physics agencies. By contrast, for the three topics addressed in this subsection, the main funding is likely to come from US and Asian agencies or from the European particle physics and astronomy communities.

7. Neutrino mixing and mass hierarchy

Neutrino oscillation – implying neutrino mixing and thus the existence of non-zero neutrino masses – was discovered by experiments with solar and atmospheric neutrinos and rewarded with Nobel Prizes in 2002 and 2015. For precise determination of the intricacies of neutrino mixing – including the much-anticipated violation of matter/anti-matter symmetry in the neutrino sector, and the neutrino mass hierarchy – dedicated accelerator neutrino beams and neutrinos from nuclear reactors are ideal. With the Double Chooz concept, the Borexino liquid scintillator and the ICARUS liquid-argon time-projection-chamber technologies, Europe was a pioneer in this field and large-scale facilities are now envisaged in the US (the DUNE long-baseline neutrino experiment) and Asia (the JUNO reactor neutrino experiment); DUNE emerged after the first of a series of global neutrino physics strategy meetings co-initiated by APPEC in 2014. Together with the Hyper-Kamiokande proposal in Japan, DUNE and JUNO define the future of this field. Both DUNE and Hyper-Kamiokande will also incorporate unsurpassed and complementary sensitivities for low-energy cosmic messengers (e.g. supernova neutrinos) and for the much-sought-after proton decay.

From a scientific perspective and as part of a global strategy, APPEC strongly endorses European participation in DUNE and Hyper-Kamiokande experiments – exploiting long-baseline neutrino beam facilities – as well as in the JUNO nuclear reactor neutrino experiment.

8. Cosmic microwave background (CMB)

ESA's Planck satellite mission gave Europe a major role in space-based experiments in this field, while the US leads the way in ground-based experiments. Apart from better precision, the next generation of experiments primarily aims at trying to identify the tell-tale sign of cosmic inflation: the imprint of primordial gravitational waves on CMB polarisation modes.

APPEC strongly endorses a European-led satellite mission (such as COrE) to map the CMB from space. APPEC will encourage detector R&D towards a next-generation ground-based experiment complementary to initiatives in the US. APPEC continues to contribute to global coordination of this field following the Florence CMB Workshop series that started in 2015.

9. Dark Energy

Together with Dark Matter, Dark Energy – the hypothetical form of energy behind the Universe's accelerated expansion – constitutes the least-understood component of the cosmos. It is studied via large galaxy-survey campaigns (both satellite-based and ground-based) that combine spectroscopic, photometric and weak-lensing techniques to reconstruct the growth of cosmic structures.

APPEC supports the forthcoming ESA Euclid satellite mission, which will establish clear European leadership in space-based Dark Energy research. Because of their complementarity to Euclid, APPEC encourages continued European participation in the US-led DESI and LSST ground-based research projects. To benefit fully from the combined power of satellite-based and ground-based experiments, the exchange of data is essential.

Foundations

Underpinning, driving and facilitating the experiments summarised above are vibrant programmes in theoretical physics, cutting-edge detector R&D and efforts to provide the necessary computing resources. APPEC has every intention of continuing to support and stimulate all of these activities in whatever way it can. In addition, APPEC recognises the uniqueness of the infrastructures provided by Europe's deep-underground laboratories. Without these, key APPEC research objectives would become impossible to achieve.

10. Astroparticle theory

Astroparticle physics research is a concerted effort between theory and experiment. As well as inspiring a vast spectrum of experiments, unified theories of fundamental interactions are indispensable to the analysis and interpretation of experimental data. Many European institutes recognise the exciting challenges presented by astroparticle physics and, accordingly, are expanding their activities in the field of theory.

APPEC supports an ambitious theory programme in the field of astroparticle physics, with special attention focused on adjacent disciplines such as particle physics, astronomy and cosmology. APPEC encourages the establishment of a centre for astroparticle physics theory in one of its member countries.

11. Detector R&D

Frontier experiments in the field of astroparticle physics rely on innovative particle detection technologies and instrumentation that are rarely available as off-the-shelf products. Occasionally, new technologies even open up entirely new detection concepts or industrial applications. With activities in many European institutes, detector R&D constitutes a cornerstone of the astroparticle physics community.

APPEC stimulates and supports a range of detector R&D projects through targeted common calls and technology fora that bring scientists and industries together. APPEC encourages consortia to apply for EU (technology) grants such as those achieved by SENSE for low-level light-sensor technologies. APPEC welcomes the ATTRACT initiative, which aims to accelerate development of particle-radiation detector and imaging technologies for the science community and for the wider market.

12. Computing and data policies

To date, the computing needs of the European astroparticle physics community have been modest and could be accommodated by the Worldwide LHC Computer Grid. However, several of the future large observatories dedicated to multi-messenger studies of our Universe will require massive computing resources for data simulation, template matching and data analysis/storage. In parallel, awareness is growing that much can be gained by the sharing of 'big data' and best practice between experiments and communities.

APPEC requests all relevant experiments to have their computing requirements scrutinised. APPEC will engage with the particle physics and astronomy communities (e.g. within the context of EU-T0) to secure for the future a balance between available European computing resources and needs. Furthermore, APPEC encourages the use of data format standards to facilitate data access between experiments. APPEC supports the transition to Open Access publication strategies and encourages the making of data publicly available (as 'open data') to foster 'citizen science', for example.

13. Unique infrastructures: deep-underground laboratories

Shielded by thousands of metres of rock, deep-underground laboratories host a diverse suite of extremely low-background experiments that are often unique. These facilities also provide a platform for multidisciplinary collaboration.

With a view to maintaining a good match between available capacity and planned activities, APPEC fosters continued support for and cooperation between underground laboratories – as advocated, for example, by the DULIA (Deep Underground Laboratory Integrated Activity) initiative.

Organisational issues

As a 'big science' research field, astroparticle physics critically relies on large infrastructures that require large investments. This makes collaboration – national, European and even global – absolutely essential. Similarly, as an interdisciplinary field, astroparticle physics not only naturally interacts closely with the astronomy and particle physics communities but also offers opportunities to other fields of research and industry.

14. European Commission
European astroparticle physics successfully contributes to the Commission's aim of strengthening the excellence and attractiveness of European research and innovation, and Europe's economic and industrial competitiveness. The present APPEC consortium is building on the past success of the EU-supported ASPERA project, while ESFRI status and EU structural and regional funding play an increasingly important role in the realisation of our large research infrastructures. ERC grants often drive original ideas that would otherwise be difficult to pursue. Importantly, astroparticle physics technology has already demonstrated that it can have innovative commercial applications.

APPEC will continue to work with the European Commission in order to strengthen the EU's ability to capitalise on astroparticle physics technologies and ideas, as well as to make optimal use of the opportunities that already exist within various EU programmes in terms of advancing science and generating economic value.

15. European collaboration and coordination
The roadmap presented in this document is the result of an intense process that culminated in the Town Meeting of the European astroparticle physics community which took place in Paris in April 2016. Prominent flagship astroparticle physics infrastructures (e.g. the CTA and KM3NeT ESFRI projects and the future ET project) require capital investments that surpass the capabilities of a single European country.

APPEC will explore ways of aligning the realistically available funding in Europe to maintain the excellent discovery potential of European scientists. Project governance, management, computing needs and running costs all require serious attention.

16. Global collaboration and coordination
Some research directions warrant a global strategy. In some cases, this may be due to substantial capital requirements or running expenses (e.g. for multi-messenger facilities); in others, it may be because of the advantages in pursuing complementary technologies (e.g. for next-generation Dark Matter searches and the measurement of neutrino properties). In some instances, cooperation between different observatories working as a single interconnected network can lead to much better precision or much deeper understanding (e.g. in the field of gravitational-wave detection or, ultimately, all multi-messenger observatories).

APPEC will continue to seek collaboration and coordination with its partners worldwide – scientists and funding agencies – to advance the design, construction, sustainable exploitation (including computing needs) and governance of the next-generation world-class large research infrastructures required to achieve the scientific discoveries of which we all dream.

Organisational issues

17. Astronomy and particle physics communities

APPEC's field of interest naturally touches astronomy and particle physics. ESO and CERN are already long-term observers at APPEC meetings and events. In the context of possible future space-based projects such as Euclid, COrE and LISA, ESA is becoming another important partner.

APPEC will enhance its interactions with its present observers ESO and CERN in areas of mutual interest and will seek to engage with ESA in view of upcoming astroparticle-physics-oriented space missions. This will ensure scientific complementarity, where appropriate, and allow closer collaboration with our colleagues in the astronomy and particle physics communities. APPEC therefore welcomes ASTERICS, which serves as a platform for closer collaboration between the ESFRI-listed projects SKA, CTA, KM3NeT and E-ELT.

18. Interdisciplinary opportunities

Some of our infrastructures offer unique opportunities for other research disciplines or for industry. Cabled deep-sea and deep-ice neutrino telescopes, for example, are of great interest to marine biologists and geologists, while deep-underground laboratories offer test facilities ideal for biologists studying the evolution of life in low-radioactivity environments and microbial life under extreme conditions.

APPEC will further develop interdisciplinary workshops and will promote to the outside world – including both academia and industry – interdisciplinary access to its full research infrastructure.

Societal issues

Astroparticle physics is a perfect example of curiosity-driven research. A combination of excitement about the mysteries of the Universe and spectacular discoveries easily spark public interest, giving rise to a surge of outreach activities that in turn capture the imagination of all kinds of people and increase the skills base for the future. The inherent high-tech aspects of instrumentation in our field provide ample opportunity for industrial collaboration, not only in terms of delivering the technologies required for astroparticle physics projects but also in applying these technologies to other challenges. In this way, pure science generates significant economic growth.

19. Gender balance

APPEC is fully committed to promoting an inclusive, gender-neutral working environment. Historically, physics is a field with low representation of female researchers, especially in leading positions. Despite prominent role models, women still remain underrepresented in our field of research.

Inspired by the H2020 project GENERA, APPEC will develop a gender balance policy for all of its activities and will urge projects to develop and implement Gender Equality Plans.

20. Education and outreach

Astroparticle physics research attracts strong interest from students and the general public alike, as demonstrated recently by the huge publicity surrounding the discovery of gravitational waves.

Given the rapid expansion of the field of astroparticle physics, APPEC encourages (e.g. in cooperation with the IPPOG) the exchange of best practice in the sphere of outreach. At its frontier research facilities, APPEC will implement more structured organisation of dedicated astroparticle physics summer schools and studentships. APPEC will also enhance its presence on the web and social media.

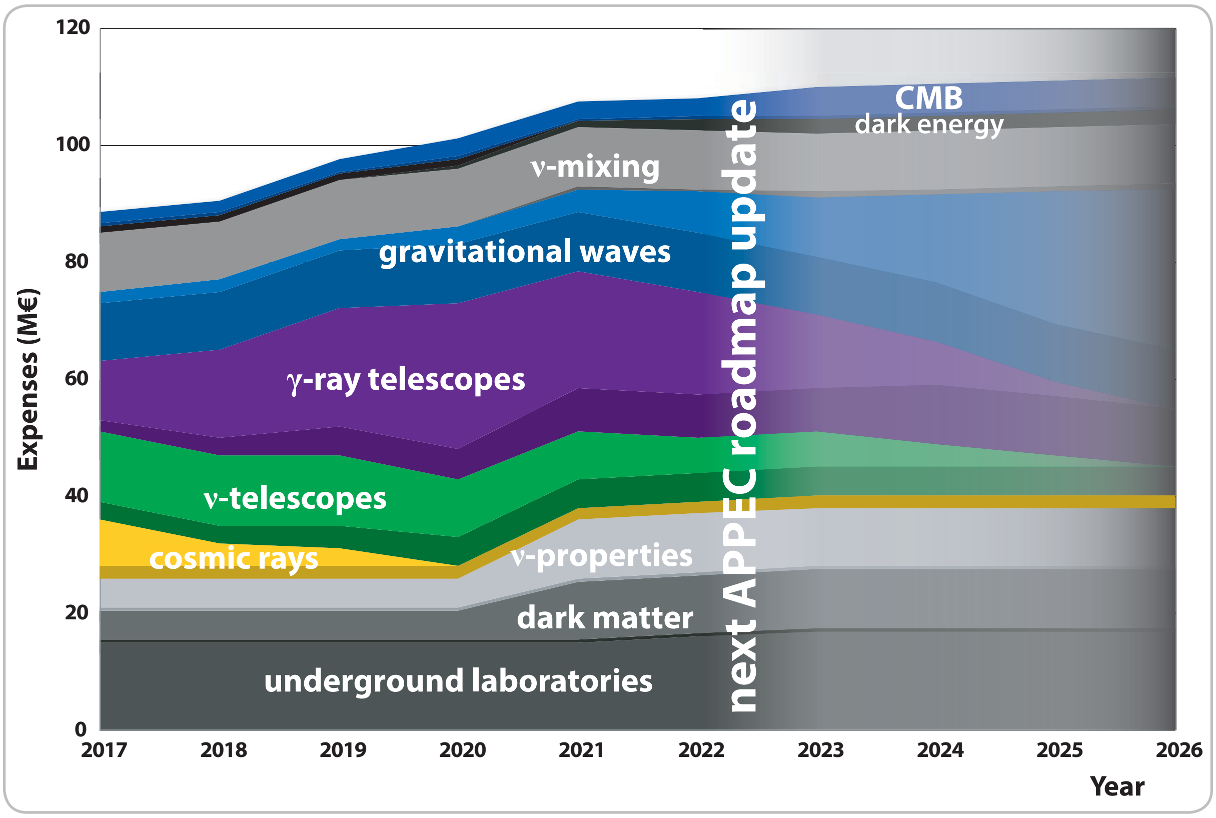
21. Industry

Astroparticle physics creates and uses advanced technologies. As a result, close cooperation with high-tech industry is vital. This interplay between basic research and innovation generates knowledge and technology with potential societal benefits. For example, cosmic-ray muon tomography is used to image volcanos, nuclear material, burial sites and blast furnaces; large-scale networks of seismic sensors, capitalising on experiences gained in gravitational-wave research, have been developed for oil exploration and perimeter security.

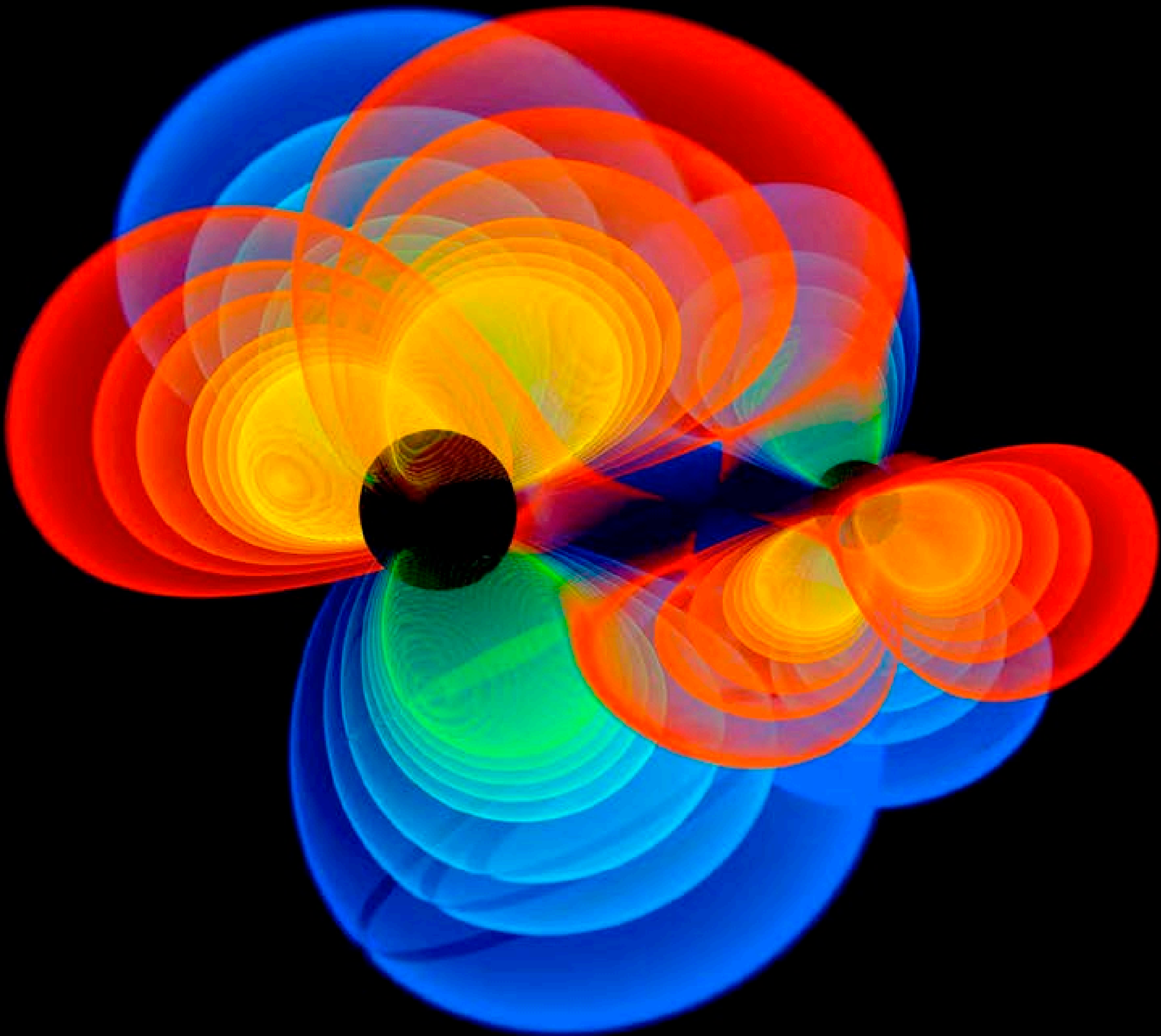
APPEC will increase its efforts to identify potential applications of astroparticle physics expertise for societal benefit. In parallel, APPEC will continue to organise its successful technology fora on targeted technologies and use these as a platform for discussion and collaboration involving industry and academia.

Projected annual costs

Projected annual capital investment (for instrument prototyping and construction, excluding manpower) and projected annual running costs (for consumables and employee expenses, i.e. travel and manpower; included in the shaded area) anticipated from the European astroparticle physics funding agencies and required to realise APPEC's 'European Strategy for Astroparticle Physics'. Costs related to actual scientific exploitation (data calibration, analysis, interpretation, publication etc.) are not considered in this projection. Also excluded are other, often substantial subsidies notably from regional and EU structural funds and from the European astronomy and particle physics research communities, and contributions from APPEC's non-European partners. The uncertainties in this projection increase rapidly with time.



Part 2: Astroparticle Physics Research Landscape

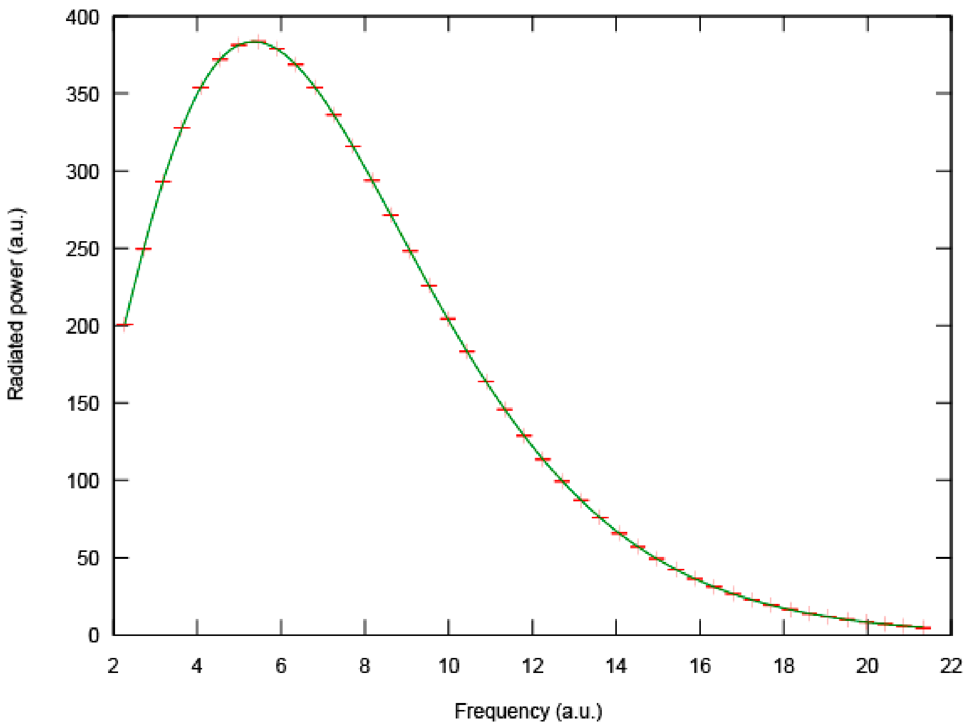


1. Connecting the Infinitely Large and Infinitely Small

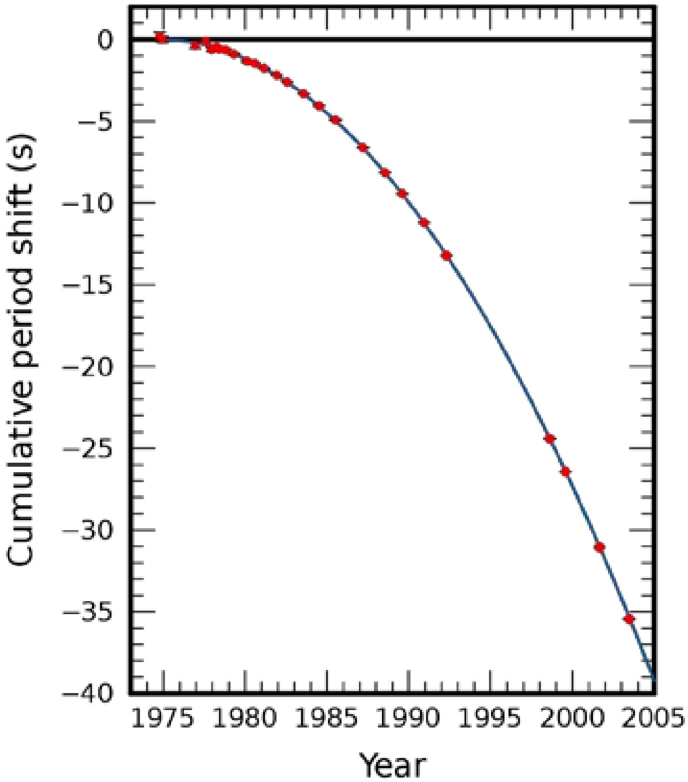
By extracting new knowledge and understanding from the tiniest particles that hurtle through the cosmos, astroparticle physics not only sheds light on some of the biggest and most intriguing questions about our Universe – it also has the potential to deliver valuable scientific breakthroughs that benefit people's day-to-day lives.

Ever wondered about microelectronics and GPS navigation?
Over the past century, physics has achieved and enabled many remarkable advances. For example, it really is impossible to imagine the modern world without the innumerable benefits originating in two of the most fascinating spheres of fundamental science – quantum mechanics and relativity. These extraordinary concepts have a key characteristic in common: both were introduced to resolve loose ends in classical physics.

In 1900, German theoretical physicist Max Planck first introduced the idea of 'light quanta' – a term describing packets of energy whose energy increased in steps rather than evenly and continuously. Planck devised this concept to reconcile physics theory with measurements of the radiation spectrum emitted by so-called 'black bodies' (objects kept at a specific temperature). The most dramatic example of black-body radiation is the faint, ubiquitous afterglow of the Big Bang known as the cosmic microwave background (CMB); first observed in 1964, today this corresponds to a temperature of minus 270.4°C (less than 3°C above absolute zero). Planck's work provided the springboard for the development of quantum mechanics – often described as 'the science of the very small' – which in turn provided the basis for the invention of the electronic transistor in 1947, which in its course opened the door to the world of microelectronics.



Radiated power as function of frequency of the cosmic microwave background as measured by the COBE satellite (points). The line shows the blackbody spectrum.



Observed cumulative decrease in the period (points) of the Hulse-Taylor binary star system. The line shows the expected decrease based on the emission of gravitational waves as predicted by Einstein's General Theory of Relativity. This observation was the first – albeit indirect – evidence for the existence of gravitational waves and was awarded with the 1993 Physics Nobel Prize.

Just five years after Planck's proposal of light quanta, another German-born theoretical physicist – Albert Einstein – postulated that the velocity of light in a vacuum was the same for all inertial observers (an observer that drifts in gravity-free space without being accelerated); his aim was to account for the fact that Earth's velocity apparently had no effect on the speed of light. This work culminated in Einstein's General Theory of Relativity, a revolutionary and integrated approach towards space, time, mass and energy; for example, Einstein's theory predicted the existence of gravitational waves, which would not be directly observed until 2015 (when they were traced back to the coalescence of two black holes). Interestingly, without a detailed understanding of relativity, we simply could not keep the precise time on satellites – and global navigation systems such as GPS and Galileo simply could not function.

From a stunning understanding of everything around us…

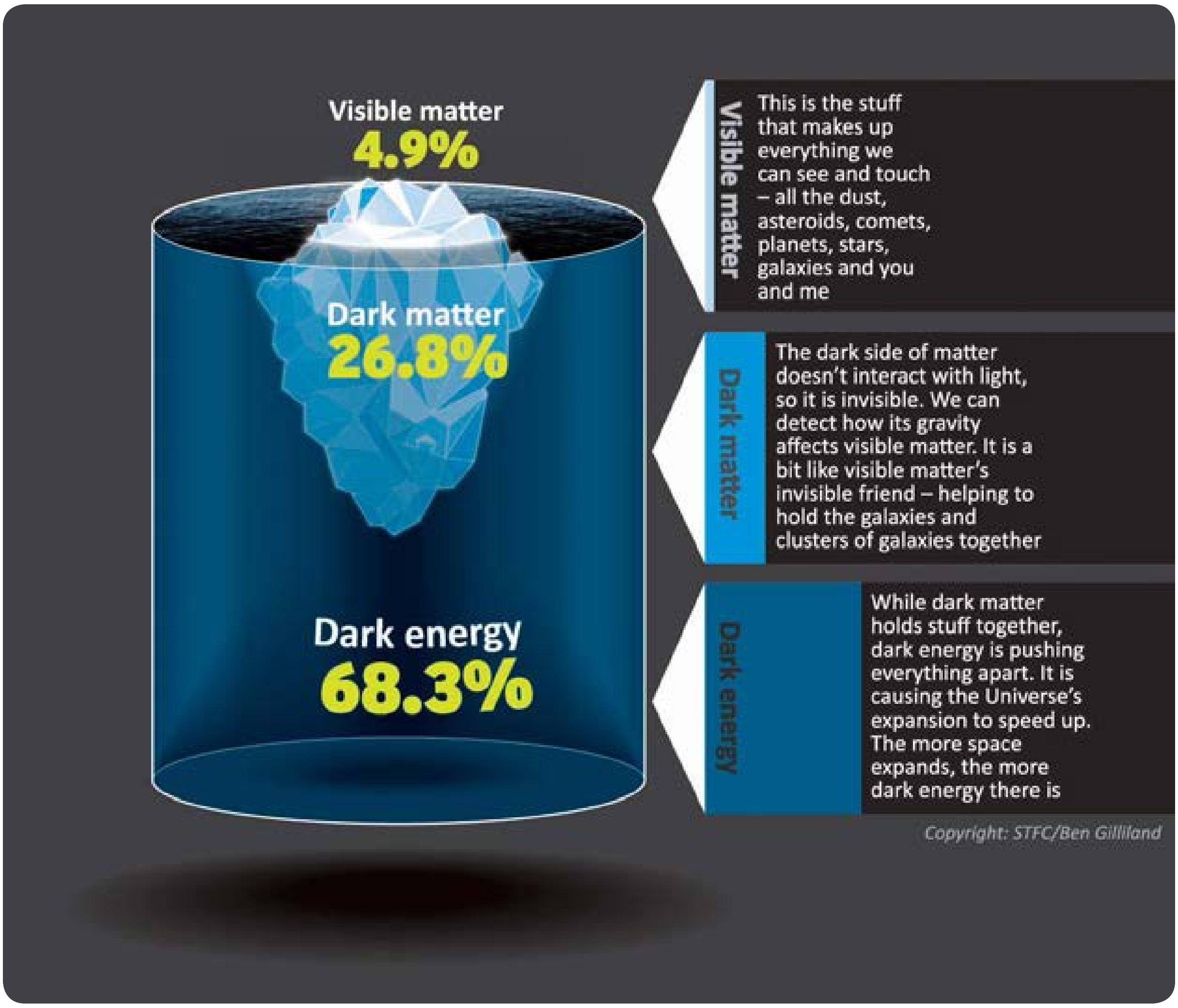
Physics, then, can change the way we lead our lives as well as how we view the Universe. At the most fundamental level, the principles underlying quantum mechanics and relativity have provided the foundation for an extensively tested, impressively accurate description of the Universe both at the smallest attainable scale (the 'micro-cosmos') and at the very largest (the 'macro-cosmos').

The **micro-cosmos** – the domain of elementary particles and their fundamental interactions (see Box A page 17) – is captured in the so-called Standard Model of particle physics. This model has passed numerous experimental tests with flying colours – in particular, but not exclusively, involving experiments using particle accelerators operating right at the frontier of the feasible in terms of energy and intensity. Moreover, it has predicted the existence of particles and phenomena that were all later discovered successfully, with the discovery of the Higgs particle at the Large Hadron Collider (LHC) in 2012 the undisputed highlight.

The **macro-cosmos** – the world of celestial objects and their evolution – has its own Standard Model in the shape of the Big Bang Model of cosmology (see Box B page 18). This successfully predicted, for instance, the existence and properties of the CMB.

In the first minutes after the Big Bang, nearly 14 billion years ago, the Universe was so hot that only the simplest structures (the elementary particles) could exist and both Standard Models – covering the infinitely small and the infinitely large – came into play. Perhaps the best illustration of this relates to the number of different 'flavours' of light neutrino particles: from precision experiments at high-energy accelerators, we know this number to be three as set out in the Standard Model of particle physics; but this same number is also required by the Big Bang Model of cosmology, particularly in order to understand the abundance of light chemical elements observed in connection with the process of nucleosynthesis that occurred in the first few minutes after the Big Bang.

…to new challenges pointing to unknown paths
Nevertheless, our quest for a detailed understanding of the Universe remains incomplete. From a theoretical perspective, coherent descriptions of the cosmos almost invariably require the existence of new particles – in other words, particles additional to those included in the Standard Model of particle physics. From an experimental perspective, meanwhile, observations of the large-scale structure of the cosmos and the intricacies of the CMB, for example, point to the existence of unknown forms of matter and energy, such as Dark Matter and Dark Energy.



The relative abundances of the three presumed constituents of mass-energy in our Universe: visible matter, dark matter and dark energy (Credit: STFC/Ben Gilliland)

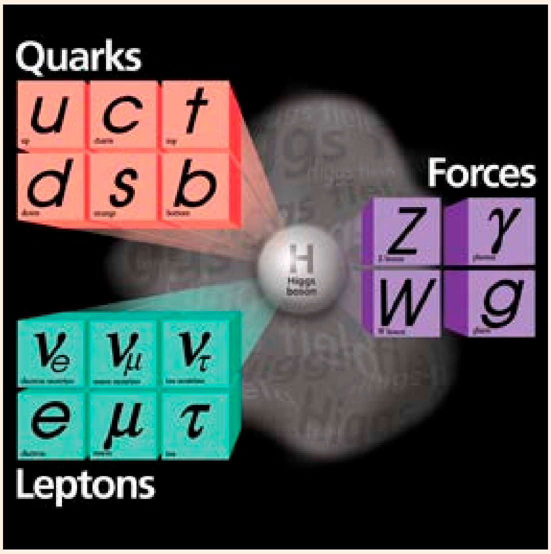
Box A: The Elementary Particles

The chemical elements, the atomic nucleus, electrons, protons and neutrons – at some time in history, all have been identified as the Universe's smallest constituent. Of these, however, only the electron, discovered in 1897, still deserves its status as an 'elementary particle'.

Protons and neutrons are now understood to be composite particles, each consisting of three quarks (two 'up' quarks and one 'down' quark for the proton, two 'down' quarks and one 'up' quark for the neutron) bound together by the 'strong nuclear force'. Protons and neutrons cluster in roughly equal numbers to form atomic nuclei whose chemical properties are determined by the number of protons they contain (e.g. one proton for hydrogen, 79 protons for gold). Pairing a nucleus that contains a certain number of protons with the same number of electrons – which carry the opposite electrical charge from protons – results in an electrically neutral atom, thanks to the 'electromagnetic force'. The 'weak nuclear force', meanwhile, can change protons into neutrons and vice versa, mutating one chemical element into another – a process that involves neutrinos.

The neutrino, the electron, the 'up' quark and the 'down' quark are the four elementary particles that suffice to describe almost everything we see around us. We call these particles 'the first family'. For reasons we do not yet understand, Nature has replicated this first family not once but twice – with particles that (apart from their masses) are identical to their corresponding particles in the first family. For instance, the muon and the tau are simply more massive versions of the electron. The heaviest of all elementary particles is the 'top' quark; discovered in 1995, this has a mass similar to that of a gold nucleus.

The Standard Model of particle physics provides a detailed, quantitative description of the electromagnetic, weak nuclear and strong nuclear forces between elementary particles; it

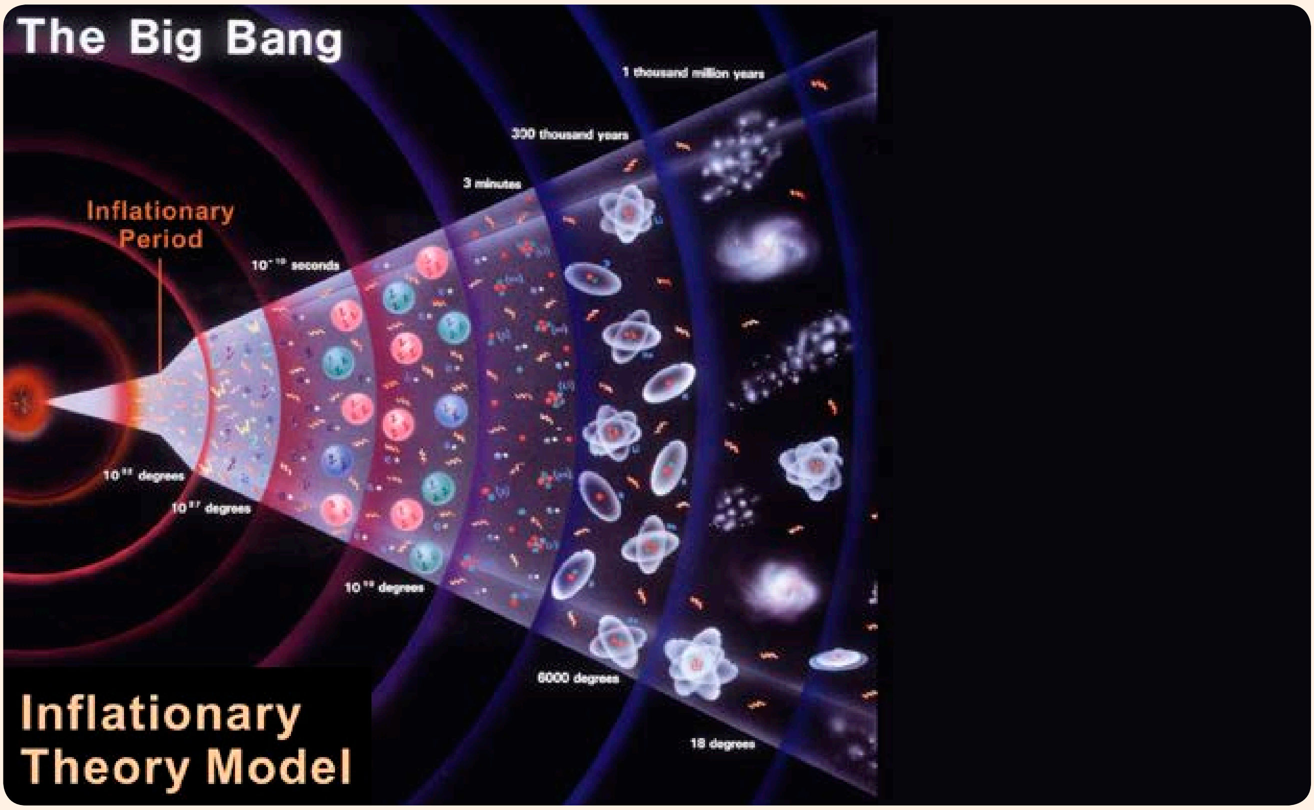


only omits the surprisingly feeble gravitational force. Each force – or 'interaction' – is put to work via the exchange of a so-called 'force-specific mediator particle': the massless photon for the electromagnetic force; the massless gluon for the strong nuclear force; and the massive Z and W bosons, discovered in 1983, for the weak nuclear force.

A pivotal aspect of this Standard Model is the Brout-Englert-Higgs mechanism, invented in 1964, by which the Z and W bosons acquire their mass; this mechanism also endows each elementary particle with its mass and predicted the existence of a unique particle – the Higgs boson. The discovery of the Higgs boson in 2012, recognised by the awarding of a Nobel Prize in 2013, crowned the phenomenal success of the Standard Model of particle physics. Even non-zero neutrino masses and neutrino mixing can be incorporated within the model (notwithstanding the fact that neutrino masses are many orders of magnitude smaller than those of the other elementary particles).

On the other hand, none of the Standard Model particles are compatible with the properties required to describe Dark Matter. This is where the Standard Model currently falls short – and where experiments in the field of astroparticle physics enter the game!

Box B: The Early Universe and its Evolution



The Big Bang Model of cosmology is one of the most extraordinary feats of human intellect. With this model, we begin to secure a detailed quantitative understanding of how our Universe evolved from its extremely hot 'birth' in the Big Bang about 14 billion years ago, to the literally 'cool' cosmos we live in today.

About a century ago, it was discovered that, on average, galaxies are flying away from our own Milky Way galaxy with a velocity roughly proportional to their distances from it; in other words, our Universe is expanding. While expanding, the Universe gradually cooled down and so allowed ever more complicated structures to be formed: initially, only the most fundamental constituents (i.e. elementary particles) but subsequently protons and neutrons, atomic nuclei, neutral chemical elements, stars, galaxies and, eventually, human beings. By extrapolating the observed expansion rate backwards in time, we can determine the age of our Universe.

Rewind the clock to when the Universe was nearly 400,000 years old and we find an opaque plasma of, notably, photons, electrons and atomic nuclei at a temperature of about 3000oC. At this temperature, the electrons and the nuclei start to combine to form electrically neutral chemical elements, suddenly allowing photons to travel freely. Today, these same photons provide us with an image of the infant, 400,000-year-old Universe in the shape of the CMB first observed in 1964. Since the Universe continued to expand and cool down, today this corresponds to a temperature of minus 270.4°C.

Rewind the clock even further, to just a few minutes after the Big Bang, and we find ourselves in an almost unimaginably hot Universe of about 1,000,000,000°C where, for example, protons and neutrons bounce around freely. At such temperatures, the protons and neutrons start to clot together to form light atomic nuclei such as hydrogen, helium and lithium. The relative abundance of these critically depends on two factors: firstly, the Universe's cool-down rate (influenced especially by the number of massless or nearly massless elementary particles – notably the number of neutrinos); secondly, the lifetime of unstable neutrons (if short, only hydrogen nuclei – single protons – will survive; if long, many nuclei of heavier elements will also form). Given the measured lifetime of the neutron of almost 900 seconds, the observed abundances of the chemical elements are in perfect agreement with the 'three neutrino hypothesis' included in the Standard Model of particle physics.

A few seconds after the Big Bang, things were even hotter. The Universe attained a temperature of about 10,000,000,000°C. Just below this temperature – a fraction of a second later – collisions between protons and electrons lacked the necessary energy to overcome the small mass difference between neutrons and protons and produce neutrons and electron-neutrinos. As a result, protons and neutrons started to evolve independently. Essentially, this left the neutrinos free; in other words, the Universe suddenly became transparent for them. These primordial neutrinos still float around in the Universe to this day, with a density of about 100 per cubic centimetre for each neutrino type – and just waiting for astroparticle physicists to find them…

Turn the clock back even further and we enter uncharted territory. First we encounter the moment when, out of the primordial plasma of quarks and gluons, stable protons and neutrons began to be formed. But before that, a remarkable – as yet unexplained – event must have occurred: the original symmetry between matter and anti-matter was broken. This resulted in a tiny imbalance between particles and anti-particles of about one in a billion, which in turn – after the annihilation of particles with their corresponding anti-particles – acted as a seed for our present matter-dominated Universe…and therefore for our own existence!

Even more speculative is the hypothesis that, very shortly after the Big Bang, our Universe underwent a period of huge expansion, a process dubbed 'inflation'. Inflation would explain the uniformity of the CMB, as well as the near-flatness of the Universe's space-time fabric and the absence of magnetic monopoles (a lone magnetic south or north pole). Quantum fluctuations during this period should have given rise to tiny density variations and consequently to ripples in the space-time fabric. We should still be able to observe these ripples in the form of primordial gravitational waves, either directly or via the imprint they left on the CMB. These are challenges that the astroparticle physics community is eager to address.

Another exciting portal extending beyond the two Standard Models arises from an already confirmed but still poorly understood elementary particle: the neutrino. A range of laboratory experiments are frantically searching for new – possibly sterile – neutrinos as well as trying to determine the still unknown masses of the three confirmed neutrino flavours. At the same time, astrophysical surveys studying the evolution of large-scale structures of galaxies, galaxy clusters and even super-clusters of galaxies, combined with detailed measurements of the CMB, enable us to put stringent constraints on the number and masses of these neutrinos. Tantalisingly, comparison of these two complementary datasets will soon either confirm or refute the accuracy of the two Standard Models.

Last but by no means least, the combined power of the Standard Models falls way short of explaining how our Universe evolved from, on the one hand, a balance between matter and anti-matter at the time of the Big Bang to, on the other, the present matter-dominated Universe. Explaining this will certainly depend on establishing the existence of new phenomena beyond those included in the Standard Models.

So, much remains to discover, dissect and digest. But if the direction of travel and eventual destination are relatively clear, how can we make sure we actually arrive there?

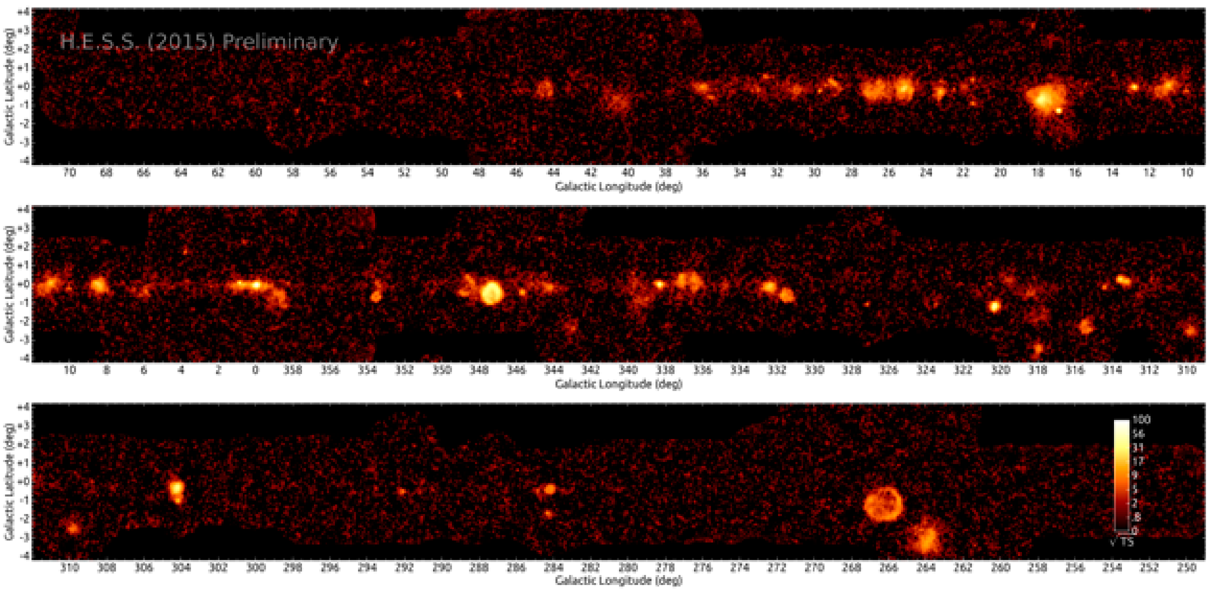
Astroparticle physics: a key component in our quest

As a field of research, astroparticle physics is relatively new. It is also evolving rapidly. Positioned at the interface of particle physics, astronomy and cosmology, it is ideally placed to deliver further advances in our understanding of both the infinitely small and the infinitely large.

From a historical perspective, astroparticle physics can claim to be over a century old, tracing its origins back to 1911 and the discovery of highly penetrating radiation coming from outer space – a type of radiation dubbed 'cosmic rays'. Cosmic rays are now understood to be initiated by extremely high-energy atomic nuclei hurled towards Earth by as yet unknown sources in the Universe. In the debris that cosmic rays create in our atmosphere, the first anti-particle – the anti-electron, or positron – was observed in 1932. Four years later, the muon – a heavy copy of the electron and the first known particle of the so-called 'second family' – was discovered in cosmic rays. Another two decades then passed before confirmation of the neutrino hypothesis by what we now refer to as a nuclear reactor short-baseline experiment.

It was in the 1980s, though, that the field of astroparticle physics really took off with the discovery of supernova SN 1987A in the Tarantula nebula (achieved by detecting its radiation in neutrinos) and of the very-high-energy photon radiation coming from the Crab pulsar. The next leap forward came in 1998, when it was discovered that neutrinos can change identity – implying that, contrary to the Standard Model of particle physics, neutrinos cannot be massless. As a result, astroparticle physics extended into the now flourishing field of neutrino oscillations, using atmospheric, solar, reactor and accelerator neutrinos, and complementing long-established direct measurements of nuclear beta decay to reveal neutrinos' nature. Meanwhile, astrophysicists and astroparticle physicists were collecting abundant, though indirect, evidence for the existence of the mysterious, ubiquitous Dark Matter and Dark Energy, which together comprise 95% of the Universe's mass-energy content. Unveiling the exact nature of Dark Matter and Dark Energy is a cornerstone of the astroparticle physics research mission, while studies of the CMB also form an integral part of the landscape.

Astroparticle physics also aims to shed new light on cataclysmic, unimaginably violent phenomena occurring in our Universe by complementing well-established observations across the electromagnetic spectrum with measurements of high-energy cosmic rays, high-energy gamma rays, high-energy neutrinos and gravitational waves. The utilisation of these multiple 'messengers' and the priceless information and potential insights they bring with them – along with the discovery of PeV-scale cosmic neutrinos (in 2013) and the first direct detections of gravitational waves (in 2015) – means we are now truly entering a new era: the era of multi-messenger astronomy.



High Energy Stereoscopic System survey of the Milky Way

1. Connecting the Infinitely Large and Infinitely Small

Animation of a cosmic-ray shower in the sky above the city of London.

Tiny particles, huge questions
Astroparticle physics is a dynamic, interdisciplinary research field. Consequently, its precise scope can be hard to define; indeed, definitions vary slightly from country to country. Nevertheless, a general consensus surrounds the fundamental questions that astroparticle physics aims to address.
More than that, generating an answer to any of these questions will almost certainly constitute nothing less than a major breakthrough in our understanding of the Universe. For example:

- *What is Dark Matter?*
- *What is Dark Energy?*
- *What caused our Universe to become dominated by matter and not anti-matter?*
- *Can we probe deeper into the earliest phases of our Universe's existence?*
- *What are the properties of neutrinos?*
- *Can we identify the sources of high-energy neutrinos?*
- *What is the origin of cosmic rays?*
- *Do protons decay?*
- *What do gravitational waves tell us about General Relativity and cosmology?*
- *What will multi-messenger astronomy teach us?*

The Large Hadron Collider is the world's largest and most powerful particle accelerator (Credit: CERN)

Connections: four fields of research
Astroparticle physics research is often subdivided into the quest for a better understanding of the extreme Universe, the dark Universe, mysterious neutrinos and the early Universe. Despite this division, these four subfields are intimately connected to one another – not least because, from a theoretical perspective, the overarching 'holy grail' is to capture all our knowledge and incorporate it in an all-encompassing framework extending beyond our present understanding as set out in the Standard Model of particle physics and the Big Bang Model of cosmology.

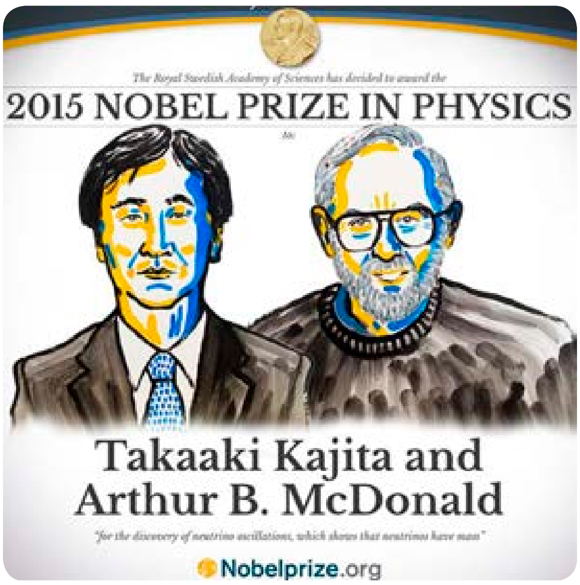
Furthermore, these fields are complementary from an experimental perspective. Take neutrino properties, for instance. As well as dedicated neutrino experiments, measurements of the CMB provide information on the sum of the three neutrino masses, while high-energy neutrino telescopes can potentially shed light on neutrino mass ordering. On the other hand, the near-megaton-scale detectors used for long-baseline neutrino beam experiments will also be able to detect neutrino bursts emitted by supernova explosions as well as to probe proton stability. High-energy gamma-ray and neutrino telescopes, meanwhile, can be used to search for indirect signals of Dark Matter annihilation at specific locations in the Universe, complementing direct searches for the scattering of Dark Matter particles by experiments deep underground as well as the hunt for Dark Matter signatures in collider experiments such as those at the LHC.

Such synergies only serve to underline the close connections, interrelationships and interdependencies between the various fields of research that collectively make up the astroparticle physics landscape.

A very bright future
Over the past decades, astroparticle physics has established itself as an important scientific discipline – just as particle physics, astronomy and cosmology have done. Like those sister disciplines, it has generated knowledge and insights with potential to generate spin-off benefits: for example, innovative technologies for low-level light sensors and high-precision seismic sensors, and revolutionary imaging concepts using cosmic-ray muons.

This emergence of astroparticle physics as a core scientific discipline is reflected by a string of Nobel Prizes awarded in this field since the turn of the century:

- 2002: for work on '…detection of cosmic neutrinos…';
- 2006: for work on '…anisotropy of the cosmic microwave background…';
- 2011: for work on the '…accelerating expansion of the Universe …'; and
- 2015: for the '…discovery of neutrino oscillations…'.



The discovery of cosmic neutrinos in 2013 and the detection of gravitational waves in 2015 are further causes for excitement and confidence in the future. Moreover, several next-generation experiments have just started or are about to begin operations: these include advanced gravitational-wave detectors and ton-scale direct Dark Matter and neutrinoless double-beta decay searches. Others are in the early phases of construction: these include the KM3NeT neutrino telescope and the CTA next-generation high-energy gamma-ray observatory. Others, such as long-baseline neutrino facilities and next-generation reactor neutrino experiments, have reached the advanced planning stage. At the same time, the astroparticle physics community is thinking about future experiments such as next-generation gravitational-wave detectors here on Earth (ET) and up in space (LISA).

It may be too early to speculate about exactly where the field of astroparticle physics will stand a decade from now. One thing, though, is absolutely certain. This is a field of science where the potential for influential, impactful new discoveries is high. Unlocking that potential requires sufficient investment and exploitation funding – and just a little cooperation from Mother Nature.

High-school students – next generation scientists – displaying and explaining their findings on cosmic-rays using home-made particle detectors.

2. The Extreme Universe: a Multi-Messenger Approach

In astroparticle physics, there really is no such thing as too much information. The more we can explore and examine the full range of particles at large in the cosmos – and the more we can link our discoveries and findings together – the better we can understand the Universe, its most extreme characteristics and its most fascinating and awe-inspiring phenomena.

Messages from above

Surprisingly, most of the visible light and other electromagnetic radiation we observe from our Universe is emitted by objects in near-thermal equilibrium – in other words, by objects at an almost uniform temperature – and follows Planck's law of black-body radiation. The spectrum of our Sun matches Planck's prediction for an object with a temperature of about 6000°C. The afterglow of the Big Bang matches Planck's law (to about one in 100,000), having a temperature just under 3°C above absolute zero. We ourselves emit black-body radiation corresponding to an effective skin temperature of about 30°C. Even black holes are believed to emit black-body radiation (known as Hawking radiation in this case), implying that they can be assigned a temperature too. Apparently, then, we live in a 'thermal' Universe.

But what of non-thermal behaviour in our Universe – equally important to providing a robust and comprehensive picture of the cosmos and its workings? Primary evidence of such behaviour comes from cosmic rays, which occasionally reach astonishing energies of up to 100 billion GeV. With the exception of the Big Bang, not even the most extreme astronomical objects can attain the temperatures required to emit particles with such energies. Instead, these can be produced when ultra-relativistic particles – produced, for example, in the aftermath of a cataclysmic event such as a supernova explosion – interact with ambient gas, photons or magnetic fields. Alternatively, as they decay, super-heavy and as yet unknown particles could spawn very-high-energy secondary particles. Even more exciting, they could be the result of mechanisms that are as yet entirely unknown.

In terms of shedding light on non-thermal events that occur in our Universe, however, cosmic rays have significant limitations. It may be relatively easy to reconstruct their energies and directions, but as a messenger particle they have one severe drawback: from a measurement point of view, their directions are scrambled by galactic and intergalactic magnetic fields. Unless their energy is extremely high, it can be hard to track them back to their sources.

A multitude of messengers
Fortunately, with respect to non-thermal events, other messenger particles have been observed: high-energy gamma rays, high-energy neutrinos and, very recently, gravitational waves. Unlike cosmic rays, these are not affected by galactic and intergalactic magnetic fields. Nevertheless, each has its own peculiarities. For example, gamma rays are easily absorbed by interstellar dust, while neutrinos and gravitational waves are notoriously difficult to detect.

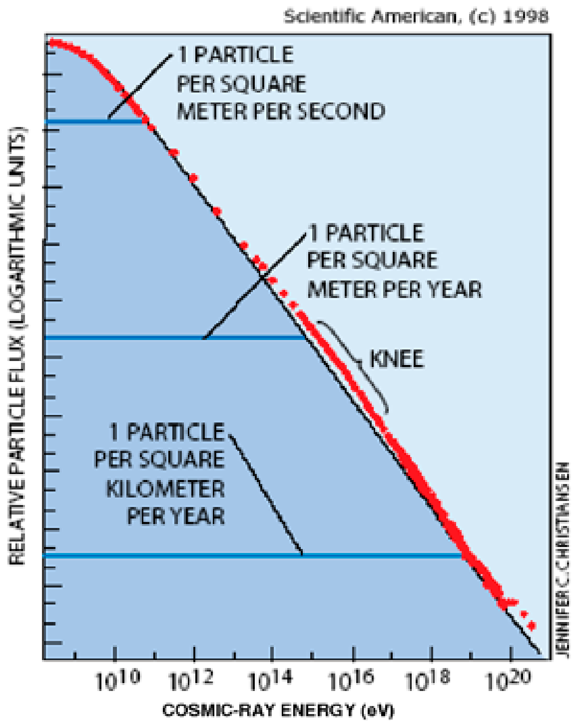
The key to a better understanding of the non-thermal Universe – and to pinpointing the sources of high-energy cosmic rays – is to combine the data that can be obtained by analysing all four types of messenger: high-energy cosmic rays, high-energy gamma rays, high-energy neutrinos and gravitational waves. This is called **'the multi-messenger approach'**. Crucial to its success is the already ongoing process of interconnecting multi-messenger observatories with one other, as well as with 'traditional' observatories limited to viewing the electromagnetic spectrum. In this way, it is hoped, the source of a cataclysmic event can be pinpointed by triggering rapid follow-up observations harnessing the widest range of technologies.

The multi-messenger approach also enables a wide array of other exciting work, such as searches for the decay of extremely heavy particles and for Dark Matter annihilation – even the violation of 'sacred symmetries' such as so-called Lorentz invariance (one of the cornerstones of physics). Just as intriguingly, detailed studies of gravitational waves will provide unprecedented tests of the General Theory of Relativity.

So what precisely are these four messengers – and how can we study them?

High-energy cosmic rays

World-record energies
Cosmic rays are predominantly protons and heavier atomic nuclei. They hit molecules in Earth's atmosphere at an altitude of 15-20 kilometres, generating avalanches of secondary particles called 'air showers'. Cosmic rays span a gigantic energy range, from sub-GeV to record energies of at least



The all-particle spectrum of cosmic rays
(Credit: Scientific American)

100 billion GeV – roughly the kinetic energy of a hard-hit tennis ball. Although low-energy cosmic rays are known to come from the Sun and other stars, the sources that spit out atomic nuclei with energies millions of times higher than anything humans can achieve even in our most powerful particle accelerator – the LHC – remain a mystery.

'Low-energy' rays: balloons and satellites
Primary cosmic rays can only be measured directly by detectors flown on balloons in the stratosphere or on satellites. Due to weight limitations, space-borne detectors can reach a few TeV at most. Nevertheless, sub-TeV cosmic rays offer a rich harvest of scientific information – as shown convincingly, for example, by the Pamela satellite launched in 2006 and the AMS experiment installed on the International Space Station five years later. With exquisite accuracy, these measured primary cosmic-ray mass composition and the energy spectra of photons, electrons, protons and helium and other light nuclei, as well as their anti-particles. Interesting features observed in some of these spectra triggered animated debates on possible origins: could they be attributed to the decay of new particles, such as Dark Matter, or was an astrophysical cause more likely? The jury is still out.

The Alpha Magnetic Spectrometer experiment – AMS (Credit: NASA)

'High-energy' rays: huge-surface detectors
In 1938, French physicist Pierre Auger demonstrated that high-energy cosmic-ray air showers can reach the ground, allowing them to be recorded using a ground-based detector array. Since, on average, only a single 10 billion GeV cosmic ray will slam into each square kilometre of Earth's atmosphere per year, in practice a huge surface area must be instrumented if sizeable samples of high-energy cosmic rays are to be collected. The focus is on the highest-energy cosmic rays (probably of extragalactic origin), for two reasons: firstly because only these can realistically be back-tracked to their sources; secondly because, for primary protons, they should exhibit a cut-off around 50 billion GeV (due to the strongly enhanced probability of interacting with the ubiquitous photons in the CMB).

The Pierre Auger Observatory (known simply as 'Auger'), installed on the Pampa Amarilla in Argentina and completed in 2008, is the world's largest and most sensitive air-shower detector. It comprises 3000 square kilometres of prairie (about ten times the size of Paris) carpeted with 1600 water-filled tanks to record the air-shower particles (electrons and muons) hitting the ground. This array is overlooked by five telescopes that record – during darkness – the faint fluorescent light caused by air showers in the atmosphere. Combining these two measurements to determine the direction and energy of the original incoming cosmic ray significantly reduces uncertainties.

At the highest energies, Auger typically records tens of events per year. Along with the tens of thousands of events at lower energies, these have already produced tantalising results including hints of sources and a clear flux suppression around the expected 50 billion GeV. It also became clear, though, that further progress would hinge critically on much better mass differentiation. To achieve this, Auger will augment the water tanks with large scintillators in order to get a handle on the electron-to-muon fraction in each air shower; this fraction is correlated to the mass (i.e. charge) of the primary cosmic ray. Installation should be complete by 2019.

In addition Telescope Array (TA), a smaller air-shower detector installed in Utah in the US and completed in 2007, will upgrade the size of its array by a factor of four to become comparable

Schematic rendering of the Pierre Auger Observatory (Credit: Pierre Auger Observatory)

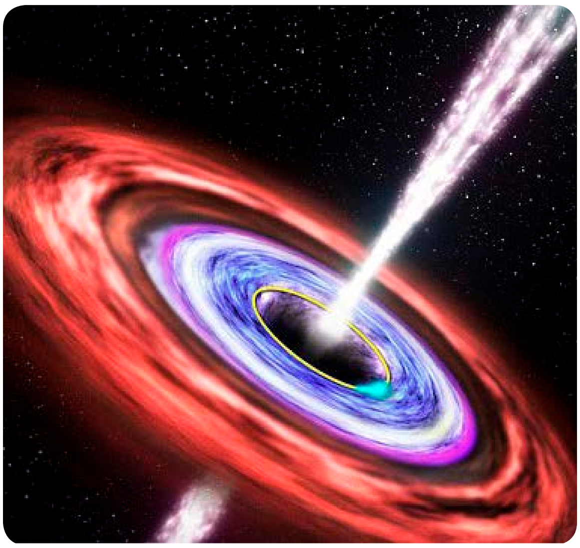
The Pierre Auger Observatory at Malargue, Argentina (Credit: Pierre Auger Observatory)

in size to Auger. Together, the two observatories cover the whole sky and are working towards combined data analyses. With their upgrades, they are expected to begin shedding light on the mechanisms behind the strong decline of the cosmic-ray flux at the highest energies, which should aid discovery of the sources that are hurling those 100 billion GeV particles towards us.

New detection techniques
The global cosmic-ray community is already working towards next-generation observatories. In view of costs, a 'simple' tenfold expansion of current observatories is unrealistic. Instead, new detection technologies and concepts are being explored. On the ground, very promising results have been shown by test campaigns to detect cosmic rays using radio antennas to pick up the tiny radio waves induced by air showers moving in Earth's magnetic field. In space, meanwhile, the JEM-EUSO project plans to observe the fluorescent light from air showers using a telescope mounted on the International Space Station or orbiting as a free flyer.

High-energy gamma rays

The observable electromagnetic spectrum: pushing the limits
Humans have studied the Universe for centuries, using an ever-increasing range of the electromagnetic spectrum: from eV energy photons in visible light to lower-energy radio photons and higher-energy roentgen photons. Over recent decades, to observe extremely energetic photons – high-energy gamma rays – with energies ranging typically from 100 GeV to 30 TeV, a new instrument has been developed: the Imaging Atmospheric Cherenkov Telescope (IACT). When a high-energy gamma ray hits Earth's atmosphere, it creates a cascade or 'shower' of secondary particles. This gives rise to Cherenkov radiation, a faint bluish light, which is viewed by positioning at least two IACTs to produce a stereo image of the shower. From this image, the direction and energy of the original high-energy gamma ray can be determined.



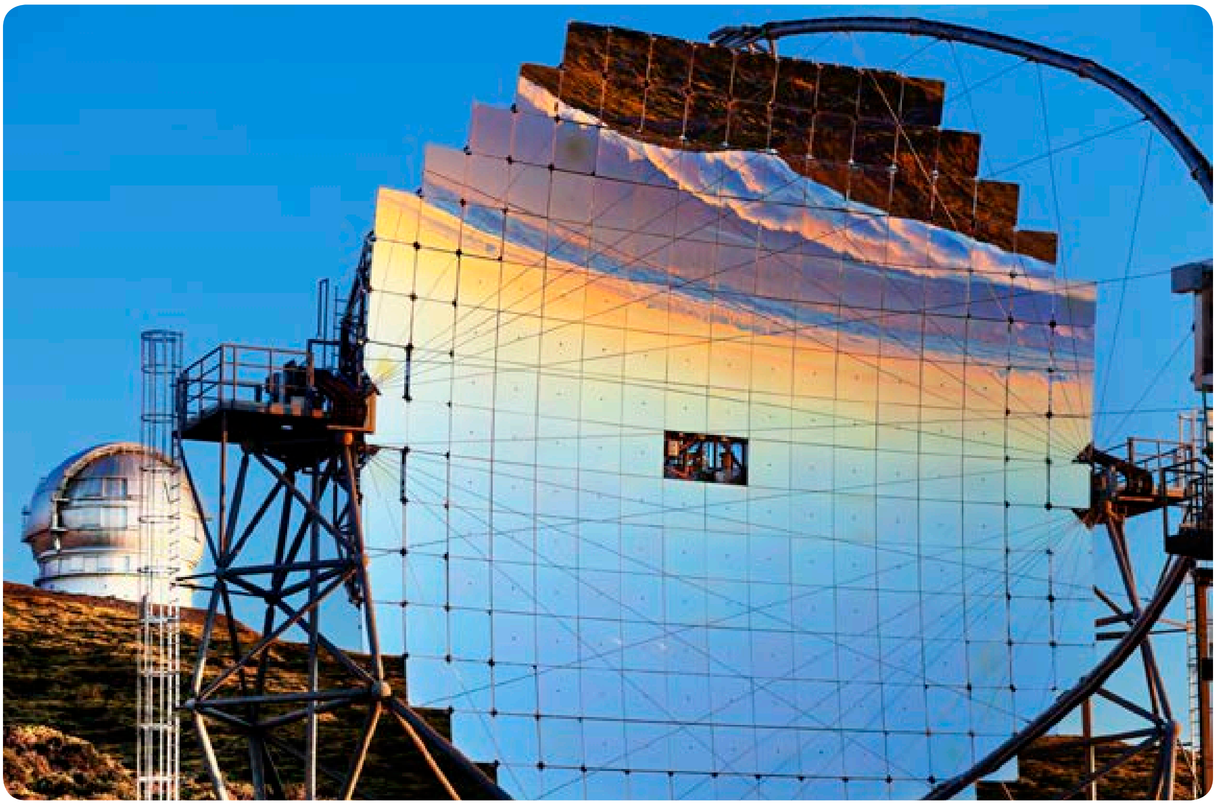
Gamma ray burst schematic

The Imaging Atmospheric Cherenkov Telescope principle (Credit: CTA)

This technology was perfected by the HESS experiment in the southern hemisphere and by the MAGIC and VERITAS experiments in the northern hemisphere. Collectively, these have identified and studied more than 150 high-energy gamma ray sources, including breath-taking objects such as supernova remnants, pulsars, binary stars and active galaxies presumably hosting super-massive black holes at their centres. The measured fluxes, energy spectra and arrival directions of these gamma rays will help to elucidate the origin of these non-thermal particles and provide us with information on the morphology, (form, shape or structure), of the source, for example, or where super-heavy particles proliferate and what their masses are. More speculatively, some models of theories on quantum gravity predict that the speed of light has a tiny energy-dependence – which would be a violation of Lorentz invariance – and the extremely short wavelength of high-energy gamma rays could eventually reveal whether or not this is the case.

From experiment to observatory

To exploit fully the discovery potential of the study of high-energy gamma rays, a large community of astronomers and astroparticle physicists joined forces in support of a global project: the Cherenkov Telescope Array or CTA, which acquired ESFRI status in 2008. Unlike its predecessors which were operated as typical particle physics



MAGIC telescope, La Palma (Credit: CTA)

Artist's impression of the Cherenkov Telescope Array, Southern hemisphere array (Credit: CTA)

experiments, with members of the collaboration deciding the measurement programme and taking care not only of data collection, reconstruction and analysis but also of scientific publications, CTA will adopt standard astronomy practice and operate as an observatory. It will also be accessible to the whole astronomy and astroparticle physics community. As a result, in addition to its key science projects, it will accept and support project proposals from researchers outside the collaboration.

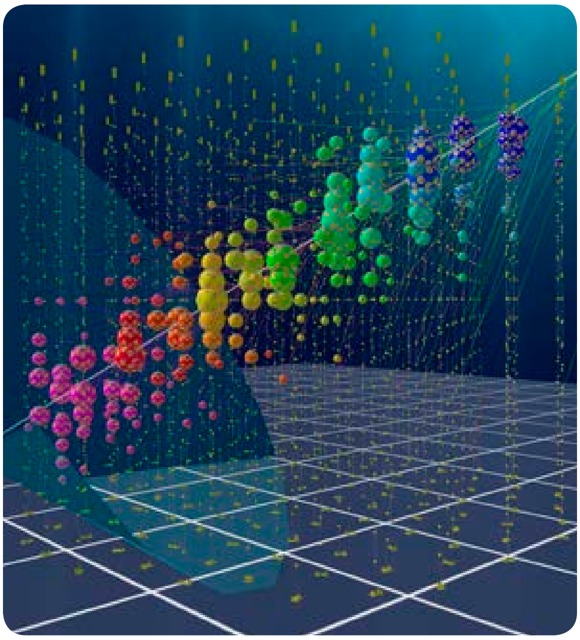
CTA will measure high-energy gamma rays over the entire sky, from as low as 20 GeV to as high as 300 TeV. The plan is therefore to install a total of about 100 telescopes across two sites: the ESO in Chile and the Roque de los Muchachos Observatory in Spain. Several prototype telescopes, still exploring alternative design options, have now been procured and tested. Negotiations have started among the main partners regarding how to share the overall CTA investment costs (about €300M) and exploitation costs (about €15M per year). In order to benefit from common data obtained through Fermi satellite observations of gamma rays with energies from 10 keV up to 300 GeV until at least 2018, it is desirable to start serial production soon. If this can be achieved, the large and diverse CTA user community will soon be able to embark on a very rich, very exciting programme of science.

Cherenkov Telescope Array prototype (Credit: CTA)

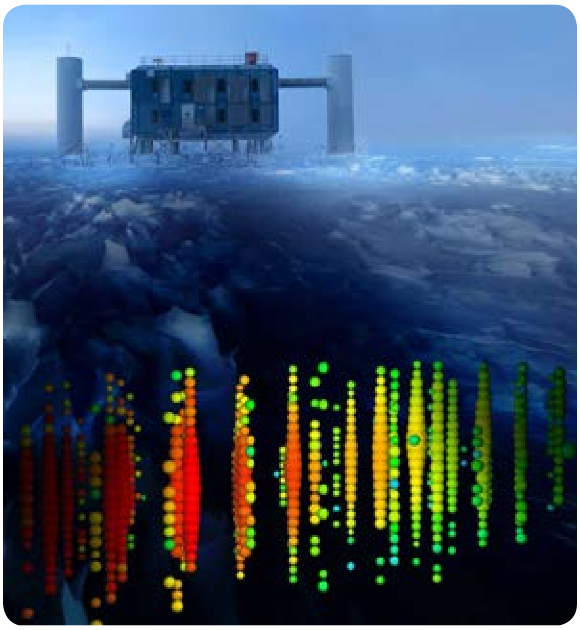
High-energy neutrinos

Extreme telescopes, extreme environments
Travelling more or less undisturbed, neutrinos can reach Earth from the most remote and densest regions of the Universe – allowing us to study the Universe with a completely new perspective. High-energy neutrinos can be detected through their interactions with matter, which result in the production of charged particles that, in turn, produce Cherenkov light flashes. Because of the extremely low probability of neutrino interaction, the targets used to observe these flashes need to be huge in volume. The target medium must be dark, transparent and cheap, and must allow for installation of a 3D grid of light sensors. Perhaps surprisingly, both deep-sea water and Antarctic ice meet this list of criteria.

Deployed in 2008 in the Mediterranean Sea at a depth of 2500 metres, the ANTARES neutrino telescope is obtaining data using 800 light sensors attached to 12 vertical lines; this corresponds to an instrumented volume of 0.01 of a cubic kilometre. The IceCube collaboration, meanwhile, has transformed 1 cubic kilometre of Antarctic ice 1.5 kilometres below the geographic South Pole into the world's largest neutrino telescope. Completed in 2010, it is obtaining data using over 5000 light sensors attached to 86 vertical lines.



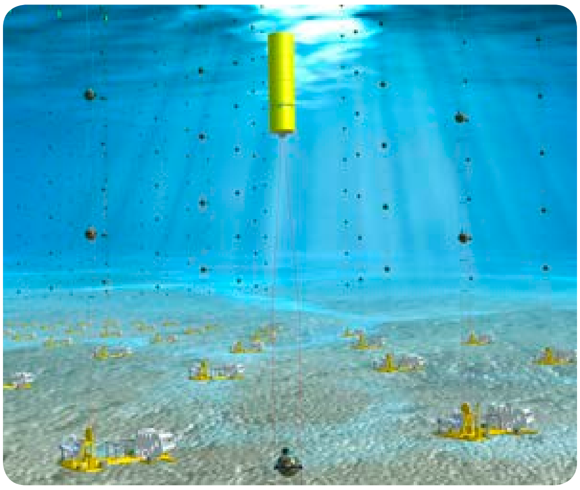
World's largest particle detector IceCube detects high-energy neutrinos from the cosmos



ICECUBE PeV event

2013 saw an important breakthrough when IceCube published an excess of events at very high energies. By the end of 2016, about 100 such events ranging up to 3PeV had been identified – enough to unambiguously ascribe a cosmic origin to these neutrinos. Various types of event have been studied: interactions of up-going and down-going neutrinos; 'showers' (dense energy depositions expected for electron-neutrino and neutral-current interactions); and 'tracks' (the signatures of charged-current muon-neutrino interactions). Overall flux is comparable to the diffuse gamma-ray flux observed by the Fermi satellite, suggesting common astrophysical sources. To identify these sources, the few track-like events (about ten per year) are of particular interest because the direction of the neutrinos can be determined most accurately. Unfortunately, to date, the statistics have been insufficient to identify unambiguously a neutrino point source.

The observation of cosmic neutrinos has boosted plans for the construction of next-generation neutrino telescopes. At the South Pole, IceCube has conceptual plans for a detector with an instrumented volume of 10 cubic kilometres – IceCube-Gen2. Baikal GVD, meanwhile, recently deployed the first two of its eight to twelve planned clusters designed to instrument a volume of about 1 cubic kilometre at a depth of 1500 metres in Siberia's Lake Baikal by 2020. In the



Artist's impression of Neutrino telescope KM3NeT (Credit: KM3NeT)

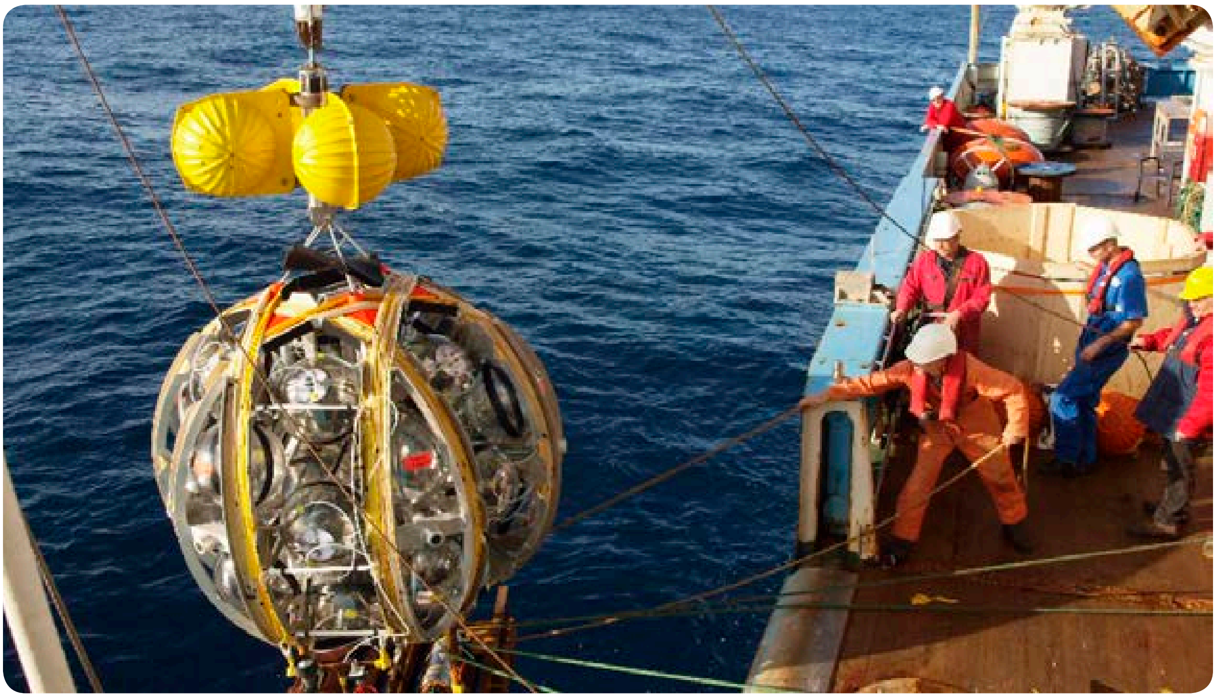
Mediterranean Sea, ESFRI project KM3NeT has begun installation of the 1-2 cubic kilometre ARCA detector at a depth of 3500 metres off the coast of Sicily. Unlike its predecessor ANTARES, ARCA employs as a light sensor an innovative multi-PMT digital optical module, with a reusable launcher vehicle allowing efficient, economic installation of lines on the sea bed. The first ARCA line was successfully deployed in December 2015.

Background signals: the neutrino mass hierarchy

While atmospheric neutrinos constitute a background for the detection of high-energy neutrinos of cosmic origin, they can also be harnessed as a unique signal to determine the so-called neutrino mass hierarchy – in other words, the order of the masses of the three neutrino mass eigenstates. The observed oscillation pattern of low-energy atmospheric neutrinos subtly depends on this hierarchy, due to the effects of matter. The accurate reconstruction of neutrinos with energies down to a few GeV, which is needed to determine the mass hierarchy, requires far denser instrumentation with light sensors than that used in high-energy neutrino telescopes. To address the mass hierarchy question, both the IceCube and the KM3NeT collaborations have put forward proposals – PINGU and ORCA, respectively – based on their already proven technologies.

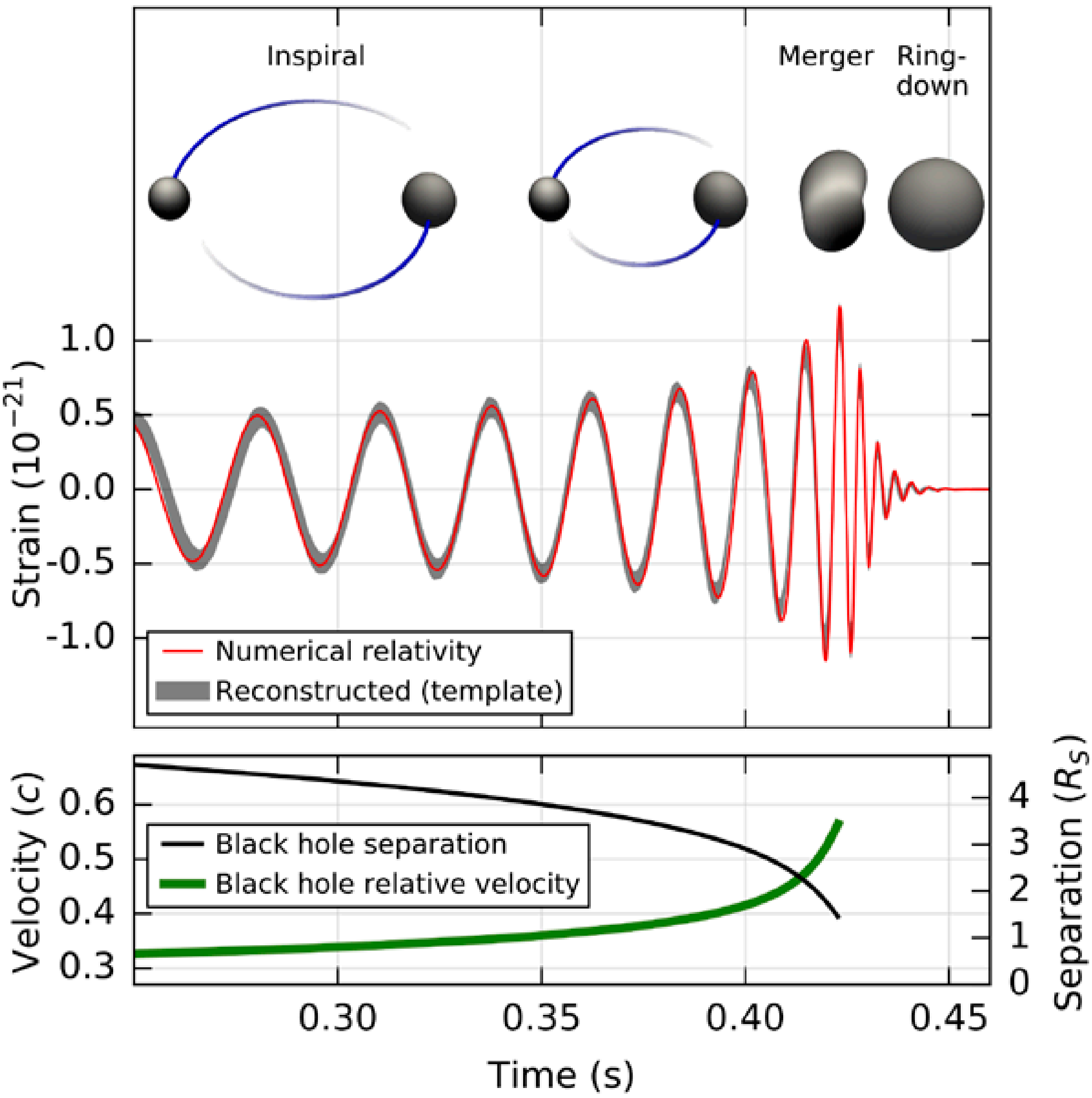
The ability of the worldwide neutrino telescope community to make breakthrough contributions to the long-standing questions of neutrino mass hierarchy and the sources of high-energy cosmic neutrinos, meanwhile, hinges on realisation of at least one densely instrumented megaton-order detector by 2020 and of sparsely instrumented 2-10 cubic kilometre detectors covering both northern and southern hemispheres – ideally using complementary technologies – early in the next decade.

String deployment of KM3NeT (Credit: KM3NeT)

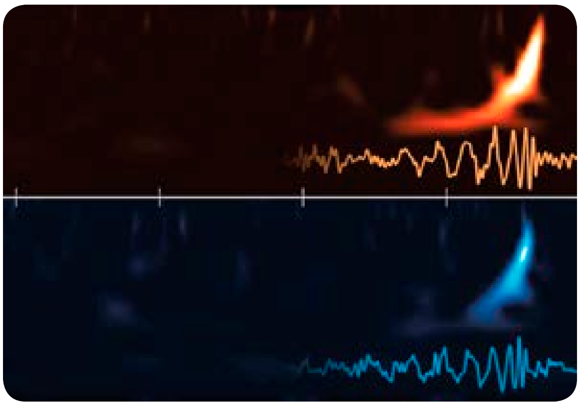


Gravitational waves

Detecting the undetectable
Einstein first predicted gravitational waves in 1916 but considered them too weak ever to be detected. Nevertheless, convincing indirect evidence for their existence was reported by Russell Hulse and Joseph Taylor in 1974 – work that secured them a Nobel Prize in 1993. But it was a century after Einstein's prediction that the LIGO-Virgo Consortium announced the first direct observation of a gravitational wave: a signal named GW150914 from 'gravitational wave' and the date of the initial signal. This incredible event was traced back to the coalescence of two large black holes, each of about 30 solar masses, which left behind a single black hole and radiated, within a fraction of a second, gravitational waves equivalent in energy to three solar masses. This was a real watershed, producing a torrent of scientific papers and opening yet another entirely new window on our Universe: gravitational-wave astronomy.



First direct observation of black holes – signal principle



Ringing chirp: the waveform of LIGO event observed at both locations (Credit: Physics World)

Messengers of catastrophe

Produced by the acceleration of mass, gravitational waves are tiny vibrations in space-time that propagate at the speed of light. Two orbiting compact objects – such as neutron stars or black holes – will emit a very characteristic 'chirp' when they coalesce. Indeed, at the moment of coalescence, this signal is incredibly powerful, briefly exceeding the combined power that all stars in the visible Universe emit as light.

Gravitational waves are visible out to extreme distances and allow many precision tests of General Relativity, as already shown convincingly using GW150914. They can also be used as distance markers ('standard candles') and so help map the Universe's expansion history (e.g. to provide independent information on Dark Energy). Within our own Milky Way, gravitational waves emitted by a supernova would allow us to peek right into its core. Perhaps most exciting of all, the brief period of inflation which occurred very soon after the Big Bang filled the cosmos with a faint background of gravitational waves, similar to the CMB. As a result, observation of these waves has the potential to yield a fascinating picture of our Universe as it was just after the Big Bang…

Extreme precision

It seems that Einstein had a point after all. Directly observing the tiny space-time ripples caused by a passing gravitational wave requires astonishing precision – typically one part in 10^{21}. First attempts at direct detection of gravitational waves started in the 1960s, using ton-scale bars designed to

Inspecting the LIGO mirrors (Credit: LIGO)

Aerial view of Virgo (Credit: Virgo)

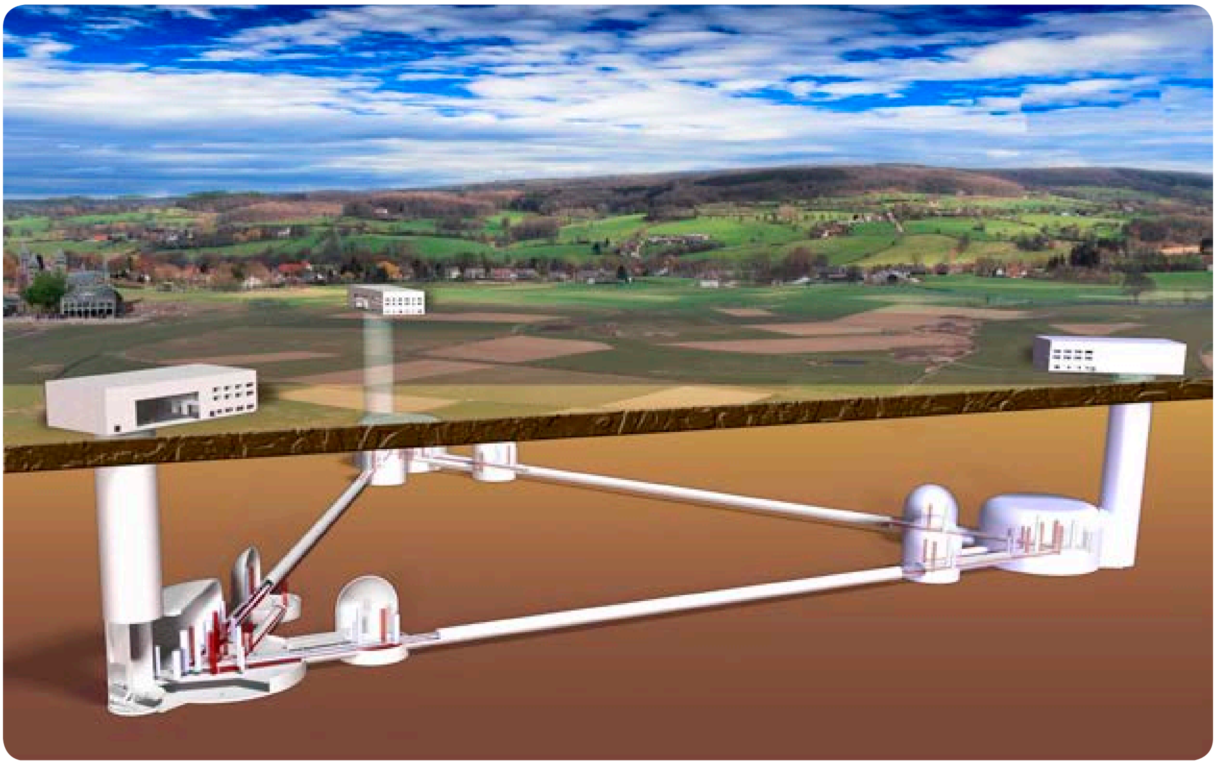
resonate at around 1kHz after a gravitational wave passed through them. They failed. Since the 1980s, the focus has shifted towards long-baseline (3-5 kilometres) laser interferometry with broadband sensitivity in the 100-1000Hz region for ground-based observatories.

First-generation interferometers on the ground ran until 2010-11. These projects established the infrastructures and key technologies needed to attain the required precision and, just as importantly, forged a closely collaborating global community ready to exploit the discovery potential of gravitational-wave physics. In particular, LIGO and Virgo operations are now conducted through the LIGO-Virgo collaboration, with coordinated data-taking periods, data-sharing, joint data-analyses and co-authorship of publications.

Next-generation ground-based interferometer projects – Advanced LIGO (US), Advanced Virgo (Italy), GEO-HF (Germany) and KAGRA (Japan) – have been funded. Advanced LIGO started its first science operations in 2015 and almost immediately recorded GW150914 (and subsequently at least two more events) which, apart from excellent science, generated public attention that was, in both senses, astronomical. Advanced Virgo is expected to join LIGO's next science run in 2017. With these two instruments obtaining data, tens of detections per year are anticipated – gravitational-wave astronomy (and physics) is clearly taking off! Detection rates and source localisation will be further enhanced if LIGO-India (foreseen for some time after 2020) becomes a reality and when KAGRA joins the already established LIGO-Virgo network.

Boosted by these first direct observations, R&D is progressing towards full third-generation gravitational-wave observatories. On Earth, the Einstein Telescope (ET) is the most advanced project; probing a thousand-times-larger volume of deep space, it will elevate gravitational-wave physics from weekly or monthly detections to a high-statistics era allowing high-precision astronomy and confronting the General Theory of Relativity with a plethora of experimental tests.

In space, LISA is the undisputed flagship project. Selected by ESA for its Gravitational Universe mission, with a launch date around 2030, LISA is best adapted to gravitational waves in the 10^{-4}-1Hz range, complementing the higher frequencies accessible to ground-based observatories. (Gravitational waves at even lower frequencies can be accessed by other technologies.) The LISA science programme includes observation of coalescing supermassive black-hole binaries out to redshifts of at least 10, and of the cannibalism of small black holes captured by supermassive black-holes out to redshifts of about 1. LISA will also probe our own Milky Way galaxy, providing a census of the 100 million relativistic compact binaries (comprising white dwarfs, neutron stars and stellar-mass black holes) estimated to exist there.



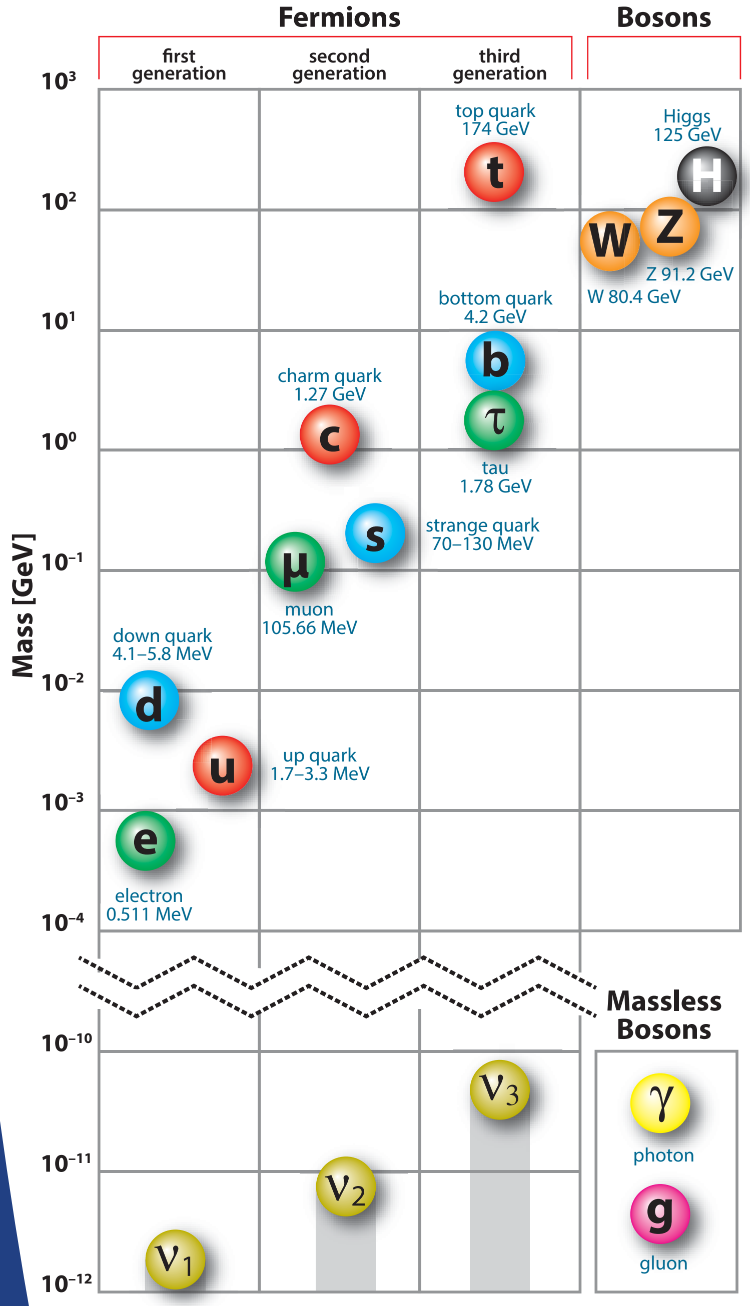
Artist's impression of the Einstein Telescope, a third-generation gravitational-wave (GW) detector (Credit: AEI)

3. Mysterious Neutrinos

Of all the elementary particles that make up the Universe and of all the messengers that form the focus of astroparticle physics, it is perhaps the neutrino that is the most enigmatic, curious and mystifying – stimulating a vibrant and vigorous quest for knowledge.

In the beginning: detection and discoveries

The concept of the neutrino was first introduced in 1930 by Austrian-born theoretical physicist Wolfgang Pauli. His aim was to rescue the sacred law of the conservation of energy – as well as momentum and angular momentum – which (if neutrinos did not exist) appeared to be violated during nuclear beta-decay. Yet it took experimenters until 1956 to record the first neutrino interaction (in fact, this involved an anti-neutrino) – a heroic task rewarded by a Nobel Prize in 1995.

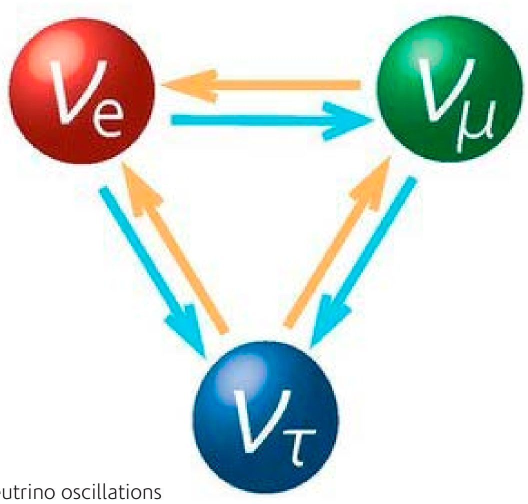


Masses of the particles in the Standard Model. The electron-, muon- and tau-neutrinos are mixtures of the mass-eigenstate neutrinos (ν_1, ν_2 and ν_3) shown in the illustration.

3. Mysterious Neutrinos

The reason why it took so many years to record the first interaction was not the rarity of neutrinos – on the contrary, we are literally swamped by them. The problem was that the neutrino's tendency to interact with matter is truly tiny. For example, the nuclear fusion processes in the centre of the Sun blast every square centimetre of Earth's surface with 60 billion neutrinos per second, but only a handful of these do not pass through unnoticed. A supernova – the violent terminal phase of certain classes of star – is an even more extreme neutrino factory, shedding around 10^{57} of the mysterious particles. Painstaking experiments (awarded the 2002 Nobel Prize), shielded deep underground from cosmic-ray muons, have revealed neutrinos from our Sun and even a few from the SN 1987A supernova explosion. Again, the neutrino had a surprise in store: the measured solar neutrino flux fell a factor two to three short of expectations – posing the so-called solar neutrino problem.

Detailed follow-up studies using, in particular, cosmic-ray-induced atmospheric neutrinos came to the rescue. The implications were profound: neutrinos created in the Sun's core and carrying electron 'flavour' can mutate (i.e. oscillate) into another neutrino flavour not only on their tortuous path up towards the Sun's surface but also while zipping through the near vacuum between the Sun and Earth. These mutations were not detected by the first-generation solar neutrino detectors – and this explained the measured deficit. This discovery of neutrino oscillations, which was awarded the 2015 Nobel Prize, constitutes the only direct and undisputed experimental proof of the inadequacy of the immensely successful Standard Model of particle physics. Incidentally, the discovery of multiple neutrino flavours – electron, muon and tau, and especially the muon flavour – was rewarded with a Nobel Prize in 1963. Accounting for four Nobel Prizes, the neutrino can certainly claim to be the most 'noble' particle…



Neutrino oscillations

Notwithstanding the many neutrino-related discoveries that have been made, neutrinos remain the most mysterious known particle. For example, now that neutrino oscillations have been established, neutrinos cannot be massless; but experiments have so far failed to determine any absolute neutrino masses and we only know that these are incredibly small. With neutrinos that have mass, charge-parity violation (i.e. a difference in the behaviour of neutrinos and anti-neutrinos) also becomes an open question which only experiments can answer. If charge parity is violated, it could very well be that it is thanks to neutrinos that we live in a matter-dominated world (in other words, that we are alive at all!). Moreover, as a neutral particle, the neutrino and its anti-neutrino could either be different particles from each other, like all others (i.e. they could be Dirac-type particles); or they could be the same (i.e. they could be a Majorana-type particle). Experiments should show which of these two possibilities is true.

Shortly after the Big Bang, the three neutrino species briefly played a prominent role in determining the relative abundance of chemical elements. After that, they essentially decoupled – leaving behind a hovering density of neutrinos (about 300 per cubic centimetre) for us to unveil. Measurements of this so-called primordial neutrino background would give us a picture of the Universe as it was only a few seconds after the Big Bang.

Collectively, these as yet unsolved mysteries help to explain why neutrino physics is currently as lively and as creative as ever…

Neutrino mass and neutrino nature

The traditional way to determine the mass of the electron-neutrino is to measure the electrons from tritium beta-decay, a process in which a neutron inside a nucleus transforms into a proton while emitting an electron and an anti-neutrino. From such experiments – and taking into account the very tiny values of the neutrino mass differences obtained from neutrino oscillation experiments – we can conclude that the heaviest of the three neutrinos has to be lighter than a couple of eV (i.e. just four-millionths of the mass of an electron).

As for the neutrino's nature (i.e. Dirac or Majorana), this can be explored via the very rare nuclear process in which two neutrons in a nucleus simultaneously undergo beta decay ('double-beta decay'). For standard double-beta decay, if the neutrino is Dirac-type, we would expect the release of two electrons and two anti-neutrinos. The observation of neutrinoless double-beta decay would therefore unambiguously prove the neutrino to be a Majorana-type particle. This would have a tremendous impact on our vision of Nature, involving discovery of a new type of matter (Majorana), and the so-called lepton number would no longer be a symmetry of Nature – potentially paving the way towards an understanding of how the asymmetry between matter and anti-matter in the Universe developed. Moreover, a new mass-generation mechanism (additional to the Higgs mechanism) could be at stake, providing a natural explanation of why neutrino masses are so tiny.

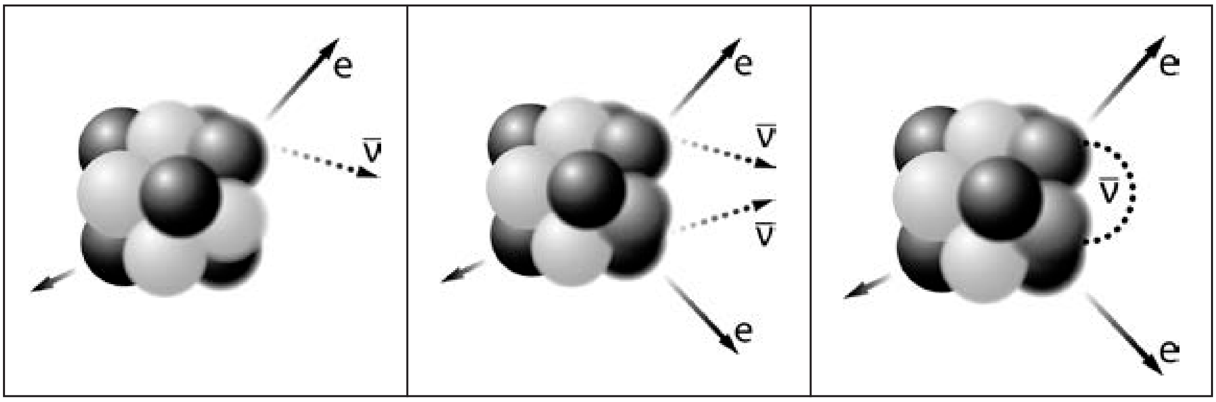
Absolute neutrino mass

Direct measurement of the electron-anti-neutrino's mass will be performed with high and, for the moment, unrivalled sensitivity by KATRIN, a world-leading experiment exploiting tritium beta-decay and located at the Karlsruhe Institute of Technology in Germany. Data-taking began in 2016. Calorimetric experiments at low temperatures, which exploit the electron-capture decay of holmium-163 and, unlike KATRIN, are sensitive to electron-neutrino mass, are currently at the R&D stage both in Europe (ECHo and HOLMES) and in the US. These promising searches require several years' development before being able to reach KATRIN's sensitivity but represent valuable efforts as they are based on a completely different concept and, in principle, are easier to expand than KATRIN.

Dirac versus Majorana

Neutrinoless double-beta decay is an extremely rare nuclear transition, possible only for a few tens of isotopes. The simplest mechanism enabling it to occur relates to the rate of the decay process to the square of the so-called 'effective Majorana neutrino mass', which is essentially a linear combination of the three different neutrino masses.

Current limits on Majorana neutrino mass are in the 60-600meV range and are being achieved in Europe by two running experiments located at LNGS: GERDA, which makes use of the isotope germanium-76; and CUORE using the isotope



single-beta decay | double-beta decay | neutrinoless double-beta decay

The Cryogenic Underground Observatory for Rare Events, CUORE (Credit: INFN)

tellurium-130. Analogous experiments exist in the US and Japan. Current-generation searches do not have the potential to explore the inverted neutrino mass hierarchy region, which corresponds to the range 15-50meV. The double-beta decay community is discussing possible next-generation experiments capable of attacking and potentially fully covering and surpassing such a region – a goal requiring an isotope-sensitive mass of the order of at least a few hundred kilograms.

The present experimental situation is characterised by a rich variety of projects and approaches, which can be grouped into three main classes of experiment according to the configuration of the source: fluid-embedded, crystal-embedded and external. In Europe, all three techniques are used, at Canfranc (fluid-embedded source), LNGS (crystal-embedded source) and Modane (external source). Existing infrastructures in Europe (GERDA and CUORE) already allow housing of a few hundred kilograms of isotope mass. Extensions up to this mass level are under discussion (i.e. the GERDA upgrade, a joint GERDA-MAJORANA experiment – coined LEGEND – and the proposed CUORE follow-up called CUPID). In parallel, several consortia are pursuing other promising technologies such as scintillating bolometers (LUMINEU, LUCIFER), external-source configurations (SuperNEMO) and a xenon-gas-filled time-projection chamber (NEXT).

Due to the high enrichment cost (in the €20–80M range), it is unlikely that there will be more than one next-generation experiment in Europe. Two may be possible, with US or general non-European participation. The next two to three years will be crucial in defining the technology employed by these future searches; essential indications will come from the performance – and especially the

The Germanium Detector Array (or GERDA) experiment is searching for neutrino-less double beta decay at the underground Laboratori Nazionali del Gran Sasso (LNGS) background levels – achieved by current-generation projects. Experiments and R&D activities based in Europe are at the forefront of all the options outlined above. A large investment in Europe – of the order of €60-80M – will be essential to support next-generation searches starting from 2018 and covering the period up to 2030.

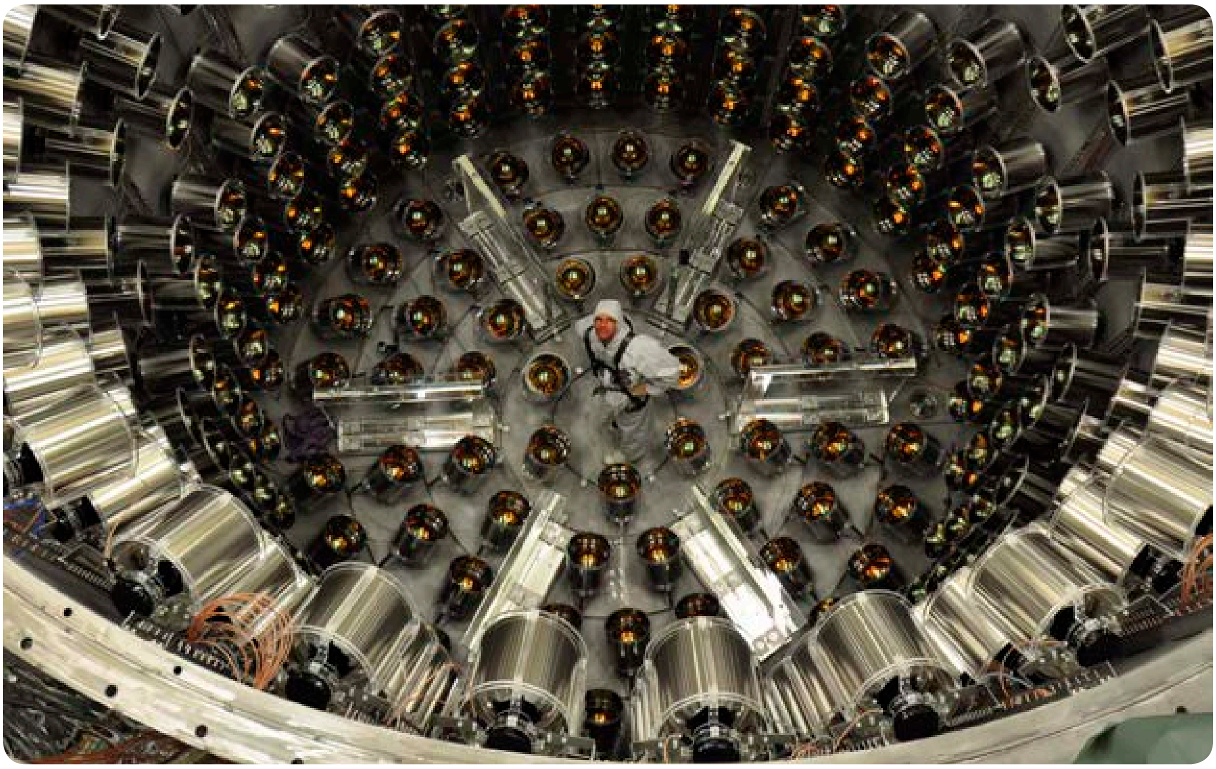
Neutrino mixing, mass hierarchy and more

A decade of revolutionary and ingenious experiments has unravelled the issue of neutrino flavours and solved the long-standing problem of solar neutrinos. We also have a diverse suite of experiments observing solar, reactor, accelerator and atmospheric neutrinos (and anti-neutrinos). The big question that is still outstanding is whether neutrinos, like quarks, exhibit charge-parity violation (i.e. a difference between certain neutrino processes and the corresponding anti-neutrino processes). Even though current experiments may give hints of neutrino charge-parity violation, new facilities are needed to settle this issue unambiguously (as well as the still-outstanding issue of the neutrino mass hierarchy). Whereas the observed charge-parity violation in the quark sector falls several orders of magnitude short with respect to explaining the observed asymmetry between matter and anti-matter in our Universe, such violation in the neutrino sector remains a promising and exciting potential explanation of this asymmetry and thus of our own existence.

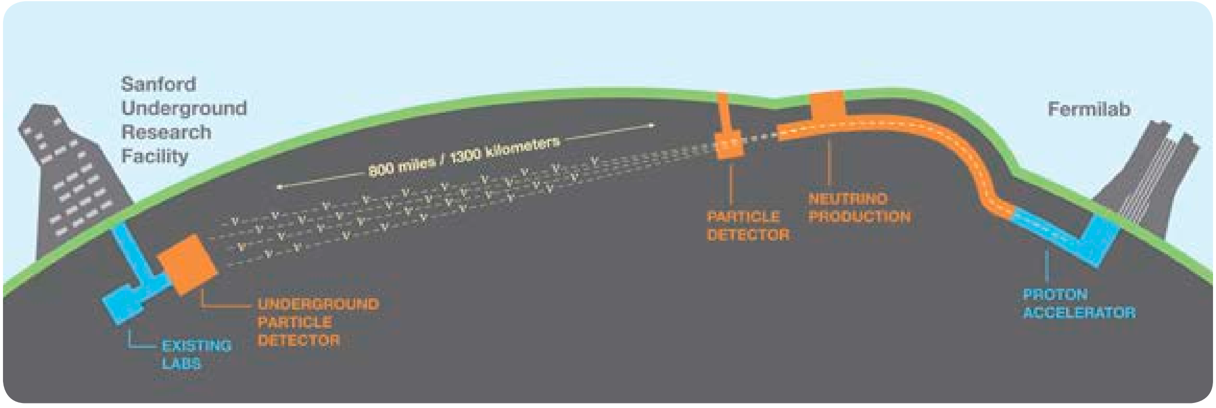
Vast detectors

Capitalising on the successes of pioneering neutrino experiments that explored neutrinos from nuclear reactors and also of long-baseline neutrino beams, construction of detectors that are an order of magnitude bigger is about to begin.

Several European research groups have joined the JUNO 20,000-ton liquid scintillator experiment in China, which will use electron-anti-neutrinos from a nuclear reactor complex that has a thermal power rating of around 36GW and is situated about 50 kilometres away. Although almost entirely funded by China, JUNO relies on key contributions from Europe. With data-taking scheduled from 2020 onwards, its primary aim is to resolve the neutrino mass hierarchy within five to six years of that date. The experiment's key performance indicator will be its excellent energy resolution for MeV neutrinos.



Core of the Double Chooz neutrino detector (Credit: CEA)



Artist's impression of the long baseline of DUNE, United States (Credit: Fermilab)

The real flagship future projects, however, are long-baseline neutrino beams. In the US, the LBNF, which will send a neutrino beam from Fermilab near Chicago to SURF 1300 kilometres away, received a major boost after the 2014 APPEC co-initiated workshop in Paris led a large number of European groups to direct their efforts there. DUNE, meanwhile, will employ one near detector and one huge, 40,000-ton far detector, both using a cryogenic liquid-argon time-projection chamber; this technology was developed in Europe and was successfully demonstrated by the 760-ton ICARUS experiment at the underground Gran Sasso laboratory that viewed neutrinos sent from CERN 730 kilometres away. Several European laboratories are working together within the WA105 collaboration at CERN towards a realistic implementation of this huge detector and its services at SURF. The first 10,000-ton module is expected to commence data-taking in 2024, with others to follow at a rate of one per year. Once completed, DUNE, with both muon-neutrino and anti-neutrino beams, will be the best-positioned experiment to address neutrino charge-parity violation. DUNE will also settle the neutrino mass hierarchy (if this has not been clarified earlier) and will significantly improve on many recently determined neutrino parameters.

Japan intends to upgrade the very successful Super-Kamiokande experiment from its present 50,000-ton water Cherenkov detector to an approximately 1,000,000-ton experiment called Hyper-Kamiokande. This experiment, in which various European groups intend to participate, will receive a neutrino beam from JPARC, located about 295 kilometres away. Studies are ongoing to install about half of the foreseen Hyper-Kamiokande upgrade in South Korea 1100 kilometres away; this would greatly enhance sensitivity to charge-parity violation. Irrespective of this, Hyper-Kamiokande and DUNE complement each other in many key respects: for example, water Cherenkov versus liquid-argon detection technology, narrow-band (off-axis) versus wide-band (on-axis) neutrino beam, and low (about 0.7 GeV) versus high (about 3 GeV) neutrino-beam energy. This will allow detailed studies of the effects of the different systems.

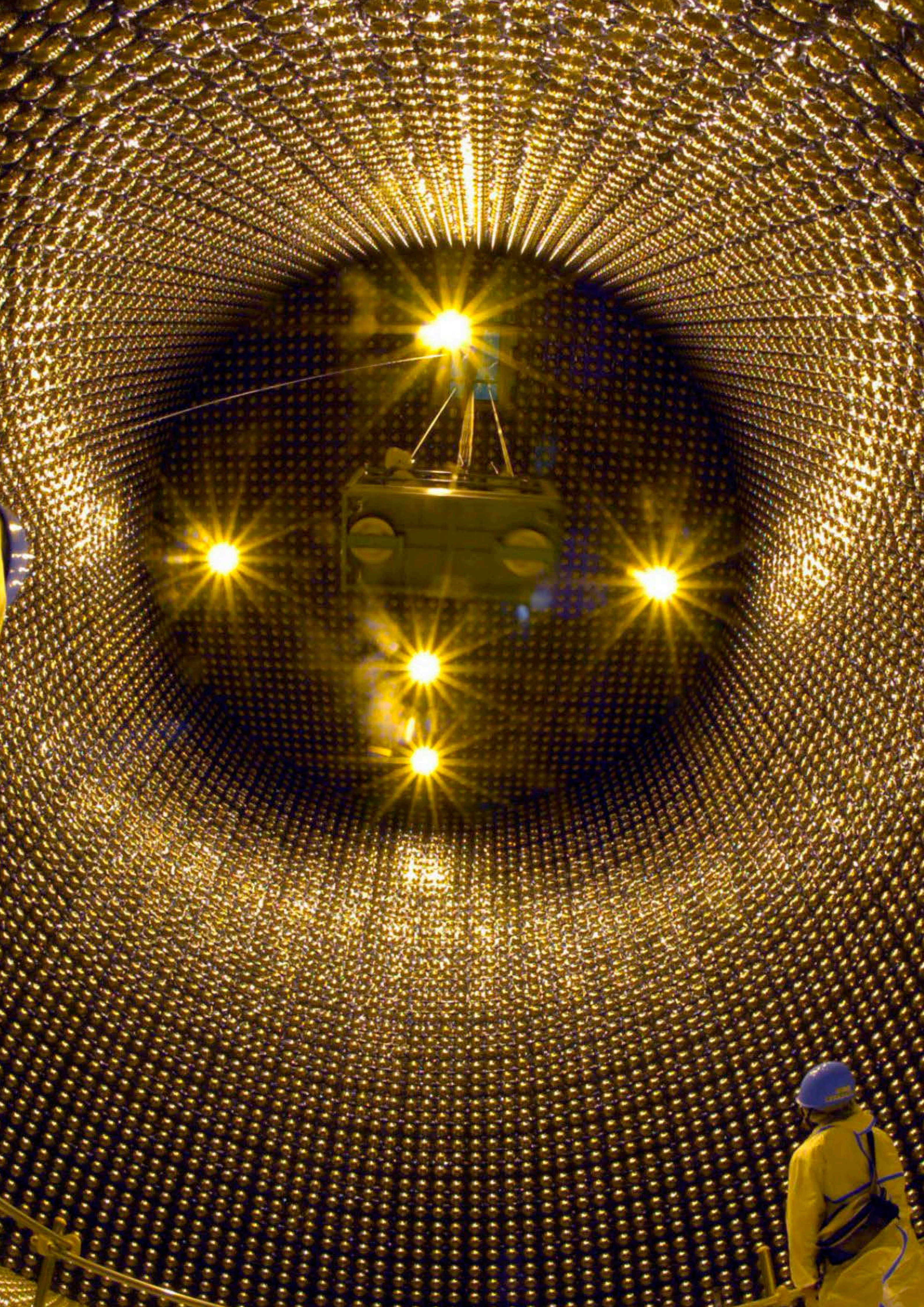
A big bonus: proton decay and neutrino astrophysics

The extraordinary precision and sheer mass of both the long-baseline neutrino beam and nuclear-reactor neutrino detectors give rise to other exciting opportunities too.

Several theories going beyond the Standard Model of particle physics predict that the proton has a finite but nevertheless extraordinarily long lifetime of at least 10^{35} years. Presently, Super-Kamiokande has set a lower limit on the proton lifetime at 10^{34} years, tantalisingly close to some of the theoretical predictions. With next-generation experiments typically containing more protons by almost an order of magnitude, we could witness the death of a proton! It may not affect us directly but it would profoundly change our understanding of the Universe.

These large detectors are also very well-suited to high-statistics and thus higher-precision studies of atmospheric, solar and supernova neutrinos. Whereas atmospheric and solar neutrinos have already been well-studied, only a handful of neutrinos from a single supernova (SN 1987A) have so far been observed. With the next generation of experiments, thousands of neutrinos will be recorded from a supernova in our own Milky Way galaxy. This would not only allow us to peer inside a newly formed neutron star or to 'see' the birth of a black hole – the distribution of the observed neutrinos in terms of the timing of their arrival could also provide valuable information on neutrino masses.

Image opposite: The "Super-Kamiokande" neutrino detector operated by the University of Tokyo's Institute for Cosmic Ray Research helped scientist Takaaki Kajita win a share of the Nobel Prize in Physics, along with Canadian Arthur B. McDonald. KYODO /LANDOV



4. The Early Universe

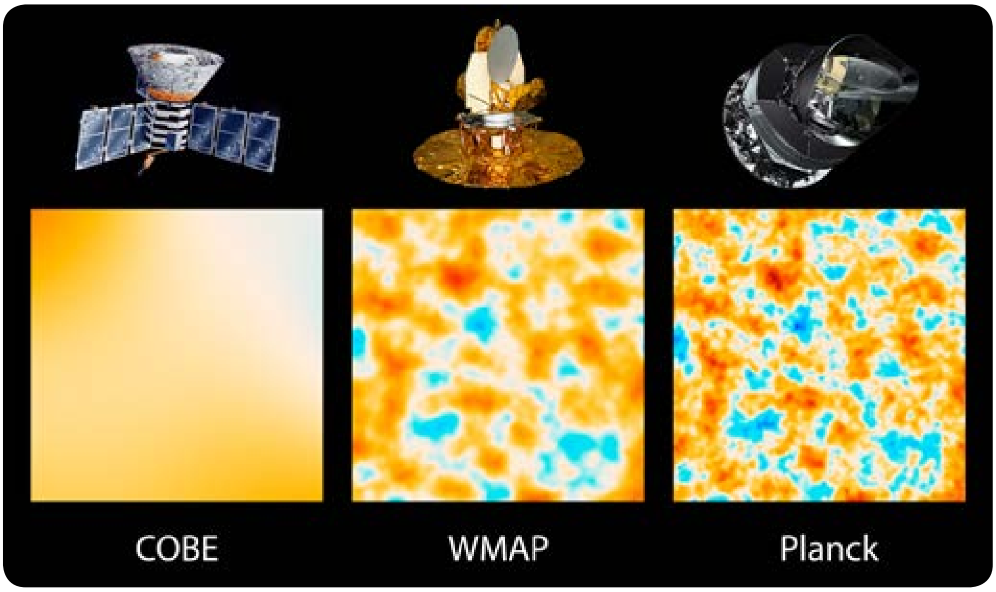
A place and time of unimaginable violence, extraordinary forces and events whose echoes we can still detect today, the early Universe holds secrets crucial to our understanding of the past, the present and the future. Astroparticle physics is a key tool for unravelling them.

Imaging the infant Universe

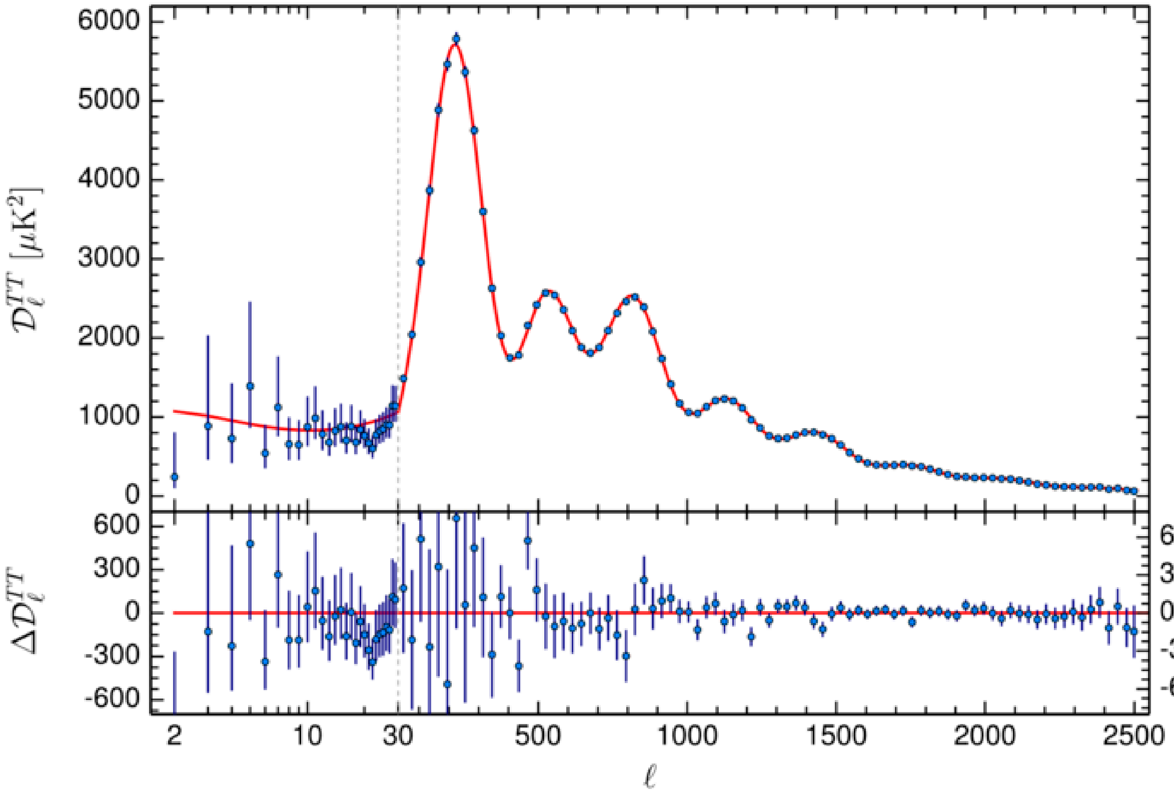
Today, it is only possible to reproduce conditions prevailing in the primordial plasma of the early Universe in the head-on particle collisions that take place in the most powerful, highest-energy manmade particle colliders. A detailed two-pronged investigation of the processes occurring in the infant Universe – involving direct observation of signals from the early Universe that are reaching us today and laboratory studies of conditions prevailing in the early Universe, replicated by man – is probably the most effective way to advance beyond our present understanding of the Big Bang Model of cosmology and the Standard Model of particle physics.

As outlined in Chapter 1, the discovery of the CMB in 1964 is our only direct window onto the Universe when it was just 400,000 years old. Establishing the astonishing uniformity of the CMB sky map, down to about one part in a thousand, stands as a major landmark in the development of the Big Bang theory.

The extreme violence of the Big Bang created a series of ripples in the primordial plasma. More specifically, the tiny quantum fluctuations that occurred during the period of inflation were 'trapped' in the form of macroscopic density fluctuations. In the era of recombination – about 400,000 years after the Big Bang, when the temperature had dropped to a level that allowed electrons and protons (and other nuclei) to form neutral atoms and render the Universe transparent to photons (i.e. light) – these fluctuations translated into tiny temperature variations in the photons that formed the hot and cold patches in the CMB sky map we observe today (a discovery that secured a Nobel Prize in 2006). Detailed analysis



Anisotropy of Cosmic Microwave Background as seen by COBE, WMAP and Planck



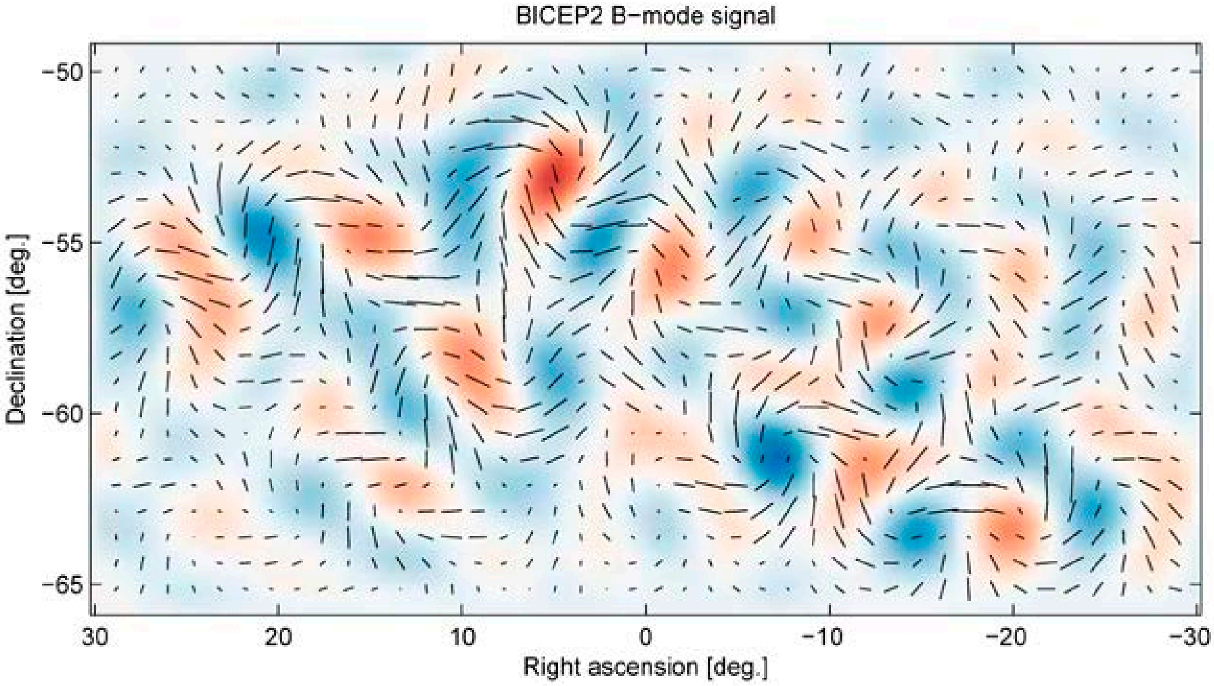
Planck power spectrum (Credit: ESA)

of these miniscule irregularities or 'anisotropies' provides information, for example, on the Universe's Dark Matter and Dark Energy content and on neutrino masses. These same irregularities are expected to comprise the seeds of galaxy and galaxy-cluster formation, providing further strong support for the Big Bang theory of cosmology.

At the level of about one part per million, the CMB turns out to be polarised; in other words, the underlying oscillations of the electric and magnetic fields, jointly constituting CMB light, exhibit a minute directional anisotropy. Two types of polarisation have been identified, coined electric (E) mode and magnetic (B) mode. Whereas E-modes can easily be traced back to small density variations in the opaque plasma that existed at the time of photon decoupling, B-modes are more exciting. Gravitational lensing (the bending of light in the vicinity of large masses) of E-modes in the early Universe can give rise to B-modes and provide information on the distribution of matter, including Dark Matter and neutrinos in the entire visible Universe. More exciting still, gravitational waves associated with the period of inflation – and possibly going back to the earliest conceivable time (the so-called 'Planck time' about 10–43 seconds after the Big Bang) – can also give rise to B-modes. Indisputable evidence of B-modes induced by gravitational waves would allow us to study inflation and, hopefully, elucidate the mechanism(s) behind it. This would unlock one of the most formidable, most elusive secrets of all: what our Universe was like practically at the moment of its birth!

Taking a two-pronged approach

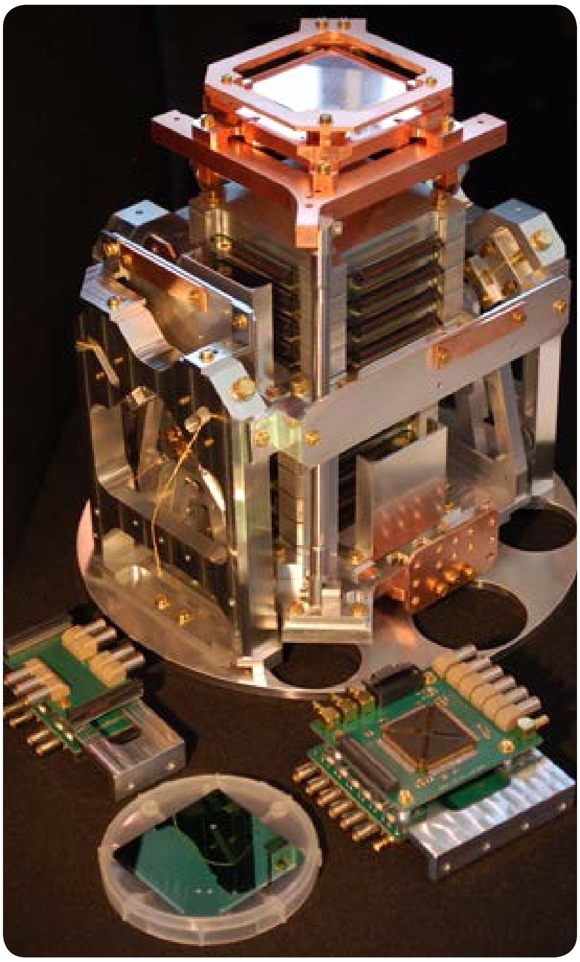
Unravelling the secrets hidden in the B-modes requires combined observations from space and from the ground. Ground-based CMB experiments permit deployment of very large detector arrays and so yield exquisite angular resolution. Space-based measurements, on the other hand, are not limited by the atmosphere and can probe a wide frequency range to provide unsurpassed parametrisation of the 'foreground' – B-modes arising from gravitational-lensed E-modes. It is this foreground that must be subtracted to reveal the true 'holy grail': primordial B-modes induced by gravitational waves.



The 'curly' B-modes of polarization in the cosmic microwave background (Credit: Harvard University/BICEP2)

In recent years, with the Planck satellite mission, Europe has clearly secured leadership in space-based CMB studies. Moreover, it looks set for an equally exciting future as a result of the recently submitted COrE satellite mission proposal, which is primarily aimed at studying the B-modes and therefore primordial gravitational waves.

Both on the ground and in the exploitation of high-altitude balloon flights, the US currently dominates CMB research. A plethora of experiments are already taking data or are at the planning stage for the near future: ACT, CLASS, POLARBEAR and the Simons Array in Chile's Atacama desert; SPT, BICEP2/BICEP3 and the Keck Array at the South Pole; and, in the field of (ultra-)long-duration balloon flights, EBEX, SPIDER and PIPER. Nevertheless, a few European ground-based CMB programmes already exist: QUBIC (in Argentina), QIJOTE and NIKA2 (both in Spain), and the LSPE and OLIMPO balloon flights. To improve significantly sensitivity for B-modes in particular, next-generation ground-based experiments are exploring new, cryogenic detection technologies such as TES and KIDs. Building on the EU-funded SPACEKIDS project, Europe is leading the development of KIDs technology – a technology not only well-suited to next-generation CMB experiments but also expected, as CCDs of the future, to have industrial applications.



Qubic 1/4 of the focal plane

An exhilarating future

The future CMB programme sets the stage for a range of opportunities to link key themes together and provides a potential stepping-stone towards further fundamental discoveries. Firstly, the prospect of measuring the parameters of inflation – possibly associated with the recently discovered Higgs particle – could connect physics at the electroweak scale to physics at the scale of inflation. Secondly, comparison of neutrino characteristics inferred from cosmological measurements with those determined in laboratory experiments is likely to become a portal to New Physics – in other words, physics beyond the Standard Model of particle physics and the Big Bang Model of cosmology. Thirdly, the study of correlations between primordial fluctuations revealed in the CMB and large-scale structures in the visible Universe – especially those studied in Dark Energy surveys – will guide the way towards a unified description of the complete, visible and 'invisible' (i.e. dark) Universe.

Furthermore, the astroparticle physics community will continue to ponder how to explore the treasures hidden in another primordial cosmic-messenger signal: the ubiquitous neutrino background, set free a few seconds after the Big Bang and now corresponding to a temperature of about minus 271.2°C. Once observed, these primordial neutrinos will give us a glimpse of our Universe when it had only been in existence for a few seconds.

POLARBEAR telescope in Chile's Atacama Desert

5. The Dark Universe

Perhaps nothing is as tantalising as something you cannot see – especially when it holds one of the keys to comprehending how the Universe functions and what its future may hold. When it comes to Dark Matter and Dark Energy, astroparticle physics can help pick the lock and open up a hitherto sealed chamber of extraordinary secrets.

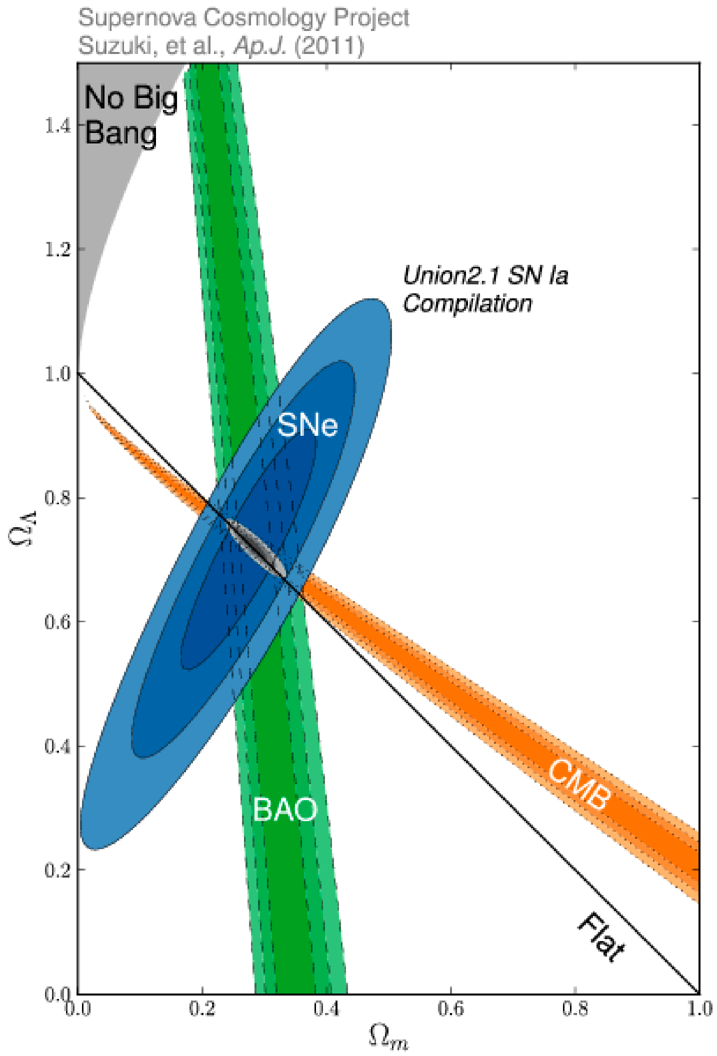
Out of the darkness…

Most of our Universe is actually 'dark'. Arguably, this discovery represents the most astonishing surprise of all in our never-ending quest to crack the secrets of the micro- and macro-cosmos. Indeed, the Universe is dark not simply in the technical sense of being invisible, but also in the more abstract sense of being beyond our comprehension.

Proof that the total quantity of matter present in galaxies and galaxy clusters far exceeds the quantity of visible matter (i.e. stars and gas clouds) has continued to accumulate over the last four decades. In fact, invisible matter – dubbed Dark Matter – exceeds the amount of visible matter by about a factor of five. But what particles does Dark Matter contain? Confronting the combined power of the Big Bang Model of cosmology and Standard Model of particle physics on the one hand with astrophysical observations on the other yields an astonishing conclusion: Dark Matter does not match the characteristics of any known elementary particle…

The result is the realisation that there is almost certainly a branch of physics beyond the one we are familiar with. This is the realm of New Physics, where a plethora of models have been proposed involving Dark Matter candidates such as 'axions', 'wimpzillas' and 'sterile neutrinos' – particles with an enormous variety of masses, ranging from axion masses of a millionth of an eV to wimpzilla masses 30 orders of magnitude bigger. One class of Dark Matter candidates stands out, however: WIMPs. These can 'naturally' reproduce the observed density of Dark Matter and are predicted to exist by several well-meaning extensions to the Standard Model of particle physics.

The Dark Matter enigma has undoubtedly come as a real surprise to the fields of physics, astronomy and cosmology. Given the numerous elementary particles discovered over the past century, however, it is by no means impossible that some particles are still undiscovered. By contrast, what really does seems inconceivable is a discovery made at the end of the 20th century in connection with our Universe's expansion. Given that this expansion was set in motion by the 'explosion' of the Big Bang, it was taken as an indisputable fact that the speed at which galaxies were drifting apart would decrease with time. Indeed, two projects aimed to measure the actual slowdown of the expansion rate of the Universe.



Allowed Dark Matter and Dark Energy bands in the Universe from various measurements.

Against all expectations, both groups found that the expansion was actually accelerating! This extraordinary discovery was rewarded with a Nobel Prize in 2011. Crucially, according to General Relativity, only a new kind of (uniformly distributed) energy could be causing such an accelerated expansion – a new form of energy with negative pressure. Perhaps a little unimaginatively, this 'new' energy was given the name Dark Energy. As it turns out, today Dark Energy constitutes most of the mass-energy content of the Universe: ordinary matter provides around 5%, Dark Matter around 27%, while Dark Energy accounts for the remaining 68%.

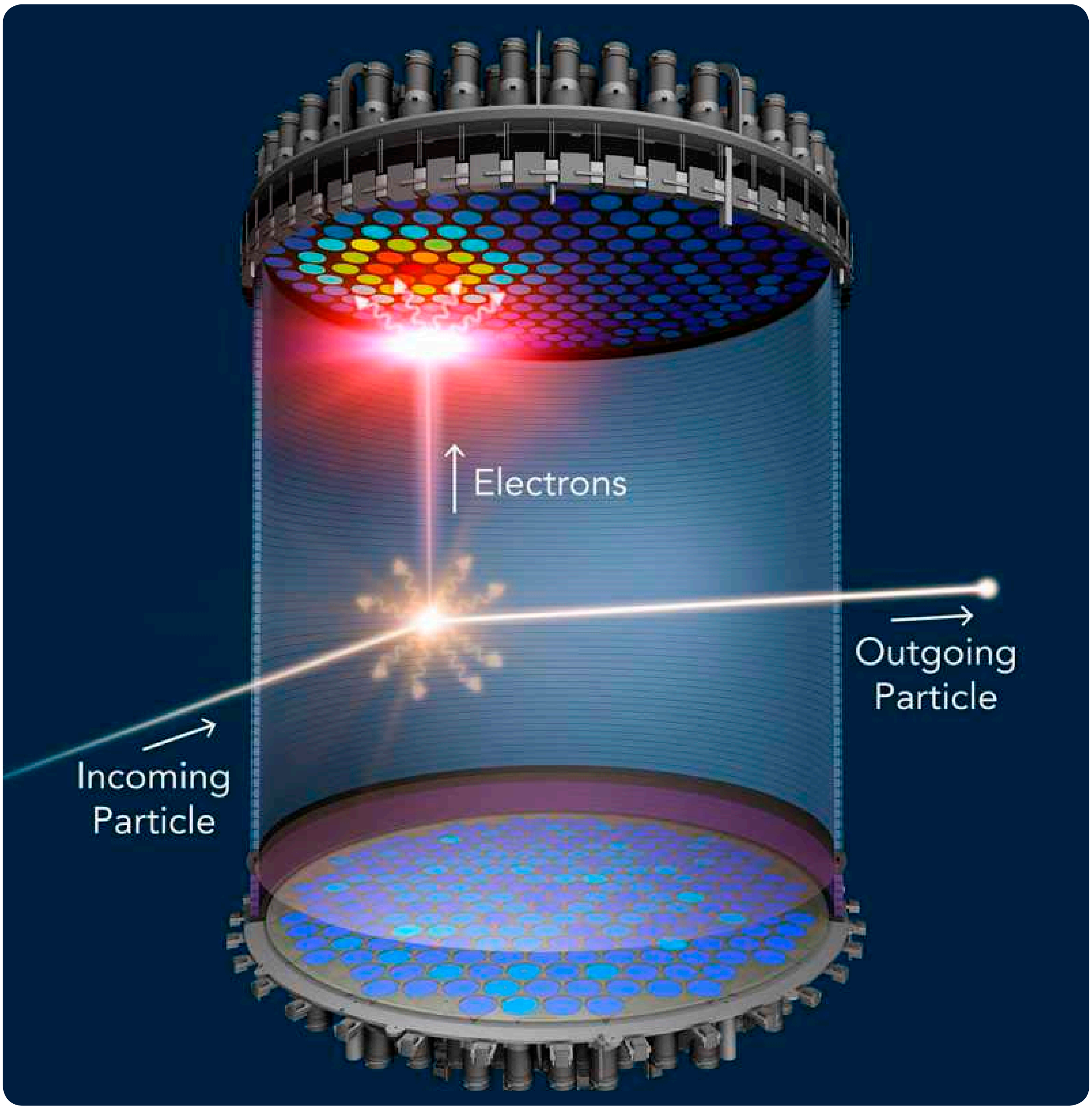
Dark Energy could be stationary in time – corresponding, for example, to the (infamous) cosmological constant in Einstein's formulation of General Relativity. Alternatively, it could vary in time and be related, for instance, to the changing potential energy of some scalar field (i.e. a field fully described by a numerical value alone, such as the Higgs field). Only experiments will be able to resolve this question and several groups are working to do so, not only repeating the detailed studies of supernovas of the 1990s but also accurately mapping the distribution of galaxies in the Universe.

The nature of Dark Matter and Dark Energy is still a mystery, but an even more disturbing and profound dilemma is posed by Dark Energy's density. Since Dark Energy is uniformly distributed throughout the entire Universe, its density (i.e. the amount of Dark Energy per unit volume of space) is embarrassingly small, corresponding to an energy scale of only 10^{-3}eV. This is very difficult (if not impossible) to accommodate in any known theoretical scheme and is often called the 'cosmological constant problem' – yet another manifestation of the difficulty of formulating a coherent theory that encompasses both General Relativity and quantum mechanics. In fact, it is widely considered to be the mother of all problems currently confronting us in the sphere of (particle) physics.

So how are we addressing these huge questions that are, quite literally, shrouded in darkness?

Dark Matter

Discovering the nature of Dark Matter is almost synonymous with gaining access to the realm of fundamental physics beyond the Standard Model of particle physics. Not surprisingly, this is an issue being attacked from a range of directions. Dark Matter creation is frantically being sought at the world's most powerful particle colliders, such as the LHC, and falls beyond the scope of astroparticle physics. On the other hand, the annihilation of Dark Matter in regions where it is expected to accumulate (e.g. the centre of the Sun,



Dark Matter detection principle for Noble liquids experiments the centre of our galaxy, and dwarf galaxies) can be identified by observing, on top of the astrophysical background, an excess of (high-energy) photons, neutrinos or cosmic rays, for example; this is a sub-topic being explored by observatories discussed in Chapter 2. Meanwhile, observation of the scattering of Dark Matter particles, especially WIMPs, is being pursued in the laboratory; this 'direct detection', which directly probes the density of Dark Matter here on Earth, is discussed below.

Beating background interference

Direct searches for Dark Matter hunt for signals from excited nuclei produced by the scattering of a passing Dark Matter particle. To suppress background interference due particularly to cosmic rays and the decay of radioactive isotopes, the detectors must be extremely radio-pure and located deep underground. Several European groups are currently involved in a broad range of such experiments aiming to detect WIMP-induced light flashes, heat release or ionisation. The combination of two or more of these three signatures provides the best way of 'beating the background'. For instance, detectors filled with noble liquids combine detection of ionisation and light flashes, whereas cryogenic crystals can be used to detect heat release and light flashes or heat release and ionisation. Collectively, they have reached unprecedented sensitivities over a wide WIMP-mass range, probing WIMP-nucleon cross-sections below 10^{-45} per centimetre squared for WIMP masses around 40 GeV.

The highest sensitivity for WIMPs in a mass range of around 5 GeV to 10 TeV is reached by experiments using, as a target, liquid xenon (notable examples include LUX in the US, PandaX in China and XENON100 in Italy) and liquid argon (e.g. DEAP in Canada, DarkSide-50 in Italy, pioneering the use of argon depleted in argon-39, and ArDM in Spain). A ton-scale xenon detector, XENON1T, is being commissioned and, after two years of continuous operation, can access cross-sections as low as 10^{-47} per centimetre squared. For the near future, multi-ton-scale liquefied noble-gas detectors with strong European participation are already at an advanced planning stage: namely, XENONnT (8 tons of xenon), LZ (7 tons of xenon) and DarkSide-20k (20 tons of argon). For lower-mass WIMPs (below 6-7 GeV), the best performance is achieved using a combination of light and heat signals or ionisation and heat signals in cryogenic detectors cooled down almost to absolute zero: for example, CRESST (at LNGS in Italy) combines light and heat signals, while EDELWEISS (at LSM in France) combines ionisation and heat signals. In the U.S. and Canada, SuperCDMS and DAMIC are also pursuing low-mass dark matter.

DarkSide detector (credit: DarkSide)

XENON1T installation in the underground hall of Laboratori Nazionali del Gran Sasso (Credit: Roberto Corrieri and Patrick De Perio)

Detector Mounting at the CRESST experiment, Gran Sasso. Near the detectors, all work has to be done under clean room conditions. (Credit: CRESST)

None of the experiments summarised above has been able to claim discovery of Dark Matter. Instead, they have reported upper limits on the WIMP-scattering cross-section. The DAMA/LIBRA collaboration in Italy, however, which has studied light flashes in sodium iodide crystals over the past 15 years, has consistently reported an intriguing, very convincing annual modulation of their event rate exactly in phase with the expected modulation due to Earth orbiting the Sun; this is difficult to reconcile, however, with the upper limits reported by many other experiments. To ascertain whether the DAMA/LIBRA modulation is indeed due to Dark Matter particles, independent confirmation is needed from other experiments and especially from those now planned at LNGS and in the southern hemisphere.

Towards the ultimate direct search

Present technologies can be pushed until they hit the background produced by coherent scattering of solar and atmospheric neutrinos – albeit an interesting signal in itself. In Europe, to probe WIMP masses up to 10 GeV, the EURECA consortium aims to push cryogenic detectors as used by CRESST and EDELWEISS to the ton-scale. Similarly, the DARWIN (50 tons of xenon) and Argo (200 tons of argon) consortia plan to construct the ultimate noble-liquid detectors to explore WIMP masses in the 10 GeV to 1 TeV range.

Going beyond the coherent neutrino-scattering wall will require direction-sensitive detectors. As long as convincing Dark Matter signals are found, such detectors will almost certainly be crucial to assessing the detailed nature as well as the astrophysical origin of Dark Matter. Anticipating this, detector R&D in this sphere has already begun.

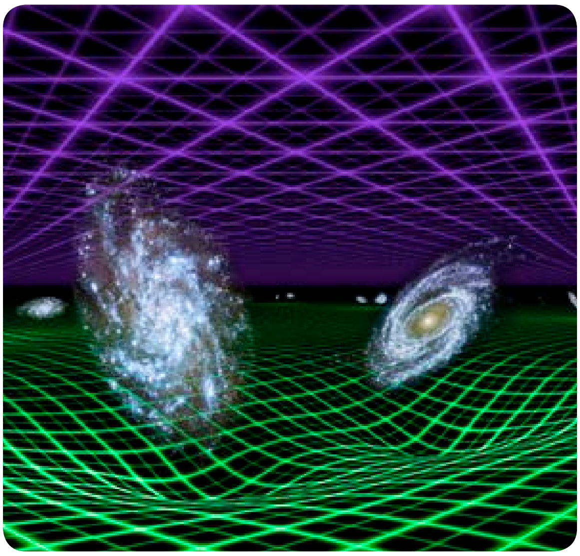
Dark Energy

Unravelling the exact nature of Dark Energy poses an enormous challenge. Dark Energy could be incorporated into General Relativity as Einstein's cosmological constant (and possibly even related to quantum vacuum energy); or it could be the potential energy of a new fundamental scalar field (generally dubbed 'quintessence'). Even though current observations are consistent with a flat, cosmological-constant-dominated Universe, alternative explanations of Dark Energy should not be ruled out. For example, we cannot exclude the possibility that the General Theory of Relativity falls short at extremely large scales – a path followed by proponents of modified gravity theories. Dark Energy could even be due to something which, to date, has completely eluded our imagination.

To begin building a better understanding of Dark Energy, we need precise mapping of two things: the evolution of the expansion rate of the Universe; and the growth rate of structures in the Universe. Dark Energy affects both, but in different ways. By accurately measuring each of these rates, we will be able, for instance, to start disentangling explanations based on theories of modified gravity from explanations that include a genuinely new component (e.g. Einstein's cosmological constant or a new scalar field).

Mapping the entire Universe

Spectroscopic surveys of galaxies measure the spectra – and thus the redshifts – of a given set of galaxies in order to yield a detailed 3D map of galaxy distributions in the Universe. Because they rely on a pre-selected set of galaxies, however, they are incomplete and the procedure itself is demanding in terms of both resources and observation time. Imaging – or photometric – surveys, on the other hand, are very efficient and almost unbiased but, due to their limited



In this artist's conception, dark energy is represented by the purple grid above, and gravity by the green grid below. Gravity emanates from all matter in the universe, but its effects are localised and drop off quickly over large distances.
Credit: NASA/JPL-Caltech

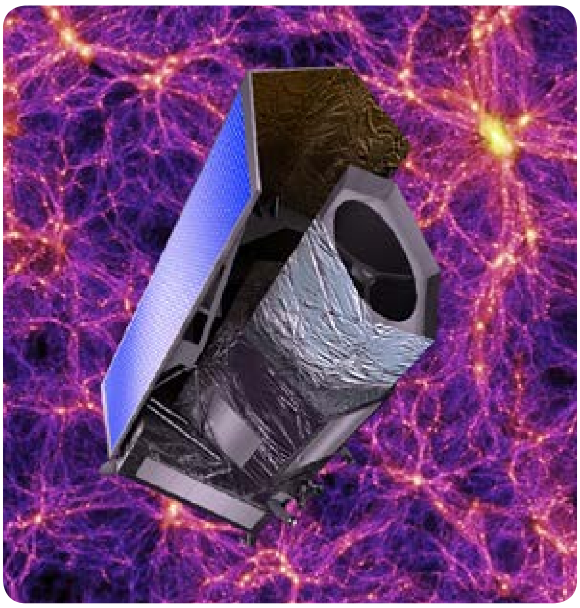

Artist's impression of the Large Synoptic Survey Telescope, LSST (Credit: LSST)

resolution along the galaxy's line of sight, do not provide a complete 3D view of the Universe. Nevertheless, imaging surveys are invaluable because of the large volume they cover – crucial to understanding the Universe's Dark Energy and Dark Matter content. This is especially so in view of the so-called weak-lensing technique, which allows reconstruction of an 'invisible' foreground mass using this mass's lensing (i.e. gravitational bending) of the light from an ensemble of galaxies located further away, and as such constitutes one of the most precise probes for Dark Energy (as well as for Dark Matter).

The view from the ground – and space
Ground-based Dark Energy research – spectrometric and photometric – is dominated by the US. DES, the photometric galaxy survey at the Cerro Tololo Inter-American Observatory in Chile, is expected to improve our understanding of both the Universe's historical expansion rate and the historical rate of growth of structures in the Universe out to redshifts of about 1.3 (i.e. when the Universe was about 5 billion years old). These results will be augmented by the DESI spectroscopic survey at Kitt Peak National Observatory in Arizona, scheduled to start operations in 2018. DESI will provide a very precise measurement of expansion history, from today back to a redshift of 3.5 when the Universe was just 2 billion years old. Several European groups are participating in DES and DESI.

The largest ground survey of all will be undertaken by LSST, a wide-field telescope to be located in Chile and expected to start operations is 2021. A US-led project with strong French input and several other European countries considering joining, LSST will cover billions of galaxies deeper, wider and faster than any optical survey to date; in particular, thanks to its fast cadence, it will collect detailed images of the Universe at an unprecedented rate. The efficient, timely analysis of the estimated volume of annual data that will be generated – in the order of 10 petabytes – poses a key challenge.

In terms of space-based Dark Energy research, Europe is expected to take a lead in the coming decade with ESA's Euclid mission scheduled for launch in 2020. Euclid combines weak-lensing imaging techniques such as those incorporated in LSST with a spectroscopic survey such as that performed by DESI. Unhindered by Earth's atmosphere, it will also be able to push the weak-lensing technique to its limit. Euclid will rely on ground-based imaging surveys to determine reliably the (photometric) redshifts of the billion-plus galaxies it is expected to measure. Euclid is therefore negotiating with such surveys; an agreement to exchange data with LSST, in particular, would ensure that Euclid is an excellent example of global collaboration and would maximise the progress achieved by this exciting field of research.


An artist's concept of the Euclid dark energy telescope in space (Credit: ESA)

6. Outlook

So…what next?

Within just a matter of decades, astroparticle physics has evolved into a mature, exhilarating and illuminating field of research comparable in size to accelerator-based particle physics. Its core activities – the multi-messenger exploration of the extreme Universe, the quest for Dark Matter and the search for the true nature of neutrinos – are all in full swing. Discoveries such as neutrino oscillations and cosmic PeV-scale neutrinos and the recent direct observation of gravitational waves constitute revolutionary – often Nobel Prize-worthy – breakthroughs. With new facilities already under construction or at an advanced planning stage, the prospects for the near future are excellent.

If Europe is to play a prominent role, however – given the ambitious plans and fierce competition originating from, especially, the US, China and Japan – it will be essential to align its collective funding so that, in particular, flagship initiatives such the ESFRI-listed CTA and KM3NeT projects can be realised in a timely manner along with, on a slightly longer timescale, next-generation European Dark Matter and double-beta decay experiments, as well as next-generation gravitational-wave observatories such as the ET on Earth and the LISA satellite in space.

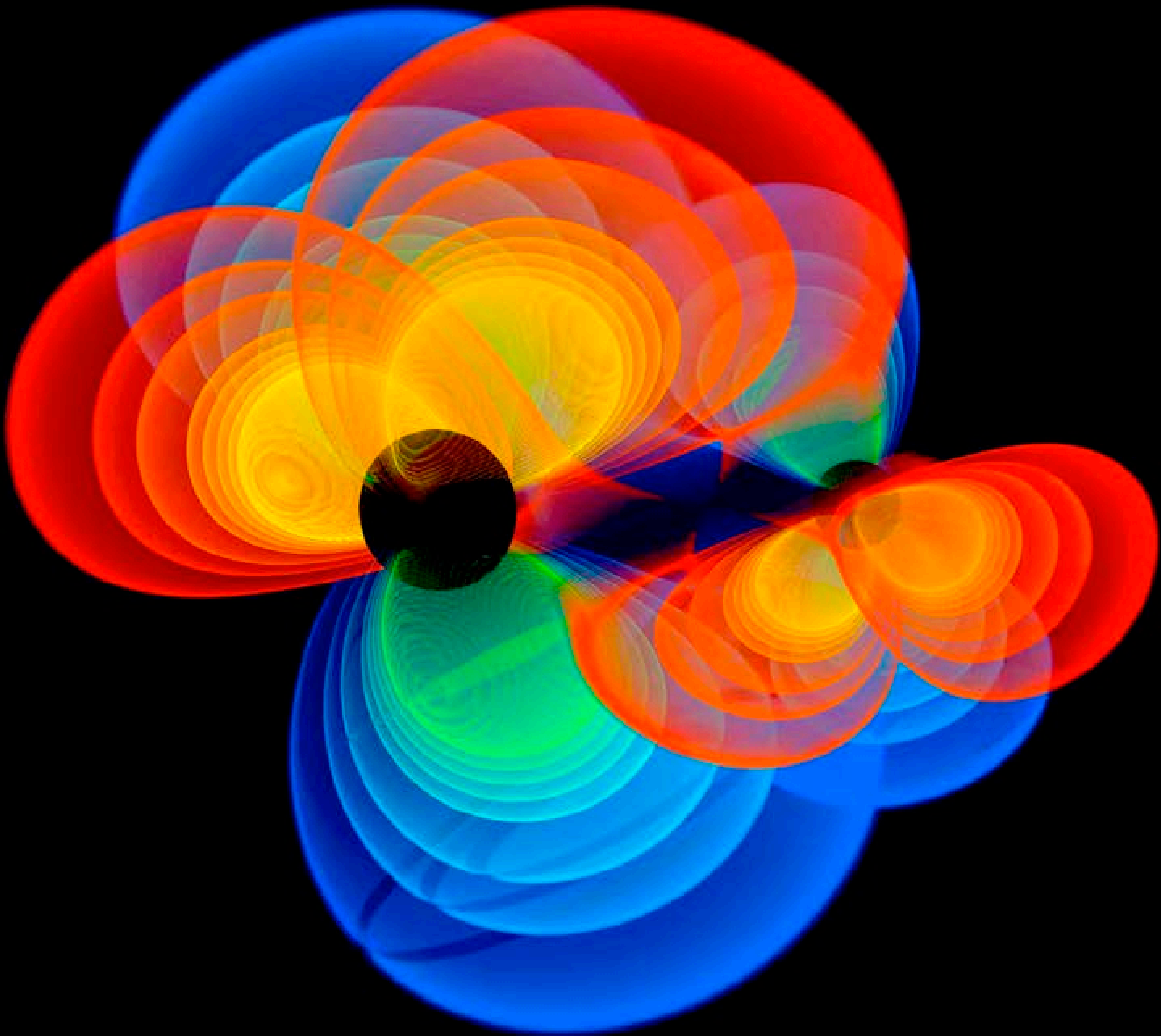
In a number of countries, the scope of astroparticle physics has recently been expanded to include experiments targeted at a better, more detailed understanding of Dark Energy and the CMB. These are important topics in their own right, but each also provides independent and often complementary information on subjects such as neutrino properties and the overall composition and evolution of our Universe. With upcoming Dark Energy facilities on the ground (DESI and LSST) and in space (Euclid) offering performance improvements of an order of magnitude compared with their precursors, and with next-generation CMB research directed specifically at the discovery of B-mode polarisation – the tell-tale signal of the period of inflation in the very early Universe – ground-breaking discoveries are anticipated.

Considering together, in an integrated strategy, the extreme, dark and early Universe and experiments in pursuit of neutrinos' true nature is probably the most efficient and effective way not just to unveil the intricacies of our Universe but also to solve many of the mysteries it poses. Progress in these fields will help to expose the limits of the Standard Model of particle physics and the Big Bang Model of cosmology and thus guide the way to a genuinely overarching, all-encompassing theoretical framework that sets a new benchmark for human understanding of the Universe.

The strategy and recommendations set out in this roadmap document aim to put Europe in pole position in this remarkable field over the coming years. Given the rapid advances achieved to date and the number of new infrastructures expected to begin operating within the next five to seven years, we recommend that the strategy is updated by around 2022.

APPEC

Part 3: Acronyms and Abbreviations



Acronyms and Abbreviations

Note: not all capitalised names of projects, facilities etc. in this document stand for something specific (e.g. HOLMES)

ACT	Atacama Cosmology Telescope
AMS	Alpha Magnetic Spectrometer
ANTARES	Astronomy with a Neutrino Telescope and Abyss Environmental Research
APPEC	Astroparticle Physics European Consortium
ARCA	Astroparticle Research with Cosmics in the Abyss
ArDM	Argon Dark Matter
ASPERA	Astroparticle European Research Area Network
ASTERICS	Astronomy ESFRI and Research Infrastructure Cluster
BICEP	Background Imaging of Cosmic Extragalactic Polarisation
CCD	Charged Couple Device
CERN	European Organization for Nuclear Research
CLASS	Cosmology Large Angular Scale Surveyor
CMB	Cosmic Microwave Background
COrE	Cosmic Origins Explorer
CRESST	Cryogenic Rare Event Search with Superconducting Thermometers
CTA	Cherenkov Telescope Array
CUPID	CUORE Upgrade with Particle Identification
CUORE	Cryogenic Underground Observatory for Rare Events
DAMA	Dark Matter
DAMIC	DAMIC - Dark Matter in CCDs
DARWIN	Dark Matter WIMP Search with Liquid Xenon
DEAP	Dark Matter Experiment using Argon Pulse Shape
DES	Dark Energy Survey
DESI	Dark Energy Spectroscopic Instrument
DULIA	Deep Underground Laboratory Integrated Activity
DUNE	Deep Underground Neutrino Experiment
EBEX	E and B Experiment
ECHo	Electron Capture Holmium-162
EDELWEISS	Expérience pour Detecter les WIMPS en Site Souterrain
E-ELT	European Extremely Large Telescope
ERC	European Research Council
ESA	European Space Agency
ESFRI	European Strategy Forum on Research Infrastructures
ESO	European Southern Observatory

Acronyms and Abbreviations

ET	Einstein Telescope
EURECA	European-Japanese Calorimeter Array
EU-T0	European Union Tier-0
eV	Electron volt: the energy gained (or lost) by an electron passing over an electric potential difference of one volt. 1 milli-electron volt (meV) = 10^{-3} eV, 1 kilo-electron volt (keV) = 10^{3} eV, 1 mega-electron volt (MeV) = 10^{6}eV, 1 giga-electron volt (GeV) = 10^{9} eV, 1 tera-electron volt (TeV) = 10^{12} eV and 1 peta-electron volt (PeV) = 10^{15} eV
GENERA	Gender Equality Network in the European Research Area
GEP	Gender Equality Plan
GERDA	Germanium Detector Array
GNN	Global Neutrino Network
GPS	Global Positioning System
GVD	Gigaton Volume Detector
GWIC	Gravitational Wave International Committee
HESS	High Energy Stereoscopic System
Hz	Hertz: the unit of frequency, with 1Hz defined as one cycle per second. 1 kilohertz (kHz) = 10^{3}Hz
H2020	Horizon 2020
IACT	Imaging Atmospheric Cherenkov Telescope
ICARUS	Imaging Cosmic and Rare Underground Signals
IPPOG	International Particle Physics Outreach Group
JEM-EUSO	Japanese Experiment Module Extreme Universe Space Observatory
JPARC	Japan Proton Accelerator Research Network
JUNO	Jiangmen Underground Neutrino Observatory
KAGRA	Kamioka Gravitational Wave Detector
KATRIN	Karlsruhe Tritium Neutrino Experiment
KID	Kinetic Inductance Detector
KM3NeT	Cubic Kilometre Neutrino Telescope
LBNF	Long Baseline Neutrino Facility
LHC	Large Hadron Collider
LIBRA	Large Sodium Iodide Bulk for Rare Processes
LIGO	Laser Interferometer Gravitational Wave Observatory
LISA	Laser Interferometer Space Antenna
LNGS	Laborati Nazionali del Gran Sasso
LSM	Laboratoire Souterrain de Modane
LSPE	Large Scale Polarisation Explorer

Acronyms and Abbreviations

LSST	Large Synoptic Survey Telescope
LUMINEU	Luminescent Underground Molybdenum Investigation for Neutrino Mass and Nature
LUX	Large Underground Xenon
LZ	LUX-ZEPLIN (ZEPLIN = Zoned Proportional Scintillation in Liquid Noble Gases)
MAGIC	Major Atmospheric Gamma Ray Imaging Cherenkov
NEXT	NASA (National Aeronautics and Space Administration) Evolutionary Xenon Thruster
NIKA2	New Instrument of KIDs Arrays
ORCA	Oscillation Research with Cosmics in the Abyss
PandaX	Particle and Astrophysical Xenon Detector
PINGU	Precision IceCube Next Generation Upgrade
PIPER	Primordial Inflation Polarisation Explorer
PMT	Photo-Multiplier Tube
QUBIC	Q and U Bolometric Interferometer for Cosmology
R&D	Research and Development
SKA	Square Kilometre Array
SPT	South Pole Telescope
SuperCDMS	Super Cryogenic Dark Matter Search
SuperNEMO	Super Neutrino Ettore Majorana Observatory
SURF	Sanford Underground Research Facility
TA	Telescope Array
TES	Transition Edge Sensor
VERITAS	Very Energetic Radiation Imaging Telescope Array System
W	Watt: the unit of power, with 1W equivalent to one joule per second. 1 megawatt (MW) = 106W
WIMP	Weakly Interacting Massive Particle

“Squaring the circle”: a square shadow from a luminous disc is almost as hard to conceive as the often unimaginable phenomena astroparticle physics aims to solve.

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